石油资源管理系统应用指南

Guidelines for Application of the Petroleum Resources Management System

English - Chinese Version

Sponsored by:

Society of Petroleum Engineers (SPE)
American Association of Petroleum Geologists (AAPG)
World Petroleum Council (WPC)
Society of Petroleum Evaluation Engineers (SPEE)
Society of Exploration Geophysicists (SEG)

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Guidelines for Application of the Petroleum Resources Management System

英文 - 中文版

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前 言

Preface

The Guidelines for Application of the Petroleum Resources Management System (hereinafter referred to as the "Guidelines") was sponsored jointly by the Society of Petroleum Engineers (SPE), American Association of Petroleum Geologists (AAPG), World Petroleum Council (WPC), Society of Petroleum Evaluation Engineers (SPEE) and Society of Exploration Geophysicists (SEG) and published in November 2011. It currently serves as a major specification and guidelines for the petroleum resources management and evaluation practice in global industry. In this Guidelines, from the perspective of systematic engineering on the petroleum resources management, the background and nationals for the guidelines are introduced, PRMS definitions, classification and categorization are further expounded, technical Principles and applications of the key methodologies used in resources and reserves evaluation are illustrated based on typical examples, and a series of important theoretical and practice issues associated with resources management, assets evaluation and reporting are discussed as well. As the Guidelines is rich in content and practical with application examples universal and applicable, it has been widely adopted and applied in the global oil industry, and also accepted by the U.S. Securities and Exchange Commission (SEC) as an important supporting basis for its new "modernization of oil and gas reporting" rules. The Guidelines in English-Chinese version is of great significance to further promote PRMS' global application. It is not only a very useful working hand book for Chinese speaking petroleum engineers and geologists, but also a helpful reference textbook for young petroleum scholars in petroleum universities.

The translation work has been guided by the SPE oil and gas reserves committee, supported by the Department of Mineral Resources Protection and Supervision of the Ministry of Natural Resources of China, and contributed by experts mainly from China National Oil and Gas Exploration and Development Company Ltd. (CNODC), Research Institute of Petroleum Exploration and Development (RIPED) and Petroleum Industry Press (PIP). All above contributions are sincerely acknowledged. If there is any misleading translation existing in the Chinese version of the Guidelines, the original English version shall prevail. You are also welcome to feedback comments and guide our work in the coming future.

YANG, Hua

《石油资源管理系统应用指南》（以下简称“指南”）由国际石油工程师学会（SPE）、美国石油地质师协会（AAPG）、世界石油理事会（WPC）、石油评估师学会（SPEE）和勘探地球物理学家学会（SEG）联合发布于2011年11月，是指导全球石油行业开展油气资源储量管理与评估的重要规范与指南。该指南从石油资源管理系统工程的角度，介绍了指南编制的背景与依据，阐述了PRMS油气资源与储量的定义、分类与分级，通过典型案例诠释了油气资源与储量评估关键技术方法的原理与应用，并探讨了油气资源管理、资产评估与信息披露涉及的一系列重要理论与实践问题。指南内容丰富、实用性强，应用范例通用、可借鉴，已被全球石油行业广泛接受和应用，也被美国证券和交易委员会（SEC）采纳，作为其“油气披露最新规定”的重要支撑依据。指南的英中版对PRMS的进一步推广应用和促进油气资源储量标准的国际交流意义重大，其不仅是一部广大华语石油工作者非常有用的工作手册，也是一本可供石油院校广大青年学者参考与借鉴的理想教科书。

本指南的编译工作得到了SPE油气储量委员会的悉心指导，中国自然资源部矿产资源保护监督司的大力支持，以及中国石油国际勘探开发公司、中国石油集团科学技术研究院有限公司和石油工业出版社等有关单位专家的辛勤奉献，在此谨致诚挚感谢。本指南译文可能还存在一些疏漏或不尽人意之处，请以英文原文为准；也欢迎读者反馈宝贵意见，指导我们今后的工作。

杨 桦

目录
Contents

第 1 章
CHAPTER 1

绪 论
Introduction

Satinder Purewal 著， 杨 桦、黄奇生 译

1.1 Rationale for New Application Guidelines

SPE has been at the forefront of leadership in developing common standards for petroleum resource definitions. There has been recognition in the oil and gas and mineral extractive industries for some time that a set of unified common standard definitions is required that can be applied consistently by international financial, regulatory, and reporting entities. An agreed set of definitions would benefit all stakeholders and provide increased:

（1）Consistency
（2）Transparency
（3）Reliability

A milestone in standardization was achieved in 1997 when SPE and the World Petroleum Council (WPC) jointly approved the “Petroleum Reserves Definitions.” Since then, SPE has been continuously engaged in keeping the definitions updated. The definitions were updated in 2000 and approved by SPE, WPC, and the American Association of Petroleum Geologists (AAPG) as the “Petroleum Resources Classification System and Definitions.” These were updated further in 2007 and approved by SPE, WPC, AAPG, and the Society of Petroleum Evaluation Engineers (SPEE). This culminated in the publication of the current “Petroleum Resources Management System,” globally known as PRMS. PRMS has been acknowledged as the oil and gas industry standard for reference and has been used by the US Securities and Exchange Commission (SEC) as a guide for their updated rules, “Modernization of Oil and Gas Reporting,” published 31 December 2008.

SPE recognized that new applications guidelines were required for the PRMS that would supersede the 2001 Guidelines for the Evaluation of Petroleum Reserves and Resources. The original guidelines document was the starting point for this work, and has been updated significantly with addition of the following new chapters:

(1) Estimation of Petroleum Resources Using Deterministic Procedures (Chap.4)

(2) Unconventional Resources (Chap.8)

In addition, other chapters have been updated to reflect current technology and enhanced with examples. The document has been considerably expanded to provide a useful handbook for many reserves applications. The intent of these guidelines is not to provide a comprehensive document that covers all aspects of reserves calculations because that would not be possible in a short, precise update of the 2001

1.1 新应用指南的依据

国际石油工程师学会（SPE）在制订有关石油资源定义的通用标准方面，一直处于领军地位。一段时间以来，石油和矿产开采行业纷纷认识到：需要一套统一、通用的标准定义使国际金融、监管和实体机构的报告保持一致性。一套公认的标准定义将会有利于所有利益相关方，并提高：

（1）一致性；
（2）透明性；
（3）可靠性。

1997 年是标准化工作的一个里程碑——国际石油工程师学会（SPE）和世界石油大会（WPC）共同批准了《石油储量的定义》。然后，SPE 致力于保持这些定义的不断更新。2000 年，SPE、WPC 和美国石油地质学家协会（AAPG）对这些定义进行了修订，推出了《石油资源分类系统和定义》。2007 年，这些定义进一步得到了更新，由 SPE、WPC、AAPG 和石油评估工程师学会（SPEE）联合批准，最终发布了现行的《石油资源管理系统》，即全球皆知的 PRMS。PRMS 已经成为油气行业的参照标准，并被美国证券交易委员会（SEC）采用，作为其 2008 年 12 月 31 日更新颁布的《油气披露最新规定》新规则的指南。

SPE 认为《石油资源管理系统》需要编制新的应用指南，以替代 2001 年的《石油储量和资源量评估指南》。于是，在原来指南文本的基础上进行了大量更新，增加了以下新的章节：

（1）确定法程序估算石油资源（第 4 章）；

（2）非常规资源（第 8 章）。

此外，其他章节也进行了修订，以反映当前的技术进展，并增加了案例。该指南还补充了许多内容，以便为储量评估应用提供一份有用的参考手册。该指南旨在 2001 年版文档基础上进行更新，提高准确性，但尚不能指导储量评估涉及的所有环节。充实后的新指南是石油行业专家们非常有用的参考资料。

第 2 章介绍了 PRMS 更新的一些具体细节。第 3 章阐述了资源量评估过程中涉及的地球科学

document. However, these expanded new guidelines serve as a very useful reference for petroleum professionals.

Chap.2 provides specific details of PRMS, focusing on the updated information. SEG Oil and Gas Reserves Committee has taken an active role in the preparation of Chap.3, which addresses geoscience issues during evaluation of resource volumes. The chapter has been specifically updated with recent technological advances. Chap.4 covers deterministic estimation methodologies in considerable detail and can be considered as a stand-alone document for deterministic reserves calculations. Chap.5 covers approaches used in probabilistic estimation procedures and has been completely revised. Aggregation of petroleum resources within an individual project and across several projects is covered in Chap.6, which has also been updated. Chap.7 covers commercial evaluations.

Chap.8 addresses some special problems associated with unconventional reservoirs, which have become an industry focus in recent years. The topics covered in this chapter are a work in progress, and only a high-level overview could be given. However, detailed sections on coalbed methane and shale gas are included. The intent is to expand this chapter and add details on heavy oil, bitumen, tight gas, gas hydrates as well as coalbed methane, shale gas and shale oil as the best practices evolve.

Production measurement and operations issues are covered in Chapter 9 while Chapter 10 contains details of resources entitlement and ownership considerations. The intent here is not to provide a comprehensive list of all scenarios but furnish sufficient details to provide guidance on how to apply the PRMS.

A list of Reference Terms used in resources evaluations is included at the end of the guidelines. The list does not replace the PRMS Glossary, but is intended to indicate the chapters and times where the terms are used in these Guidelines.

1.2 History of Petroleum Reserves and Resources Definitions

Ron Harrell

The March 2007 adoption of PRMS by SPE and its three cosponsors, WPC, AAPG, and SPEE, followed almost 3 years and hundreds of hours of volunteer efforts of individuals representing virtually every segment of the upstream industry and based in at least 10 countries. Other organizations were represented through their observers to the SPE Oil and Gas Reserves Committee (OGRC), including the

问题，并根据最新技术进展进行了专门更新，勘探地球物理学家学会（SEG）的油气储量委员会在该章的编制过程中发挥了积极推动作用。第 4 章详细介绍了确定性评估方法，可以当作确定法储量评估的单行本。第 5 章阐述了概率法评估程序所涉及的研究方法，进行了全面修订。第 6 章探讨了单个项目以及多个项目的油气资源汇并问题，内容也有所更新。第 7 章是有关商业性评估的内容。

第 8 章阐述了近年来行业所关注的一些非常规油气藏问题。本章涉及的内容仍在研究中，现在所能给出的还只是简要概述。目前已增加煤层气和页岩气的具体章节，但下一步随着实践的进展拟进一步扩充相关内容，包括重油、沥青、致密气、天然气水合物，以及煤层气和页岩油气等方面的详实内容。

第 9 章涉及产量的计量与处理问题。第 10 章详细阐述了资源份额与权益归属。需要说明的是，本章的目标是为如何应用 PRMS 提供详实的指导性建议，而不是力图列出所有的情景。

该指南的最后部分是资源评估所涉及的参考术语列表。该列表并不替代 PRMS 的术语表，只是体现这些术语在本指南中出现的章节和次数。

1.2 石油储量与资源量定义的发展历程

Ron Harrell 著

SPE 联合 WPC、AAPG 和 SPEE 三个学术机构，由至少 10 个国家上游业务各部门的志愿工作者，经过近 3 年数百小时的努力，于 2007 年 3 月正式采纳了 PRMS。还有一些组织在 SPE 油气储量委员会（OGRC）委派了观察员，包括美国能源信息署（EIA）、国际会计准则理事会（IASB）以及勘探地球物理学家学会（SEG）。后来，SEG 与 PRMS 也签订了认可协议。PRMS 在正式批准采纳之前经历了 100 天的公示期，广泛征集了协作机构、石油公司（跨国石油公司和国家石油公司）、监管机构、会计师事务所、律师事务所、大型金融组织和其他关注方的意见。

US Energy Information Agency (EIA), the International Accounting Standards Board (IASB), and the Society of Exploration Geophysicists (SEG). SEG later endorsed PRMS. The approval followed a 100-day period during which comments were solicited from the sponsoring organizations, oil companies (IOCs and NOCs), regulators, accounting firms, law firms, the greater financial community, and other interested parties.

AAPG was founded in 1917; SPE began as part of AIME in 1922, and became an autonomous society in 1957; WPC began in 1933; and SPEE was created in 1962. Active cooperation between these organizations, particularly involving individuals holding joint membership in two or more of these organizations, has been ongoing for years but was not formally recognized until now.

The initial efforts at establishing oil reserves definitions in the US was led by the American Petroleum Institute (API). At the beginning of World War I (WWI), the US government formed the National Petroleum War Service Committee (NPWSC) to ensure adequate oil supplies for the war effort. At the close of WWI, the NPWSC was reborn as the API. In 1937, API created definitions for Proved oil reserves that they followed in their annual estimates of US oil reserves. Little attention was paid to natural gas reserves until after 1946 when the American Gas Association (AGA) created similar definitions for Proved gas reserves.

SPE’s initial involvement in establishing petroleum reserves definitions began in 1962 following a plea from US banks and other investors for a consistent set of reserves definitions that could be both understood and relied upon by the industry in financial transactions where petroleum reserves served as collateral. Individual lenders and oil producers had their own “in-house” definitions, but these varied widely in content and purpose. In 1962, the SPE Board of Directors appointed a 12-man committee of well-recognized and respected individuals. They were known as a “Special Committee on Definitions of Proved Reserves for Property Evaluation.” The group was composed of two oil producers, one pipeline company, one university professor, two banks, two insurance companies (lenders), and four petroleum consultants.

These learned men collaborated over a period of 3 years, debating the exact wording and terms of their assignment before submitting their single-page work product to the SPE Board in 1965. The SPE Board adopted the committee’s recommendation by a vote of seven in favor, three dissenting, and two abstaining. The API observer was supportive; the AGA observer opposed the result.

In 1981, SPE released updated Proved oil and gas definitions that

AAPG 创建于 1917 年；SPE 于 1922 年成为 AIME（美国采矿、冶金及石油工程师学会）的一部分，1957 年成为一个独立学术机构；WPC 创建于 1933 年；SPEE 创建于 1962 年。这些组织积极开展了多年合作，特别是两个或多个组织的会籍互认，现在已正式实现。

在美国，最早致力于建立油气储量定义的机构是美国石油学会（API）。在第一次世界大战（WWI）伊始，美国政府就成立了国家石油战争服务委员会（NPWSC），以确保战争时期有足够的石油供应。第一次世界大战结束时，美国国家石油战争服务委员会（NPWSC）改建为美国石油学会（API）。1937 年，API 创建了证实原油储量的定义，并在此后每年的美国原油储量评估中沿用了这一定义。早期，人们很少关注天然气储量，直到 1946 年美国天然气协会（AGA）创建了类似的证实天然气储量的定义。

SPE 于 1962 年开始参与石油储量定义的工作。当时，美国银行以及其他投资者呼吁“建立一套统一的储量定义，以便行业可以理解和信赖在金融交易活动中作为抵押品的油气储量”。在那时，各出借方及原油生产商都有自己的“内部”定义，但这些定义无论是在内容上还是功能用途方面都大相径庭。1962 年，SPE 董事会任命了一个“资产评估证实储量定义特别委员会”，其成员由业内公认并广受尊重的 12 名人士组成，包括 2 名石油生产商代表、1 名管道公司代表、1 名大学教授、2 名银行代表、2 名保险公司（出借方）代表以及 4 名石油咨询公司的顾问。

上述专家、学者一起合作了 3 年，一直在争论其工作任务的确切措辞和工作内容。该委员会 1965 年向 SPE 董事会提交了一页纸的工作成果，SPE 董事会以七票赞成、三票反对和两票弃权的表决结果，接受了该委员会的建议。API 的观察员表示支持，而 AGA 的观察员则对该结果持反对意见。

1981 年，SPE 发布了新的《证实油气储量定义》，该定义只是在 1965 年第一版的基础上略

contained only minor revisions of the initial 1965 version.

The 1987 SPE petroleum reserves definitions were the result of an effort initiated by SPEE, but ultimately were developed and sponsored by SPE. These definitions, issued for the first time by a large professional organization, included recognition of the unproved categories of Probable and Possible Reserves. Much discussion centered around the use of probabilistic assessment techniques as a supplement or alternative to more-traditional deterministic methods. Following the receipt of comments from members worldwide, and in particular from North America, the SPE Board rejected the inclusion of any discussion about probabilistic methods of reserves evaluation in the 1987 definitions. As a consequence, these definitions failed to garner widespread international acceptance and adoption.

The 1997 SPE/WPC reserves definitions grew out of a cooperative agreement between WPC and SPE and appropriately embraced the recognition of probabilistic assessment methods. AAPG became a sponsor of and an integral contributor to the 2000 SPE/WPC/AAPG reserves and resources definitions. The loop of cooperation was completed in 2007 with recognition of SPEE as a fourth sponsoring society.

This recitation is not intended to omit or minimize the creative influence of numerous other individuals, organizations, or countries who have made valuable contributions over time to the derivation of petroleum resources definitions out of an initial mining perspective. Further, the PRMS sponsors recognize the “evergreen” nature of reserves and resources definitions and will remain diligent in working toward periodic updates and improvements.

Future Updates. Next time PRMS is reviewed and updated, it may be worth considering inclusion and recognition of 1U, 2U, and 3U as alternative acronyms for Prospective Resources estimates for low, best, and high in a similar fashion to 1P, 2P, and 3P, and 1C, 2C, and 3C. All stakeholder societies should encourage the use of the project maturity subclasses to link reservoir recognition to investment decisions, investment approvals, and field development plans, as discussed in Chapter 2.

作了一些修订。

1987 年版 SPE 石油储量定义研究工作由 SPEE 发起，但最终由 SPE 主办和研制。这些定义首次由大型专业学术组织机构发布，认可了未证实储量级别——概算储量和可能储量。针对概率评估技术方法是否可以补充或替代传统的确定性方法进行了大量讨论。在汇集全球（尤其是北美地区）会员的意见后，SPE 董事会否决了在 1987 年版定义中涵盖概率法储量评估。也正是如此，1987 年版定义没有得到广泛的国际认可和采纳。

1997 年版 SPE/WPC 储量定义是 WPC 和 SPE 按协议合作的成果，其恰当地融入了概率评估方法。AAPG 是 2000 年版 SPE/WPC/AAPG 储量和资源量定义的协作方和不可或缺的贡献者之一。这轮合作完成于 2007 年，并得到 SPEE 的认可，也使 SPEE 成为了第四个协作机构。

上述列举内容并非忽视众多其他个人、组织或者国家的创造性作用，他们在将石油资源定义从最初采矿角度推衍出来的漫长过程中，做出了非常宝贵的贡献。此外，石油资源管理系统的协作机构也认识到储量和资源量的定义应“与时俱进”、保持“常青”，将继续努力，对其进行定期更新和改进。

未来更新工作：下一次审阅和更新 PRMS 时，可能类似于 1P、2P、3P 和 1C、2C、3C 的方式，考虑加入 1U、2U 和 3U，以作为远景资源量低估值、最佳估值和高估值的替代术语。正如第 2 章所述，所有利益相关者应鼓励使用项目成熟度亚类，把油气藏认识程度和投资决策、投资批复与开发方案相关联。

第 2 章
CHAPTER 2

石油资源定义、分类与分级指南
Petroleum Resources Definitions, Classification, and Categorization Guidelines

James G. Ross 著，刘合年、吴蕾 译

2.1 Introduction

PRMS is a fully integrated system that provides the basis for classification and categorization of all petroleum reserves and resources. Although the system encompasses the entire resource base, it is focused primarily on estimated recoverable sales quantities. Because no petroleum quantities can be recovered and sold without the installation of (or access to) the appropriate production, processing, and transportation facilities, PRMS is based on an explicit distinction between (1) the development project that has been (or will be) implemented to recover petroleum from one or more accumulations and, in particular, the chance of commerciality of that project; and (2) the range of uncertainty in the petroleum quantities that are forecast to be produced and sold in the future from that development project.

This two-axis PRMS system is illustrated in Figure 2.1.

2.1 引言

石油资源管理系统是一个完整系统，为石油储量和资源量的分类与分级提供了基础。尽管该系统涵盖了整个资源序列，但最主要的目标是评估可采销售量。而如若没有可用的生产、处理及输送设施，就无法开采出石油并销售，因此石油资源管理系统需明确界定：（1）开发一个或多个油气聚集体的开发项目已实施或即将实施，及其商业几率（后者尤为重要）；（2）该项目未来预计石油可采量与销售量的不确定性范围。

图 2.1 为石油资源管理系统的两轴示意图。

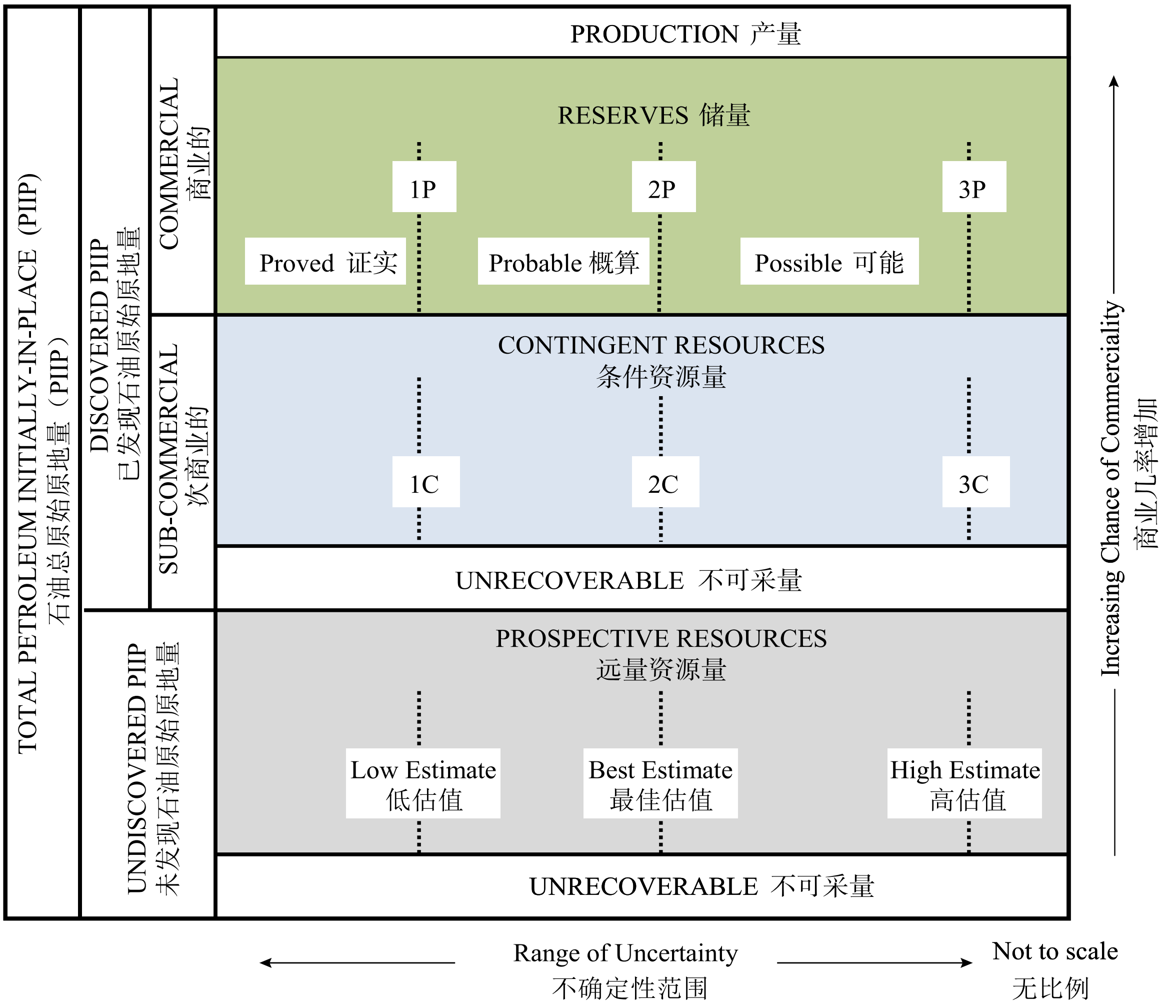

Figure 2.1　Resources Classification Framework.

图 2.1 资源分类框架

Each project is classified according to its maturity or status (broadly corresponding to its chance of commerciality) using three main classes, with the option to subdivide further using subclasses. The three classes are Reserves, Contingent Resources, and Prospective Resources. Separately, the range of uncertainty in the estimated recoverable sales quantities from that specific project is categorized based on the principle of capturing at least three estimates of the potential outcome: low, best, and high estimates.

For projects that satisfy the requirements for commerciality (as set out in Sec.2.1.2 of PRMS), Reserves may be assigned to the project, and the three estimates of the recoverable sales quantities are designated as 1P (Proved), 2P (Proved plus Probable), and 3P (Proved plus Probable plus Possible) Reserves. The equivalent categories for projects with Contingent Resources are 1C, 2C, and 3C, while the terms low estimate, best estimate, and high estimate are used for Prospective Resources. The system also accommodates the ability to categorize and report Reserve quantities incrementally as Proved, Probable, and Possible, rather than using the physically realizable scenarios of 1P, 2P, and 3P.

Historically, as discussed in Chap. 1, there was some overlap (and hence ambiguity) between the two distinct characteristics of project maturity and uncertainty in recovery, whereby Possible Reserves, for example, could be classified as such due to either the possible future implementation of a development project (reflecting a project maturity consideration) or as a reflection of some possible upside in potential recovery from a project that had been committed or even implemented (reflecting uncertainty in recovery). This ambiguity has been removed in PRMS and hence it is very important to understand clearly the basis for the fundamental distinction that is made between project classification and reserve/resource categorization.

2.2 Defining a Project

PRMS is a project-based system, where a project: “Represents the link between the petroleum accumulation and the decision-making process, including budget allocation. A project may, for example, constitute the development of a single reservoir or field, or an incremental development in a producing field, or the integrated development of a group of several fields and associated facilities with a common ownership. In general, an individual project will represent a specific maturity level at which a decision is made on whether or not to proceed (i.e., spend money), and there should be an associated range of estimated recoverable resources for that project.”

A project may be considered as an investment opportunity. Management decisions reflect the selection or rejection of investment

每一个项目可以根据其成熟度或所处状态（大致对应于其商业几率）划分为三大类别：储量、条件资源量和远景资源量，还可以进一步划分亚类。另一方面，项目的预计可采销售量的不确定性范围至少根据低估值、最佳估值和高估值三个可能结果来进行表征。

若一个项目能满足商业性要求（按 PRMS 第 2.1.2 节规定），则可以给项目核定储量，并将其估算可采销售量的三个评估结果分别确定为 1P（证实储量）、2P（证实储量 + 概算储量）和 3P（证实储量 + 概算储量 + 可能储量）。拥有条件资源量的项目可对应分级为 1C、2C 和 3C，而远景资源量则使用术语低估值、最佳估值和高估值。该系统还可以按增量法分级和报告证实储量、概算储量和可能储量，而不用 1P、2P 和 3P 情景法。

过去，如第 1 章所述，项目成熟度和可采量不确定性情形之间存在一定的交叉叠合（因而易混淆）。例如，可能储量的核定可以是一个未来可能实施的开发项目（反映项目的成熟度），也可以是一个已启动或已实施项目的潜在可采量的增量（反映可采量的不确定性）。本《石油资源管理系统》已消除了这种混淆。因此，清晰地认识项目划分和储量 / 资源量分级的根本区别是非常重要的。

2.2 定义项目

PRMS 是一个基于项目的系统。项目，“ 体现了油气聚集体与决策进程的关联，包括预算资金的分配。例如，一个项目可以是单个油气藏或油气田的开发，亦或是一个在产油气田的增产开发，也可以是共享地面设施的多个油气田的综合开发。一般而言，一个单一项目体现了特定的成熟度水平，以决策项目是否继续推进（即投入资金），并得到相应的估算可采量范围 ”。

一个项目可视为一个投资机会。管理决策则是对可用资金、投资成本以及预期投资收益（按价值核算）所构成投资组合的选择或放弃。项目

opportunities from a portfolio based on consideration of the total funds available, the cost of the specific investment, and the expected outcome (in terms of value) of that investment. The project is characterized by the investment costs (i.e., on what the money will actually be spent) and provides the fundamental basis for portfolio management and decision making. In some cases, projects are implemented strictly on the basis of strategic drivers but are nonetheless defined by these financial metrics. The critical point is the linkage between the decision to proceed with a project and the estimated future recoverable quantities associated with that project.

Defining the term "project" unambiguously can be difficult because its nature will vary with its level of maturity. For example, a mature project may be defined in great detail by a comprehensive development plan document that must be prepared and submitted to the host government or relevant regulatory authority for approval to proceed with development. This document may include full details of all the planned development wells and their locations, specifications for the surface processing and export facilities, discussion of environmental considerations, staffing requirements, market assessment, estimated capital, operating and site rehabilitation costs, etc. In contrast, the drilling of an exploration prospect represents a project that could become a commercial development if the well is successful. The assessment of the economic viability of the exploration project will still require a view of the likely development scheme, but the development plan will probably be specified only in very broad conceptual terms based on analogues.

In all cases, the decision to proceed with a project requires an assessment of future costs, based on an evaluation of the necessary development facilities, to determine the expected financial return from that investment. In this context, the development facilities include all the necessary production, processing, and transportation facilities to enable delivery of petroleum from the accumulation(s) to a product sales point (or to an internal transfer point between upstream operations and midstream/downstream operations). It is these development facilities that define the project because it is the planned investment of the capital costs that is the basis for the financial evaluation of the investment and hence the decision to proceed (or not) with the project. Evaluation of the estimated recoverable sales quantities, and the range of uncertainty in that estimate, will also be key inputs to the financial evaluation, and these can only be based on a defined development project.

A project may involve the development of a single petroleum accumulation, or a group of accumulations, or there may be more than one project implemented on a single accumulation. The following are some examples of projects:

(1) Where a detailed development plan is prepared for partner

以投资成本（即资金投向）为特征，可为投资组合的管理与决策提供基础。某些情况下，尽管项目由财务指标所定义，但其实施会基于战略因素而驱动。至关重要的是项目决策进程与项目估算可采量之间的关联关系。

毫无歧义地定义术语“项目”是很困难的，因为其特征会随着成熟度的变化而变化。例如，一个成熟项目可以通过一个综合开发方案来详细定义，并在方案得到资源国政府或相关监管机构审批后实施。该开发方案的内容可包括所有计划的开发井及其井位、地面处理与输送设施设计、环境考量的分析、人员需求、市场评价、资本、作业与现场修复费用估算等。相比之下，一个勘探目标区的钻探就是一个项目，若钻探成功，则可能成为一个商业开发项目。勘探项目的经济性评价仍需审视其可能适用的开发机理，但其开发方案的确定可能仅基于较粗略的概念性类比。

无论在什么情况下，决策一个项目是否推进，需要基于其所需开发设施来评估未来投资成本，以确定投资预期经济收益。开发设施包括石油从油气藏采出、输送到产品销售点（或上游与中 / 下游之间的一个内部交付点）所需的所有生产、加工和输送设施。正是这些开发设施定义了项目，因为其资本投资是经济评估的基础，进而影响项目的决策。可采销售量的评估结果及其不确定性范围也是经济评估的关键参数，只能来源于一个明确定义的开发项目。

一个项目可以包含一个或一组油气聚集体的开发，一个单一油气聚集体也可以实施多个项目。以下是一些案例：

（1）当一个详实的开发方案完成并提交合作伙伴和 / 或政府审批，那方案本身就定义了该项目。如果方案中有一些意向井（可选井），不需要额外的资本投资和 / 或政府批复，则不形成新的项目，但可能会成为项目可采量不确定性范围的评估内容。

（2）若一个开发项目定义为从一个具有规

and/or government approval, the plan itself defines the project. If the plan includes some optional wells that are not subject to a further capital commitment decision and/or government approval, these would not constitute a separate project, but would form part of the assessment of the range of uncertainty in potentially recoverable quantities from the project.

(2) Where a development project is defined to produce oil from an accumulation that also contains a significant gas cap and the gas cap development is not an integral part of the oil development, a separate gas development project should also be defined, even if there is currently no gas market.

(3) Where a development plan is based on primary recovery only, and a secondary recovery process is envisaged but will be subject to a separate capital commitment decision and/or approval process at the appropriate time, it should be considered as two separate projects.

(4) Where decision making is entirely on a well-by-well basis, as may be the case in mature onshore environments, and there is no overall defined development plan or any capital commitment beyond the current well, each well constitutes a separate project.

(5) Where late-life installation of gas-compression facilities is included in the original approved development plan, it is part of a single gas development project. Where compression was not part of the approved plan and is technically feasible, but will require economic justification and a capital commitment decision and/or approval before installation, the installation of gas-compression facilities represents a separate project.

(6) In the assessment of an undrilled prospect, a risked economic evaluation will be made to underpin the decision whether to drill. This evaluation must include consideration of a conceptual development plan in order to derive cost estimates and theoretically recoverable quantities (Prospective Resources) on the basis of an assumed successful outcome from the exploration well (see also discussion of commercial risk in Sec. 2.5). The project is defined by the exploration well and the conceptual development plan.

(7) In some cases, an investment decision may be requested of management that involves a combination of exploration, appraisal, and/or development activities. Because PRMS subdivides resource quantities on the basis of three main classes that reflect the distinction between these activities (i.e., Reserves, Contingent Resources, and Prospective Resources), it is appropriate in such cases to consider that the investment decision is based on implementing a group of projects, whereby each project can fit uniquely into one of the three classes.

Projects may change in character over time and can aggregate or subdivide. For example, an exploration project may initially be

模气顶的油气聚集体中开采原油，而气顶的开发并不是原油开发的必要部分，那么应另定义一个天然气开发的项目，即便当时还没有天然气市场。

（3）若一个开发方案仅基于一次开采，二次开采已设计，但需要适时进行单独的投资决策和 / 或审批程序，这种情况应视为两个相互独立的项目。

（4）若决策完全以单井为基础（如陆上成熟油田的情形），没有整体开发方案或现有井之外的其他资本投资承诺，那每口井都可构成一个单独的项目。

（5）若已批准的原始开发方案中含有后期增加天然气压缩设施的内容，则其可视为是单个天然气开发项目的一部分。若压缩设施不是已批复方案的内容，虽技术上可行，但在实施之前需要进行经济论证、资金筹措和投资决策，则天然气压缩设施的实施就代表一个单独的项目。

（6）对于一个未钻井的目标区，要根据风险后的经济评估来决策是否钻井。该评估须考虑一个概念性开发方案，即假定探井成功的基础上估算成本和理论可采量（远景资源量）（参见第 2.5 节有关商业风险的讨论），该项目则由探井及其概念性开发方案来定义。

（7）在某些情况下，投资决策可能涉及勘探、评价和 / 或开发作业活动的综合管理。由于 PRMS 根据不同的作业活动状态将油气资源划分为三个类别（即储量、条件资源量和远景资源量），此情况下，适宜将投资决策看作是基于一组项目的实施，每个项目都单独与三大资源类别之一相关联。

项目的特征会随着时间而发生改变，可进一步合并或细分。例如，某一个勘探项目最初可定义为：一旦勘探发现，油气聚集体将作为一个独立项目进行开发。然而，若发现规模比预期小，不能单独支撑外输管线的建设，那么该项目则可能会搁置和延迟，直至附近有其他发现，两个发现可作为一个项目进行开发，从而使管线建设的

defined on the basis that, if a discovery is made, the accumulation will be developed as a standalone project. However, if the discovery is smaller than expected and perhaps is unable to support an export pipeline on its own, the project might be placed in "inventory" and delayed until another discovery is made nearby, and the two discoveries could be developed as a single project that is able to justify the cost of the pipeline. The subsequent investment decision is then based on proceeding with the development of the two accumulations simultaneously using shared facilities (the pipeline), and the combined development plan then constitutes the project. Again, the key is that the project is defined by the basis on which the investment decision is made.

Similarly, a discovered accumulation may initially be considered as a single development opportunity and then subsequently be subdivided into two or more distinct projects. For example, the level of uncertainty (e.g., in reservoir performance) may be such that it is considered more prudent to implement a pilot project first. The initial concept of a single field development project then becomes two separate projects: the pilot project and the subsequent development of the remainder of the field, with the latter project contingent on the successful outcome of the first.

A key strength of using a project-based system like PRMS is that it encourages the consideration of all possible technically feasible opportunities to maximize recovery, even though some projects may not be economically viable when initially evaluated. These projects are still part of the portfolio, and identifying and classifying them ensures that they remain visible as potential investment opportunities for the future. The quantities that are estimated to be Unrecoverable should be limited to those that are currently not technically recoverable. A proportion of these Unrecoverable quantities may of course become recoverable in the future as a consequence of new technology being developed.

Technology refers to the applied technique by which petroleum is recovered to the surface and, where necessary, processed into a form in which it can be sold. Some guidelines are provided in Sec. 2.3 on the relationship between the status of technology under development and the distinction between Contingent Resources and those quantities that are currently considered as Unrecoverable.

Finally, it is very important to understand clearly the distinction between the definition of a project and the assignment of Reserves based on Reserves Status (see Sec. 2.8). Reserves Status is a subdivision of recoverable quantities within a project and does not reflect a project-based classification directly unless each well is validly defined as a separate project, as discussed above in Example（4）.

2.3 Project Classification

Under PRMS, each project must be classified individually so that

成本可合理接受。后续的投资决策则是基于两个聚集体的同时开发和共享生产设施（管网），而联合开发方案即该项目的组成部分。再次指出，项目定义的关键是投资决策的对象。

与此类似，一个已发现油气聚集体最初可被视为一个独立的开发机会，随后再拆分为两个或多个不同项目。例如，根据不确定性（如油气藏产能方面）的程度，为慎重起见，需要先实施一个先导试验项目。在这种情况下，最初单个油气田开发的项目则可分成两个独立的项目：先导试验项目和随后油气田剩余部分的开发，后一项目是在前一项目成功生产之后才实施。

基于项目的资源管理系统，如 PRMS，其主要优势在于鼓励考虑所有技术可行性，以最大程度地提升采出量，尽管有些项目在最初评估时可能是不经济的。此类项目仍是投资组合的一部分，可进一步对它们进行识别和划分，以发现其未来潜在的投资机会。评估结果中的不可采量应仅限于目前技术不可采的部分。当然，随着新技术的开发，部分不可采量仍可能在将来转变为可采量。

这里的技术是指将油气开采到地面，若需要，并处理加工为可销售产品的应用技术方法。第 2.3 节指导意见分别阐述了“ 正研发技术 ”的状态和条件资源量与不可采量的关系。

最后，非常重要的是要清楚地了解项目定义与不同储量状态下储量核定的区别（参见第 2.8 节）。储量状态是一个项目可采量的次级划分，并不直接反映基于项目的分类，除非每口井都被定义为一个单独的项目，如例（4）所讨论的情况。

2.3 项目分类

在 PRMS 系统里，每一个项目都必须进行单独分类，这样所评估的项目可采销售量才能正确地划分为储量、条件资源量或远景资源量三大类别之一（参见图 2.1）。如 PRMS 第 2.1.1 和 2.1.2 节所述，这三大类别的区分在于（a）发现与否，和（b）商业性。发现与否的评价总是在油气聚

the estimated recoverable sales quantities associated with that project can be correctly assigned to one of the three main classes: Reserves, Contingent Resources, or Prospective Resources (see Figure 2.1). The distinction between the three classes is based on the definitions of (a) discovery and (b) commerciality, as documented in Secs. 2.1.1 and 2.1.2 of PRMS, respectively. The evaluation of the existence of a discovery is always at the level of the accumulation, but the assessment of potentially recoverable quantities from that discovery must be based on a defined (at least conceptually) project. The assessment of commerciality, on the other hand, can only be performed at a project level.

Although the definition of "discovery" has been revised to some extent from that contained in the SPE/WPC/AAPG Guidelines (SPE 2001) for a "known accumulation," it remains completely independent from any considerations of commerciality. The requirement is for actual evidence (testing, sampling, and/or logging) from at least one well penetration in the accumulation (or group of accumulations) to have demonstrated a "significant quantity of potentially moveable hydrocarbons." In this context, "significant" implies that there is evidence of a sufficient quantity of petroleum to justify estimating the in-place volume demonstrated by the well(s) and for evaluating the potential for economic recovery.

The use of the phrase "potentially moveable" in the definition of "discovery" is in recognition of unconventional accumulations, such as those containing natural bitumen, that may be rendered "moveable" through the implementation of improved recovery methods or by mining.

Estimated recoverable quantities from a discovery are classified as Contingent Resources until such time that a defined project can be shown to have satisfied all the criteria necessary to reclassify some or all of the quantities as Reserves. In cases where the discovery is, for example, adjacent to existing infrastructure with sufficient excess capacity, and a commercially viable development project is immediately evident (i.e., by tying the discovery well into the available infrastructure), the estimated recoverable quantities may be classified as Reserves immediately. More commonly, the estimated recoverable quantities for a new discovery will be classified as Contingent Resources while further appraisal and/or evaluation is carried out. In-place quantities in a discovered accumulation that are not currently technically recoverable may be classified as Discovered Unrecoverable.

The criteria for commerciality (and hence assigning Reserves to a project) are set out in Sec. 2.1.2 of PRMS and should be considered with care and circumspection. While estimates of Reserve quantities will frequently change with time, including during the period before

集体层面进行，对该发现可采量的评估则必须基于一个（至少概念性的）已定义的项目。另一方面，商业性评估只能在项目层面进行。

在 SPE/WPC/AAPG 指南（SPE 2001）中，尽管“发现”的定义在“已知油气聚集体”的定义基础上进行了修订，但仍完全独立于任何商业性考虑。“发现”的要求是：至少有一口井钻遇了该油气聚集体（或该组油气聚集体），所获得的实际数据（测试、取样和/或测录井）证实了大量潜在可动的烃存在。这里的“大量”意味着有充足油气数量存在的依据，表明对某一口（或多口）井所估算的原地量和经济可采潜力是合理的。

在“发现”定义中使用词组“潜在可动的”，是为了识别非常规油气聚集体；例如天然沥青，可通过提高采收率或挖掘开采的方法成为“可动”资源。

一个“发现”所定义的项目在满足将部分或全部可采量划归储量的必需条件之前，其估算可采量应划归为条件资源量。某些情况下，例如“发现”的邻近有足够生产能力的设施，且开发项目的商业可行性显而易见（例如将发现井直接连入可用的生产设施即可），则估算可采量可以立刻划归为储量。更常见的情况是将一个新发现的估算可采量划归为条件资源量，同时进一步开展评价和/或评估工作。已发现油气聚集体中不能利用现有技术进行开采的原地量可以划归为已发现不可采量。

PRMS 第 2.1.2 节对商业性标准进行了规定（按此标准为项目核定储量），应认真考虑和谨慎对待。储量的评估结果通常会随时间而变化（包括投产前的阶段），但很少有项目在核定为储量类别之后，又重新划分为条件资源量类别。只有发生超越公司控制力的不可预见情况，才会出现这种类别的重新划分情况。例如：政治或法律的意外变化造成开发作业的延迟，超出其合理的时间计划表（按 PRMS 规定）。即便如此，如果一

production startup, it should be a rare event for a project that had been assigned to the Reserves class to subsequently be reclassified as having Contingent Resources. Such a reclassification should occur only as the consequence of an unforeseeable event that is beyond the control of the company, such as an unexpected political or legal change that causes development activities to be delayed beyond a reasonable time frame (as defined in PRMS). Even so, if there are any identifiable areas of concern regarding receipt of all the necessary approvals/contracts for a new development, it is recommended that the project remains in the Contingent Resources class until such time that the specific concern has been addressed.

Contingent Resources may be assigned for projects that are dependent on “technology under development.” It is recommended that the following guidelines are considered to distinguish these from quantities that should be classified as Unrecoverable:

(1) The technology has been demonstrated to be commercially viable in analogous reservoirs. Discovered recoverable quantities may be classified as Contingent Resources.

(2) The technology has been demonstrated to be commercially viable in other reservoirs that are not analogous, and a pilot project will be necessary to demonstrate commerciality for this reservoir. If a pilot project is planned and budgeted, discovered recoverable quantities from the full project may be classified as Contingent Resources. If no pilot project is currently planned, all quantities should be classified as Unrecoverable.

(3) The technology has not been demonstrated to be commercially viable but is currently under active development, and there is sufficient direct evidence (e.g., from a test project) to indicate that it may reasonably be expected to be available for commercial application within 5 years. Discovered Recoverable quantities from the full project may be classified as Contingent Resources.

(4) The technology has not been demonstrated to be commercially viable and is not currently under active development, and/or there is not yet any direct evidence to indicate that it may reasonably be expected to be available for commercial application within 5 years. All quantities should be classified as Unrecoverable.

2.4 Range of Uncertainty Categorization

The “range of uncertainty” (see Figure 2.1) reflects a range of estimated quantities potentially recoverable from an accumulation (or group of accumulations) by a specific, defined, project. Because all potentially recoverable quantities are estimates that are based on assumptions regarding future reservoir performance (among other

个新开发项目在获得所需审批 / 合同方面有任何质疑，建议将项目仍保留在条件资源量类别，直到这些质疑消除。

条件资源量也可以核定给“ 开采技术正研发 ” 的项目。建议在区分这些条件资源量与不可采量时考虑以下指导原则：

（1）该技术在类比油气藏中已证实是商业可行的，则已发现可采量可以被划分为条件资源量。

（2）该技术在其他非类比油气藏中已证实是商业可行的，但还需要先导试验项目来论证该技术在目标油气藏中的商业性。如果先导试验项目已完成计划和投资预算，则整个项目的已发现可采量可划归为条件资源量。如果目前还没有完成先导试验项目的设计，则所有资源量应该划归为不可采量。

（3）该技术尚未被证实是商业可行的，但目前正在积极研发中，并有足够证据（如来自测试项目）表明该技术可合理期望在 5 年内实现商业应用，则整个项目的已发现可采量可以划归为条件资源量。

（4）该技术尚未被证实是商业可行的，目前也不在积极研发中，和 / 或没有任何直接证据表明其可合理期望在 5 年内实现商业应用，则所有资源量应该划归为不可采量。

2.4 不确定性范围分级

不确定性范围（参见图 2.1）反映的是某一油气聚集体（或一组油气聚集体）通过具体定义的项目可以潜在采出的油气数量的估值范围。由于所有潜在可采量的评估都是基于对油气藏未来生产能力等因素的假设，所以对实施一个项目能获得的可采量的评估总会存在一定的不确定性。几乎任何情况下，原地量和采收率的评估都会存在相当大的不确定性，也会存在与项目相关的商业不确定性。在使用生产动态评估（例如递减曲线分析）时一定还有一些不确定性。当然，对于

things), there will always be some uncertainty in the estimate of the recoverable quantity resulting from the implementation of a specific project. In almost all cases, there will be significant uncertainty in both the estimated in-place quantities and in the recovery efficiency, and there may also be project-specific commercial uncertainties. Where performance-based estimates are used (e.g., based on decline curve analysis), there must still be some uncertainty; however, for very mature projects, the level of technical uncertainty may be relatively minor in absolute terms.

In PRMS, the range of uncertainty is characterized by three specific scenarios reflecting low, best, and high case outcomes from the project. The terminology is different depending on which class is appropriate for the project, but the underlying principle is the same regardless of the level of maturity. In summary, if the project satisfies all the criteria for Reserves, the low, best, and high estimates are designated as Proved (1P), Proved plus Probable (2P), and Proved plus Probable plus Possible (3P), respectively. The equivalent terms for Contingent Resources are 1C, 2C, and 3C, while the terms “low estimate,” “best estimate,” and “high estimate” are used for Prospective Resources.

The three estimates may be based on deterministic methods or on probabilistic methods, as discussed in Chap. 4 and Chap. 5. The relationship between the two approaches is highlighted in PRMS with the statement that:

“A deterministic estimate is a single discrete scenario within a range of outcomes that could be derived by probabilistic analysis.”

Further, “uncertainty in resource estimates is best communicated by reporting a range of potential results. However, if it is required to report a single representative result, the “best estimate” is considered the most realistic assessment of recoverable quantities. It is generally considered to represent the sum of Proved and Probable estimates (2P) when using the deterministic scenario or the probabilistic assessment methods.”

The critical point in understanding the application of PRMS is that the designation of estimated recoverable quantities as Reserves (of any category), or as Contingent Resources or Prospective Resources, is based solely on an assessment of the maturity/status of an identified project, as discussed in Sec. 2.3. In contrast, the subdivision of Reserves into 1P, 2P, and 3P (or the equivalent incremental quantities) is based solely on considerations of uncertainty in the recovery from that specific project (and similarly for Contingent/Prospective Resources). Under PRMS, therefore, provided that the project satisfies the requirements to have Reserves, there should always be a low (1P) estimate, a best

一些非常成熟的项目，其技术不确定性相对较小。

在 PRMS 中，不确定性的范围是由项目评估结果的低估值、最佳估值和高估值 3 个情景来表征。对于不同类别的项目，所采用的术语也有所不同；但不管成熟度如何，其基本原则是相同的。总之，如果该项目满足储量类别所需的所有条件，则低估值、最佳估值和高估值就可分别确认为证实储量（1P）、证实储量 + 概算储量（2P）和证实储量 + 概算储量 + 可能储量（3P）。相应地，对应条件资源量类别的术语分别是 1C、2C 和 3C，而远景资源量则使用术语“低估值”、“最佳估值”和“高估值”。

基于确定性评估方法或者概率法可以得到上述三个估值（如第 4 章和第 5 章所述）。对于这两种方法之间的关系，PRMS 强调：

“确定法评估结果是概率法评估结果分布范围中的一个离散值。”

此外，“资源估值的不确定性最好表述为一系列可能结果的分布范围。当然，如果要求报告一个代表性结果，则认为最佳估值是可采量最具有现实意义的评估结果。在使用确定情景法或概率法评估时，一般认为最佳估值表示的是证实与概算估算值之和（2P）。”

领悟 PRMS 应用的关键点在于：核定一个特定项目的可采量为储量、条件资源量或远景资源量，完全基于对该项目成熟度 / 状态的评估，如第 2.3 节所述。相对而言，将储量再划分为 1P、2P 和 3P（或相应增量）则完全基于对项目开采量的不确定性考量（条件资源量和远景资源量的情况类似）。因此，在 PRMS 系统中，如果项目满足储量类别的条件，则总是应存在一个低估值（1P）、一个最佳估值（2P）和一个高估值（3P），除非是非常特殊的情况，例如 1P（证实储量）估值为零的情形。

尽管评估可以采用确定法或概率法（或多情景法），但若要得到可对比的结果，遵循的基本

(2P) estimate, and a high (3P) estimate, unless some very specific circumstances pertain where, for example, the 1P (Proved) estimate may be recorded as zero.

While estimates may be made using deterministic or probabilistic methods (or, for that matter, using multiscenario methods), the underlying principles must be the same if comparable results are to be achieved. It is useful, therefore, to keep in mind certain characteristics of the probabilistic method when applying a deterministic approach:

(1) The range of uncertainty relates to the uncertainty in the estimate of Reserves (or Resources) for a specific project. The full range of uncertainty extends from a minimum estimated Reserve value for the project through all potential outcomes up to a maximum Reserve value. Because the absolute minimum and absolute maximum outcomes are the extreme cases, it is considered more practical to use low and high estimates as a reasonable representation of the range of uncertainty in the estimate of Reserves. Where probabilistic methods are used, the P90 and P10 outcomes are typically selected for the low and high estimates①.

(2) In the probabilistic method, probabilities actually correspond to ranges of outcomes, rather than to a specific scenario. The P90 estimate, for example, corresponds to the situation whereby there is an estimated 90% probability that the correct answer (i.e., the actual Reserves) will lie somewhere between the P90 and the P0 (maximum) outcomes. Obviously, there is a corresponding 10% probability that the correct answer lies between the P90 and the P100 (minimum) outcome, assuming of course that the evaluation of the full range of uncertainty is valid. In a deterministic context, “a high degree of confidence that the quantities will be recovered” does not mean that there is a high probability that the exact quantity designated as Proved will be the actual Reserves; it means that there is a high degree of confidence that the actual Reserves will be at least this amount.

(3) In this uncertainty-based approach, a deterministic estimate is, as stated in PRMS, a single discrete scenario that should lie within the range that would be generated by a probabilistic analysis. The range of uncertainty reflects our inability to estimate the actual recoverable quantities for a project exactly, and the 1P, 2P, and 3P Reserves estimates are simply single discrete scenarios that are representative of the extent of the range of uncertainty. In PRMS there is no attempt to consider a range of uncertainty separately for each of the 1P, 2P, or 3P scenarios, or for the incremental Proved, Probable, and Possible Reserves, because the objective is to estimate the range of uncertainty

原则必须是相同的。因此，在应用确定法时，谨记概率法的下列特点是很有用的：

（1）不确定性范围是与具体项目储量（或资源量）评估的不确定性相关。整个不确定性范围的分布是从该项目所有储量评估可能结果中的最低估值到最高估值。由于绝对最低值和绝对最高值是两个非常极端的情况，所以比较实用的是用低估值和高估值来合理代表储量评估结果的不确定性范围。在应用概率法时，通常选用 P90 和 P10 结果来代表低估值和高估值①。

（2）在概率法中，概率值实际上对应的是结果分布范围，而不是某一个具体情景。例如，P90 估值对应的情形是：正确结果（即实际储量）出现在 P90 与 P0（最大值）结果之间的概率有 90%。显然，若整个不确定性范围的评估是有效的，正确结果会相应地出现在 P90 与 P100（最小值）结果之间的概率为 10%。在确定法的文字表述中，“未来可采量的高置信度”并不意味着已认定为证实储量的确切数据成为实际储量的概率很高，而是指实际储量至少达到这个数值的置信度很高。

(3) 在不确定性因素分析中，如 PRMS 所述，确定法的评估结果是概率分析结果范围内的一个单一离散情景。不确定性范围体现了我们无法准确估算项目的实际可采量，而 1P、2P 和 3P 储量估值只是代表评估结果不确定性范围内的单一离散情景。在 PRMS 系统中，不再分别考虑 1P、2P 或 3P 情景或以增量方式表述的证实、概算与可能储量的不确定性范围，因为不确定性范围评估的目标是整个项目实际可采量。

（4）在储量评估中，不确定性分布通常近似于对数正态分布，正确结果（实际可采量）会更接近最佳估值（或 2P 情景），而不是低估值（1P）

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① Under PRMS, the requirement is for the selected cases to be “at least” 90% and 10% probability levels, respectively.
在 PRMS 系统中，要求所选择情景的概率应至少分别为 90% 和 10%。

in the actual recovery from the project as a whole.

(4) Because the distribution of uncertainty in an estimate of reserves will generally be similar to a lognormal shape, the correct answer (the actual recoverable quantities) will be more likely to be close to the best estimate (or 2P scenario) than to the low (1P) or high (3P) estimates. This point should not be confused with the fact that there is a higher probability that the correct answer will exceed the 1P estimate (at least 90%) than the probability that it will exceed the 2P estimate (at least 50%).

For very mature producing projects, it may be considered that there is such a small range of uncertainty in estimated remaining recoverable quantities that 1P, 2P, and 3P reserves can be assumed to be equal. Typically, this approach is used where a producing well has sufficient long-term production history that a forecast based on decline curve analysis is considered to be subject to relatively little uncertainty. In reality, of course, the range of uncertainty is never zero (especially when considered in the context of remaining quantities), and any assumption that the uncertainty is not material to the estimate should be carefully considered, and the basis for the assumption should be fully documented. Note that this is the only circumstance where a project can have Proved Reserves, but zero Probable and Possible Reserves.

Typically, there will be a significant range of uncertainty and hence there will be low, best, and high estimates (or a full probabilistic distribution) that characterize the range, whether for Reserves, Contingent Resources, or Prospective Resources. However, there are specific circumstances that can lead to having 2P and 3P Reserves, but zero Proved Reserves. These are described in Sec. 3.1.2 of PRMS.

Conceptually, the framework of PRMS was originally designed on the basis of the “uncertainty-based philosophy” of reserve estimation [as discussed in Sec. 2.5 of Guidelines for Evaluation of Reserves and Resources (SPE 2001)], as is clearly demonstrated by its separation of project maturity from the range of uncertainty and by the simple fact that uncertainty in any estimate (e.g., reserves attributable to a project) can only be communicated by either a complete distribution of outcomes derived from probabilistic methodologies or by reporting selected outcomes (e.g., low, best, and high scenarios) from that distribution, as may be estimated using deterministic scenario methods. However, as PRMS indicates that the “deterministic incremental (risk-based) approach” remains a valid methodology in this context, further explanation is necessary to ensure that this reference is not confused with the “risk-based philosophy” described in the guidelines (SPE 2001).

As highlighted in the guidelines (SPE 2001), a major limitation

或高估值（3P）。尽管实际可采量超过 1P 估值的概率（至少 90%）要比超过 2P 估值的概率（至少 50%）高，但请不要将两者混淆。

对于非常成熟的生产项目，可认为剩余可采量估值的不确定性范围很小，可假定 1P、2P 和 3P 储量是相等的。通常，这样做的条件是：生产井有足够长的生产历史，递减曲线分析法进行储量预测的不确定性相对很小。当然，不确定性的范围实际上永远都不会是零（尤其是剩余量），任何认为不确定性评估无关紧要的假设都应慎重考虑，并完整记录假设条件。需要注意的是，仅在 1P、2P 和 3P 储量相等的情况下，项目只有证实储量，而概算储量和可能储量均为零。

通常情况下，无论是储量、条件资源量或是远景资源量，其不确定性范围都相当大。因此，可以用低估值、最佳估值和高估值（或整个概率分布）来表征其分布范围。然而，也有一些特殊情形，可能存在 2P 储量和 3P 储量，但证实储量为零。相关内容请参见 PRMS 第 3.1.2 节。

从概念上讲，PRMS 框架的最初设计理念是基于储量评估的不确定性原理［参见《储量和资源量评估指南（SPE, 2001）》第 2.5 节］，该原理清楚地体现了项目的成熟度是按照不确定性范围进行划分，评估结果（如项目储量）的不确定性只能通过概率法得到的整个结果分布来表示，或从该分布中选定的结果（例如低估值、最佳估值和高估值）来报告，类似确定情景法评估。当然，PRMS 指出，基于风险的确定性增量法仍是一种有效方法，有必要进一步阐述以确保这一观点不与《储量和资源量评估指南（SPE, 2001）》所述的“风险理论”相混淆。

正如评估指南（SPE, 2001）所强调，风险理论的主要局限是不能将一个项目可采量的不确定性和该项目最终不能实现商业开采的风险区分开来。这一区分是 PRMS 系统非常核心的内容，显然这个方法（风险理论）不能与系统保持协调一

of the risk-based philosophy was that it failed to distinguish between uncertainty in the recoverable quantities for a project and the risk that the project may not eventually achieve commercial development. Because this distinction is at the very heart of PRMS, it is clear that such an approach could not be consistent with the system. In particular, no reserves (of any category) can be assigned unless the project satisfies all the commerciality criteria for reserves. Thus, for reserves at least, the project should be subject to very little, if any, commercial risk. The reserve categories are then used to characterize the range of uncertainty in recoverable quantities from that project.

Provided that the definitions and guidelines specified within PRMS are respected, the incremental approach (or any other methodology) can be used to estimate reserves or resources. Estimating discrete quantities associated with each of the three reserves categories (Proved, Probable, and Possible) remains valid, though it is noted that some of the definitions and guidelines may still require explicit consideration of deterministic scenarios. For example, Probable Reserves should be such that: “It is equally likely that actual remaining quantities recovered will be greater than or less than the sum of the estimated Proved plus Probable Reserves (2P)” (PRMS Sec. 2.2.2 and Table 3, emphasis added).

2.5 Methods for Estimating the Range of Uncertainty in Recoverable Quantities

There are several different approaches to estimating the range of uncertainty in recoverable quantities for a project and the terminology is often used in confusing ways. These mathematical approaches, such as Monte Carlo analysis, largely relate to volumetric methods but are also relevant to other methodologies. In this context “deterministic” is taken to mean combining a single set of discrete parameter estimates (gross rock volume, average porosity, etc.) that represent a physically realizable and realistic combination in order to derive a single, specific estimate of recoverable quantities. Such a combination of parameters represents a specific scenario. On this basis, even the probabilistic method is scenario-based. Irrespective of the approach utilized, the uncertainty in recoverable quantities is associated with the applied (or planned) project, while the risk (chance of commerciality) of the project is defined by its assignment to a resource class or subclass.

Keeping in mind that the object of the exercise is to estimate at least three outcomes (estimated recoverable quantities) that reflect the range of uncertainty for the project, broadly defined as low, best, and high estimates, it is important to recognize that the underlying philosophy must be the same, regardless of the approach used. The

致。需要特别指出的是，项目须满足储量所需所有商业性条件，否则就不能核定储量（含任何级别）。因此，至少对于储量类别，项目的商业风险（如果有的话）应该很小。项目可采量的不确定性范围则可用储量的级别来表征。

遵循 PRMS 的定义和规则，可采用增量法（或其他方法）评估储量和资源量。尽管一些定义和规则要求明确考虑确定的情景，但评估三个级别储量（证实储量、概算储量和可能储量）相应的离散值仍然是有效的。例如，概算储量应是：“ 实际剩余可采量大于或小于所估算的证实储量 + 概算储量（2P）的可能性相同 ”（参见 PRMS 第 2.2.2 节和表 3）。

2.5 可采量不确定性范围的评估方法

项目可采量的不确定性范围有几种不同的评估方法，其术语的使用经常被混淆。数学方法（如蒙特卡洛分析法）主要与容积法相关联，但也与其他方法有关。这里，“ 确定的 ” 是指一套有物理意义和现实意义的离散评估参数（如岩石总体积、平均孔隙度等）组合，可相应得到一个可采量的评估结果。该参数组合代表的就是一个特定情景。在此基础上，即使采用概率法也是基于情景。无论哪种方法，可采量的不确定性是与实施（或计划）的项目相关，而项目的风险（商业几率）是由核定的资源类别或亚类来定义。

需要牢记，评估的目标是得到至少三个结果（可采量估值），以反映项目的不确定性范围，通常为低估值、最佳估值和高估值。无论采用哪种评估方法，基本理念必须相同，认识到这点十分重要。第 4 章和第 5 章会更详细地讨论这些方法。

评估师可以选择一个以上的方法来评估某个具体项目，特别是比较复杂的开发项目。例如，对于同一项目，可以在应用蒙特卡洛分析之后，再选用三个确定情景进行评估。推荐以下术语来表述当前采用的主要方法：

methods are discussed in more detail in Chap. 4 and Chap 5.

Evaluators may choose to apply more than one method to a specific project, especially for more complex developments. For example, three deterministic scenarios may be selected after reviewing a Monte Carlo analysis of the same project. The following terminology is recommended for the primary methods in current use.

2.5.1 Deterministic (scenario) method

In this method, three discrete scenarios are developed that reflect a low, best and high estimate of recoverable quantities. These scenarios must reflect realistic combinations of parameters and particular care is required to ensure that a reasonable range is used for the uncertainty in reservoir property averages (e.g., average porosity) and that interdependencies are accounted for (e.g., a high gross rock volume estimate may have a low average porosity associated with it). It is generally not appropriate to combine the low estimate for each input parameter to determine a low case outcome, as this would not represent a realistic low case scenario (it would be closer to the absolute minimum possible outcome).

2.5.2 Deterministic (incremental) method

The deterministic (incremental) method is widely used in mature onshore environments, especially where well-spacing regulations apply. Typically, Proved Developed Reserves are assigned within the drilled spacing-unit and Proved Undeveloped Reserves are assigned to adjacent spacing-units where there is high confidence in continuity of productive reservoir. Probable and Possible Reserves are assigned in more remote areas indicating progressively less confidence. These additional quantities (e.g., Probable Reserves) are estimated discretely as opposed to defining a Proved plus Probable Reserves scenario. In such cases, particular care is required to define the project correctly (e.g., distinguishing between which wells are planned and which are contingent) and to ensure that all uncertainties, including recovery efficiency, are appropriately addressed.

2.5.3 Probabilistic method

Commonly, the probabilistic method is implemented using Monte Carlo analysis. In this case, the user defines the uncertainty distributions of the input parameters and the relationship (correlations) between them, and the technique derives an output distribution based on combining those input assumptions. As mentioned above, each iteration of the model is a single, discrete deterministic scenario. In this case, however, the software determines the combination of parameters for each iteration, rather than the user, and runs many different possible

2.5.1 确定（情景）法

在这种方法中，设计了三个单独的情景来表示可采量的低估值、最佳估值和高估值。这些情景必须反映参数组合的现实性，还需特别小心，以确保油气藏属性均值（如平均孔隙度）不确定性的合理范围，并考虑属性的相关性（例如，岩石总体积的高估值可能会与较低的平均孔隙度相关联）。一般来说，用组合中每个输入参数的低值来确定低估值情景结果是不恰当的。因为，这种组合并不代表一个实际存在的低估值情景（而是更接近可能结果的绝对最低值）。

2.5.2 确定（增量）法

确定（增量）法广泛应用于陆上成熟地区，特别是按井距部署的区域。通常，证实已开发储量可核定在已钻井的井距控制区域内，证实未开发储量可核定在相邻一个井距、与产层连通置信度高的区域。概算和可能储量则可核定到更远、置信度较低的区域。上述储量增量（如概算储量）是单独估算的，而不是定义一个证实储量 + 概算储量情景。这种情形下，需要特别注意的是：一要正确定义项目（例如，区分已计划井位和潜在井位）；二是确保适当表述了所有不确定性（包括采收率）。

2.5.3 概率法

通常，概率法的应用是采用蒙特卡洛分析。在这种情况下，由用户定义输入参数的不确定性分布以及它们的关系（相关性），然后在这些假定的输入参数组合基础上用蒙特卡洛分析技术得到一个结果分布。如上所述，运算模型的每一次迭代计算代表的都是一个离散的确定性情景。然而，每次迭代计算是由软件（而不是用户）来确定参数的组合，运算很多次不同的可能组合（通常几千次）是为了得到可能结果范围的完整概率分布，并从中选择出三个代表性结果（如 P90、P50 和 P10）。也可以应用油藏随机建模的方法

combinations (usually several thousand) in order to develop a full probability distribution of the range of possible outcomes from which three representative outcomes are selected (e.g., P90, P50 and P10). Stochastic reservoir modeling methods may also be used to generate multiple realizations.

2.5.4 Multiscenario method

The multiscenario method is a combination of the deterministic (scenario) method and the probabilistic method. In this case, a significant number of discrete deterministic scenarios are developed by the user (perhaps 100 or more) and probabilities are assigned to each possible discrete input assumption. For example, three depth conversion models may be considered possible, and each one is assigned a probability based on the user's assessment of the relative likelihood of each of the models. Each scenario leads to a single deterministic outcome, and the probabilities for each of the input parameters are combined to give a probability for that scenario/outcome. Given sufficient scenarios (which may be supplemented through the use of experimental design techniques), it is possible to develop a full probability distribution from which the three specific deterministic scenarios that lie closest to P90, P50 and P10 (for example) may be selected.

2.6 Commercial Risk and Reported Quantities

In PRMS, commercial risk can be expressed quantitatively as the chance of commerciality, which is defined as the product of two risk components:

(1) The chance that the potential accumulation will result in the discovery of petroleum. This is referred to as the “chance of discovery.”

(2) Once discovered, the chance that the accumulation will be commercially developed is referred to as the “chance of development.”

Because Reserves and Contingent Resources are only attributable to discovered accumulations, and hence the chance of discovery is 100%, the chance of commerciality becomes equivalent to the chance of development. Further, and as mentioned previously, for a project to be assigned Reserves, there should be a very high probability that it will proceed to commercial development (i.e., very little, if any, commercial risk). Consequently, commercial risk is generally ignored in the estimation and reporting of Reserves.

However, for projects with Contingent or Prospective Resources, the commercial risk is likely to be quite significant and should always be carefully considered and documented. Industry practice in the case of Prospective Resources is fairly well established, but there does not appear to be any consistency yet for Contingent Resources.

来产生多个实现。

2.5.4 多情景法

多情景法是一种结合确定（情景）法与概率法的综合方法。在这种情况下，由用户设置大量离散的确定性情景（也许 100 个或更多），并为每一个可能的输入参数赋予概率。例如，可考虑三个可能的深度转换模型，根据用户对每个模型的相对可能性来赋予其概率。每个情景会得到一个单独的确定性结果，而每个输入参数概率的叠合就可得到该情景 / 结果的概率。如果有足够多的情景（可通过实验设计技术来补充），就可以建立一个完整的概率分布，从中选择三个特定（例如，最接近 P90、P50 和 P10）的确定性情景。

2.6 商业风险与披露数量

在石油资源管理系统（PRMS）中，商业风险可以定量地表述为商业几率，并定义为两个风险因素的乘积：

（1）潜在油气聚集体实现石油发现的几率，也称为“ 发现几率 ”。

（2）一旦发现，该油气聚集体将实现商业开发的几率，称为“ 开发几率 ”。

由于储量和条件资源量只归属于已发现的油气聚集体，因此其发现几率为 100%，而商业几率则等于开发几率。此外，如前文所述，对于一个即将核定储量的项目而言，其进一步商业开发的几率应该非常高（若存在商业风险，也非常小）。因此，在储量的评估和报告中，商业风险一般都忽略不计。

当然，对有条件资源量或远景资源量的项目而言，商业风险可能很高，应认真考量与记录。对于远景资源量，已有相对多行业实践；但对于条件资源量，似乎对其商业风险的认识尚不一致。

首先，让我们看远景资源量的行业实践情况。发现几率的评估是基于形成一个油气聚集体所需的要素（烃源岩、圈闭、运移等）出现的几率。

Consider, first, industry practice for Prospective Resources. The chance of discovery is assessed based on the probability that all the necessary components for an accumulation to form (hydrocarbon source, trap, migration, etc.) are present. Separately, an evaluation of the potential size of the discovery is undertaken. Typically, this is performed probabilistically and leads to a full distribution of the range of uncertainty in potentially recoverable quantities, given that a discovery is made. Because this range may include some outcomes that are below the economic threshold for a commercially viable project, the probability of being above that threshold is used to define the chance of development, and hence a chance of commerciality is obtained by multiplying this by the chance of discovery. The distribution of potential outcomes is then recomputed for the “success case;” i.e., for a discovery that is larger than the economic threshold.

Because Prospective Resources are generally not reported externally, companies have established their own internal systems for documenting the relationship between risk and expected outcomes. Usually, if a single number is captured, it would be the “risked mean” or “risked mean success volume,” where the risk is the chance of commerciality and the mean is taken from the distribution of recoverable quantities for the “success case.” Note that it is mathematically invalid to determine a P90 of the risked success-case distribution (or any other probability level other than the mean itself) by multiplying an unrisked success-case P90 by the chance of commerciality.

It would be easy to assume that a similar process could be applied for Contingent Resources to determine a “success case” outcome, based on the probability that the estimated recoverable quantities are above a minimum economic threshold, but this would not be correct.

Once a discovery has been made, and a range of technically recoverable quantities has been assessed, these will be assigned as Contingent Resources if there are any contingencies that currently preclude the project from being classified as commercial. If the contingency is purely nontechnical (such as a problem getting an environmental approval, for example), the uncertainty in the estimated recoverable quantities generally will not be impacted by the removal of the contingency. The Contingent Resource quantities (1C, 2C, and 3C) should theoretically move directly to 1P, 2P, and 3P Reserves once the contingency is removed, provided of course that all other criteria for assigning Reserves have been satisfied and the planned recovery project has not changed in any way. In this example, the chance of commerciality is the probability that the necessary environmental permit will be obtained.

另外，还要评估“发现”的潜在规模。通常，这种评估是假定有所发现，然后采用概率法得到潜在可采量的整个不确定性分布范围。由于该分布可能包含一些低于商业项目经济界限的结果，高于经济界限部分的概率可作为开发几率，再与发现几率相乘，就得到商业几率。然后，重新计算“成功案例”（即发现规模大于最小经济油田规模）的结果分布。

由于远景资源量一般不对外披露，因此公司都建立了各自独有的内部系统来记录风险与预期结果之间的相互关系。一般来说，一个结果数值确定，应该是风险后的平均值或者风险后的平均有效体积（即大于最小经济油田规模），其风险就是商业几率，而均值就是取自成功案例的可采量分布。需要注意的是，从数学角度来讲，成功案例风险前的 P90 与商业几率相乘来计算成功案例风险后的 P90（或任何其他概率值）是无效的。

对于条件资源量，很容易假定一个类似远景资源量评估的过程——根据可采量估值高于最低经济门限的概率，来确定一个“成功案例”结果。但这样做是不对的。

一旦获得一个发现，并评估出其技术可采量范围，若当前存在任何或有因素使该项目无法划归为商业项目，那么该项目的可采量应核定为条件资源量。若该或有因素完全是非技术性的（例如环境审批方面的问题），一般其估算可采量的不确定性不会因为该或有因素的消除而受到影响。一旦该或有因素被消除，理论而言，条件资源量（1C、2C 和 3C）应直接升级为 1P、2P 和 3P 储量；当然，前提是核定储量所需的其他条件都能满足，且计划的开发项目没有任何变化。在这个案例中，商业几率就是获得环境许可的概率。

然而，另一种可能阻碍开发决策的或有因素是 1C 资源估算量太小，不足以启动该项目——即使 2C 资源量经济可行。这种情况并不少见。例如，某公司首先通过测算表明，项目的 2C 资

However, another possible contingency precluding a development decision could be that the estimated 1C quantities are considered to be too small to commit to the project, even though the 2C level is commercially viable. It is not uncommon, for example, for a company to first test that the 2C estimate satisfies all their corporate hurdles and then, as a project robustness test, to require that the low (1C) outcome is at least break-even. If the project fails this latter test and development remains contingent on satisfying this break-even test, further data acquisition (probably appraisal drilling) would be required to reduce the range of uncertainty first. In such a case, the chance of commerciality is the probability that the appraisal efforts will increase the low (1C) estimate above the break-even level, which is not the same as the probability (assessed before the additional appraisal) that the actual recovery will exceed the break-even level. In this situation, because the project will not go ahead unless the 1C estimate is increased, the “success case” range of uncertainty is different from the pre-appraisal range.

As mentioned above, there is no industry standard for the reporting of Contingent Resource estimates. However, the commercial risk associated with such projects can vary widely, with some being "almost there" with, say, an 80% chance of proceeding to development, while others might have a less than, say, 30% chance. If Contingent Resources are reported externally, the commercial risk can be communicated to users (e.g., investors) by various means, including: (1) describing the specific contingencies associated with individual projects; (2) reporting a quantitative chance of commerciality for each project; and/or (3) assigning each project to one of the Project Maturity subclasses (see Sec. 2.7).

Aggregation of quantities that are subject to commercial risk raises further complications, which are discussed in Chap.6.

2.7 Project Maturity Subclasses

Under PRMS, identified projects must always be assigned to one of the three classes: Reserves, Contingent Resources, or Prospective Resources. Further subdivision is optional, and three subclassification systems are provided in PRMS that can be used together or separately to identify particular characteristics of the project and its associated recoverable quantities. The subclassification options are project maturity subclasses, reserves status, and economic status.

As illustrated in Figure 2.2, development projects (and their associated recoverable quantities) may be subclassified according to project maturity levels and the associated actions (business decisions)

源估算量可满足公司设定的所有门限条件，然后稳健性测试要求其低估值（1C）情景至少达到盈亏平衡要求。如果项目未能通过后一项测试，而且项目的进程仍取决于是否能满足盈亏平衡要求，那么就首先需要进一步获取资料（可能钻评价井）降低不确定性的范围。在这种情况下，商业几率是通过评价工作使低估值（1C）超过盈亏平衡点的概率，而不是实际采出量超过盈亏平衡点的概率（增加评价工作之前评估的）。这时，除非低估值（1C）增加，否则项目就不能推进，所以“成功案例”的不确定性范围与增加评价工作量前的不确定性范围是不同的。

如前文所述，条件资源量的评估报告尚无行业标准。不过，这类项目的商业风险差别很大。比如，一些“接近开发”项目，大致有 80% 几率进行开发；而有些项目的开发几率则可能低于 30%。如果对外披露条件资源量，可以通过多种方式向用户（如投资者）说明其商业风险的情况，包括：（1）描述单个项目的具体或有因素；（2）报告每个项目的定量商业几率；和 / 或（3）为每个项目核定其项目成熟度亚类（参见第 2.7 节）。

油气数量的汇并会造成商业风险的进一步复杂化，相关内容在第 6 章讨论。

2.7 项目成熟度亚类

在 PRMS 中，已明确定义的项目一定可以划分为三个类别之一：储量、条件资源量或远景资源量。还可以进一步根据需要进行次级划分。PRMS 提供了三种次级划分方式（可以联合使用或单独使用）来区别项目及其可采量的具体特征。次级划分方式的选项包括项目成熟度亚类、储量状态和经济状态。

如图 2.2 所示，开发项目（及其可采量）可根据项目成熟度水平和推进项目商业生产的活动（业务决策）来进行亚类划分。该方法可在勘探和开发不同阶段为项目组合的管理提供支持，还

required to move a project toward commercial production. This approach supports managing portfolios of opportunities at various stages of exploration and development and may be supplemented by associated quantitative estimates of chance of commerciality, as discussed in Sec. 2.6. The boundaries between different levels of project maturity may align with internal (corporate) project “decision gates,” thus providing a direct link between the decision-making process within a company and characterization of its portfolio through resource classification. This link can also act to facilitate the consistent assignment of appropriate quantified risk factors for the chance of commerciality.

可辅以商业几率的定量评估，如第 2.6 节所述。项目成熟度不同水平之间的界限可能对应于内部（公司）项目的“决策点”。因此，为公司决策过程与资源分类组合特征之间建立了直接的关联关系。该关联关系也将相应地有助于为商业几率分配适当的量化风险因子。

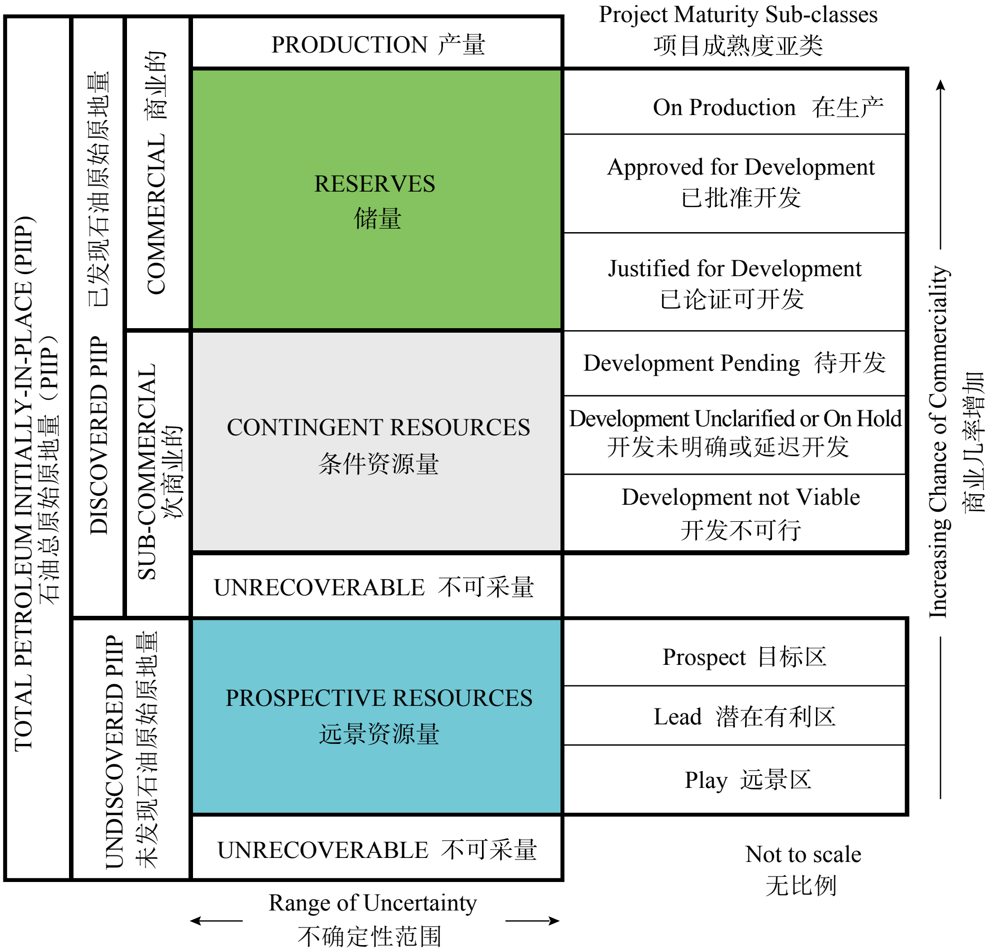

Figure 2.2 Subclasses based on project maturity.

图 2.2 项目成熟度亚类

Evaluators may adopt alternative subclasses and project maturity modifiers to align with their own decision-making process, but the concept of increasing chance of commerciality should be a key enabler in applying the overall classification system and supporting portfolio management. Note that, in quantitative terms, the “chance

评估师也可以采用其他可替代的亚类和项目成熟度调节因子，来契合自己的决策过程，但商业几率增加的理念应该是支撑整个分类系统应用和资产组合管理的一个重要驱动因素。需要注意的是，就量化而言，图 2.1 和图 2.2 中所示的“商业几率”在纵轴上并不代表线性比例。例如，一个条件资源量项目若被核定为“开发不可行”，

of commerciality" axis shown in Figures 2.1 and 2.2 is not intended to represent a linear scale, nor is it necessarily wholly sequential in the sense that a Contingent Resource project that is classified as "Development not Viable" could have a lower chance of commerciality than a low-risk prospect, for example. In general, however, quantitative estimates of the chance of commerciality will increase as a project moves "up the ladder" from an exploration concept to a field that is producing.

If the subclasses in Figure 2.2 are adopted, the following general guidelines should be considered in addition to those documented in Table 1 of PRMS:

(1) **On Production** is self-evident in that the project must be producing and selling petroleum to market as at the effective date of the evaluation. Although implementation of the project may not be 100% complete at that date, and hence some of the reserves may still be Undeveloped (see Sec. 2.8), the full project must have all necessary approvals and contracts in place, and capital funds committed. If a part of the development plan is still subject to approval and/or commitment of funds, this part should be classified as a separate project in the appropriate subclass.

(2) **Approved for Development** requires that all approvals/contracts are in place, and capital funds have been committed. Construction and installation of project facilities should be underway or due to start imminently. Only a completely unforeseeable change in circumstances that is beyond the control of the developers would be an acceptable reason for failure of the project to be developed within a reasonable time frame.

(3) Projects normally would not be expected to be classified as **Justified for Development** for very long. Essentially, it covers the period between (a) the operator and its partners agreeing that the project is commercially viable and deciding to proceed with development on the basis of an agreed development plan (i.e., there is a "firm intent"), and (b) the point at which all approvals and contracts are in place (particularly regulatory approval of the development plan, where relevant) and a "final investment decision" has been made by the developers to commit the necessary capital funds. In PRMS, the recommended benchmark is that development would be expected to be initiated within 5 years of assignment to this subclass (refer to Sec. 2.1.2 of PRMS for discussion of possible exceptions to this benchmark).

(4) **Development Pending** is limited to those projects that are actively subject to project-specific technical activities, such as appraisal drilling or detailed evaluation that is designed to confirm

这并不完全意味着其商业几率在次序上就低于风险低的目标区。当然，总的来说，当一个项目从概念勘探阶段“上台阶”为实际生产的油气田，其商业几率的定量评估值会不断增加。

如果采用图 2.2 中的亚类，那么除了 PRMS 的表 1 所明确内容外，还应考虑以下通用指导性原则。

2.7.1 在生产

不言而喻，项目在有效评估日的状态一定是正在生产，并在市场销售所生产石油产品。尽管项目的实施在评估日可能尚未 100% 完成，因而有一部分储量可能仍处于未开发状态（参见第 2.8 节），但整个项目必须已获得所需审批与合同，运营资金已承诺。如果开发方案部分内容仍需要进行审批和 / 或待资金筹措，则该部分内容应该作为一个单独项目划分为适当的亚类。

2.7.2 已批准开发

要求项目已获得所有的审批与合同，资金已到位。项目设施的建设和安装应正在进行中，或即将启动。只有出现开发商不可控且完全不可预见的情况，才可能造成项目无法在合理时期内进行开发而导致项目失败。

2.7.3 已论证可开发

正常情况下，“已论证可开发”项目不会长时间保留。基本上，该状态的时间段介于（1）作业者及其合作伙伴一致认定该项目具有商业可行性，且决定按照同意的开发方案推进开发工作（即有“明确意向”），和（2）已经获得所有批复和合同（特别是开发方案已得到主管部门批准），且生产商已做出最终投资决策（FID）承诺所需资金。在 PRMS 中，建议采用的时间界定标准是：项目核定为该亚类后，其开发应在 5 年内启动（PRMS 第 2.1.2 节讨论了时间界定标准的例外情况）。

2.7.4 待开发

仅限于正积极开展项目所需技术攻关活动的

commerciality and/or to determine the optimum development scenario. In addition, it may include projects that have nontechnical contingencies, provided these contingencies are currently being actively pursued by the developers and are expected to be resolved positively within a reasonable time frame. Such projects would be expected to have a high probability of becoming a commercial development (i.e., a high chance of commerciality).

(5) **Development Unclarified** or **On Hold** comprises two situations. Projects that are classified as On Hold would generally be where a project is considered to have at least a reasonable chance of commerciality, but where there are major nontechnical contingencies (e.g., environmental issues) that need to be resolved before the project can move toward development. The primary difference between Development Pending and On Hold is that in the former case, the only significant contingencies are ones that can be, and are being, directly influenced by the developers (e.g., through negotiations), whereas in the latter case, the primary contingencies are subject to the decisions of others over which the developers have little or no direct influence and both the outcome and the timing of those decisions is subject to significant uncertainty.

Projects are considered to be Unclarified if they are still under evaluation (e.g., a recent discovery) or require significant further appraisal to clarify the potential for development, and where the contingencies have yet to be fully defined. In such cases, the chance of commerciality may be difficult to assess with any confidence.

(6) Where a technically viable project has been assessed as being of insufficient potential to warrant any further appraisal activities or any direct efforts to remove commercial contingencies, it should be classified as **Development not Viable.** Projects in this subclass would be expected to have a low chance of commerciality.

It is important to note that while the aim is always to move projects “up the ladder” toward higher levels of maturity, and eventually to production, a change in circumstances (disappointing well results, change in fiscal regime, etc.) can lead to projects being “downgraded” to a lower subclass.

One area of possible confusion is the distinction between Development not Viable and Unrecoverable. A key goal of portfolio management should be to identify all possible incremental development options for a reservoir; it is strongly recommended that all technically feasible projects that could be applied to a reservoir are identified, even though some may not be economically viable at the time. Such

项目，例如钻评价井或者详细评估，以确认项目的商业性和 / 或确定最佳开发方式。此外，也可以包括非技术或有因素的项目，但前提条件是生产商正积极采取措施应对这些或有因素，并预期这些或有因素可在合理时期内适当解决。这些项目商业开发的几率较高（即商业几率高）。

2.7.5 开发未明确或延迟开发

开发未明确或延迟开发包括两种情况。项目被划分为延迟开发，通常是指项目至少具有合理的商业几率，但在进行开发之前仍存在重大的非技术性或有因素（例如环境问题）亟待解决。待开发和延迟开发之间的主要区别在于：前者，仅有的重大或有因素可以（和正在）受生产商直接影响而改变（例如谈判）；而后者，主要或有因素是受其他方面的决策影响，开发商的直接影响很小或者无法左右，决策结果和时间计划都存在很大的不确定性。

开发未明确指项目仍处于评估阶段（例如新发现），或者需要进一步开展大量评价工作以确定开发潜力和厘清或有因素。在这种情况下，很难评估商业几率。

2.7.6 开发不可行

若一个技术可行项目，经评估不能进一步通过评价活动或直接努力消除或有因素，那该项目应划归为开发不可行。此类项目的商业几率低。

以下认识十分重要：我们的目标总是促进项目“上台阶”，从而达到更高成熟度并最终实现生产；但实际情况的变化（如井的开发效果不理想、财税机制变化等）也可能会造成项目“降级”为成熟度水平更低的亚类。

开发不可行与不可采量之间可能容易混淆。投资组合管理的一个主要目标应该是识别一个油气藏所有可能的增产方式；所以强烈建议对油气藏适用的所有技术可行项目均进行判别，即便某些项目当

an approach highlights the extent to which identified incremental development projects would achieve a level of recovery efficiency that is at least comparable to analogous reservoirs. Or, looking at it from the other direction, if analogous reservoirs are achieving levels of recovery efficiency significantly better than the reservoir under consideration, it is possible that there are development options that have been overlooked.

A project would be classified as Development not Viable if it is not seen as having sufficient potential for eventual commercial development, at the time of reporting, to warrant further appraisal. However, the theoretically recoverable quantities are recorded so that the potential development opportunity will be recognized in the event of a major change in technology and/or commercial conditions.

Quantities should only be classified as Unrecoverable if no technically feasible projects have been identified that could lead to the recovery of any of these quantities. A portion of Unrecoverable quantities may become recoverable in the future due to the development of new technology, for example; the remaining portion may never be recovered due to physical/chemical constraints represented by subsurface interaction of fluids and reservoir rocks. See also the discussion regarding technology under development in Sec. 2.3.

2.8 Reserves Status

Estimated recoverable quantities associated with projects that fully satisfy the requirements for Reserves may be subdivided according to their operational and funding status. Under PRMS, subdivision by reserves status is optional and includes the following status levels: Developed Producing, Developed Nonproducing, and Undeveloped. In addition, although the prior (1997) definitions of these subdivisions were associated only with Proved Reserves, PRMS now explicitly allows the subdivision to be applied to all categories of Reserves (i.e., Proved, Probable, and Possible).

Reserve status has long been used as a subdivision of Reserves in certain environments, and it is obligatory under some reporting regulations to subdivide Proved Reserves to Proved Developed and Proved Undeveloped. In many other areas, subdivision by Reserves status is not required by relevant reporting regulations and is not widely used by evaluators. Unless mandated by regulation, it is up to the evaluator to determining the usefulness of these, or any of the other, subdivisions in any particular situations.

Subdivision by reserves status or by project maturity subclasses is optional and, because they are to some degree independent of each other, both can be applied together. Such an approach requires some care, as it is possible to confuse the fact that project maturity subclasses are linked

时可能不经济。这样做，可以挑出至少与类比油气藏采收率相当的增产项目。或者，换一个角度来看，如果类比油气藏的采收率远高于目标油气藏，则说明有一些可选择的开发方式被忽视了。

一个项目划归为开发不可行，则意味着该项目在报告时，尚看不到足够潜力可实现最终商业开发，没有依据进一步推进评价工作。尽管如此，应记录理论可采量，以便在技术和 / 或商业条件发生重大变化时，可以识别潜在的开发机会。

没有技术可行项目可供实施的资源数量，应划归为不可采量。不可采量的一部分有可能在未来因为某些原因而转化为可采量，例如，新技术的开发等；剩余部分则可能由于地下流体和储层岩石的物化束缚作用而永远无法采出。有关正研发技术的讨论，参见第 2.3 节。

2.8 储量状态

对于完全满足储量要求的项目可采量估值，可以根据其作业和资金状态进行次级划分。在 PRMS 中，按储量状态进行次级划分可根据需要选择。储量状态包括：已开发正生产、已开发未生产和未开发。此外，尽管以前（1997 年）储量状态的次级划分定义只涉及证实储量，但现行 PRMS 已明确允许所有级别储量（即证实、概算和可能储量）进行次级划分。

在特定情况下，储量状态可长期用于储量次级划分，某些披露规则还强制要求将证实储量进一步划分为证实已开发和证实未开发。其他许多地区，相关披露规则并不要求按储量状态进行次级划分，也并未被评估师广泛采纳。除非有规定强制要求，评估师可自行根据具体情况决定是否选用上述或任何其他次级划分方式。

按储量状态或按项目成熟度亚类进行次级划分是可选择的，因为这两种方法在一定程度上是相互独立的，可以同时应用。这样做时需要十分谨慎，避免混淆以下实际情形：项目成熟度亚类与项目整体状态相关联，而储量状态考量的是

to the status of the project as a whole, whereas reserves status considers the level of implementation of the project, essentially on a well-by-well basis. Unless each well constitutes a separate project, reserves status is a subdivision of Reserves within a project. Reserves status is not project-based, and hence there is no direct relationship between reserves status and chance of commerciality, which is a reflection of the level of project maturity.

The relationship between the two optional classification approaches may be best understood by considering all the possible combinations, as illustrated below. The table shows that a project that is On Production could have Reserves in all three reserves status subdivisions, whereas all project Reserves must be Undeveloped if the project is classified as Justified for Development.

项目执行情况，基本上是逐井考量。仅当每口井构成单独项目时，储量状态是对项目的储量类别进行次级划分。储量状态的划分并不基于项目，因此储量状态与商业几率之间不存在直接关联关系，商业几率反映的是项目成熟度水平。

如下表所示，全面考虑所有可能出现的组合情况，可以帮助我们更好地理解这两种选择性次级划分方式的相互关系。从该表中可以看出，一个正生产项目可能拥有三种储量状态的次级划分，而如果项目已划归为已论证可开发，那么项目所有储量一定为未开发状态。

Table 2.1 Relationship between Project Maturity Sub-classes and Reserves Status

表 2.1 项目成熟度亚类与储量状态的关系

Projeect Maturity Sub-classes 项目成熟度亚类	Reserves Status 储量状态		
	Developed Producing Reserves 已开发正生产	Developed Non-Producing Reserves 已开发未生产	Undeveloped Reserves 未开发
On Production 在生产	☑	☑	☑
Approved for Development 已批准开发	☒	☑	☑
Justified for Development 已论证可开发	☒	☒	☑

Applying reserves status in the absence of project maturity subclasses can lead to the mixing of two different types of Undeveloped Reserves and will hide the fact that they may be subject to different levels of project maturity:

(1) Those Reserves that are Undeveloped simply because implementation of the approved, committed and budgeted development project is ongoing and drilling of the production wells, for example, is still in progress at the date of the evaluation; and,

(2) Those Reserves that are Undeveloped because the final investment decision for the project has yet to be made and/or other approvals or contracts that are expected to be confirmed have not yet been finalized.

For portfolio analysis and decision-making purposes, it is clearly important to be able to distinguish between these two types of Undeveloped Reserves. By using project maturity subclasses, a clear distinction can be made between a project that has been Approved for Development and one that is Justified for Development, but not yet approved.

在不进行项目成熟度亚类划分情况下，储量状态的次级划分可能会造成两类不同未开发储量的混淆，从而掩盖了其不同的项目成熟度水平：

(1) 一类未开发储量，仅因为已获批复、资金到位且有投资计划的开发项目正在实施，例如生产井的钻井工作在评估日仍在进行；

(2) 另一类未开发储量，因为项目尚未做出最终投资决策，和 / 或一些所需的批复或合同还没有最终确认。

为了有助于投资组合分析和进行决策，显然，将这两种不同类型的未开发储量进行区分是很重要的。通过实施项目成熟度亚类的划分，就可以清晰地区分已批准开发项目和尚未批准的已论证可开发项目。

2.9 Economic Status

A third option for classification purposes is to subdivide Contingent Resource projects on the basis of economic status, into Marginal or Submarginal Contingent Resources. In addition, PRMS indicates that, where evaluations are incomplete such that it is premature to clearly define ultimate chance of commerciality, it is acceptable to note that project economic status is“undetermined.” As with the classification options for Reserves that are based on reserves status, this is an optional subdivision that may be used alone or in combination with project maturity subclasses.

Broadly speaking, one might expect the following approximate relationships between the two optional approaches (Table 2.2) :

2.9 经济状态

第三种可选用的次级划分方式是：按经济状态将条件资源量项目进一步划分为边际的或者次边际的。此外，PRMS 提示，评价工作尚未结束之前，确定最终商业几率的时机并不成熟，此时项目经济状态为“ 未确定 ”是可以接受的。与选用储量状态进行次级划分一样，按经济状态进行次级划分也可以单独应用，或与项目成熟度亚类划分联合应用。

总的来说，这两种可选用方式之间的近似关系如表 2.2 所示。

Table 2.2 Relationships between Project Maturity Subclass and Economic Status
表 2.2 项目成熟度亚类与经济状态的关系

Project Maturity Subclass 项目成熟度亚类	Additional Sub-classification 其他次级划分	Economic Status 经济状态
Development Pending 待开发	Pending 待定	Marginal Contingent Resources 边际条件资源量
Development Unclarified or On Hold 开发未明确或延迟开发	On Hold 延迟	
	Unclarified 未明确	Undetermined 未确定
Development not Viable 开发不可行	not Viable 不可行	Sub-marginal Contingent Resources 次边际条件资源量

References, 参考文献

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第 3 章
CHAPTER 3

地震技术应用
Seismic Applications

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3.1 Introduction

Geophysical methods, principally seismic surveys, are one of the many tools used by the petroleum industry to assess the quantity of oil and gas available for production from a field. The interpretations and conclusions from seismic data are integrated with the analysis of well logs, pressure tests, cores, geologic depositional knowledge and other information from exploration and appraisal wells to determine if a known accumulation is commercial and to formulate an initial field development plan. As development wells are drilled and put on production, the interpretation of the seismic data is revised and recalibrated to take advantage of the new borehole information and production histories. Aspects of the seismic interpretation that initially were considered ambiguous become more reliable and detailed as uncertainties in the relationships between seismic attributes and field properties are reduced. The seismic data evolve into a continuously utilized and updated subsurface tool that impacts both estimation of reserves and depletion planning.

While 2D seismic lines are useful for mapping structures, the uncertainties associated with all aspects of a seismic interpretation decreases considerably when the seismic data are acquired and processed as a 3D data volume. Not only does 3D acquisition provide full spatial coverage, but the 3D processing procedures (seismic migration in particular) are better able to move reflections to their proper positions in the subsurface, significantly improving the clarity of the seismic image. In addition, 3D seismic data can provide greater confidence in the prediction of reservoir continuity away from well control. 3D seismic offers the geoscientist the option to extract a suite of more complex seismic attributes to further improve the characterization of the subsurface. 3D data acquisition and processing improve continuously; a recent example is the development of Wide Azimuth (WAZ) seismic acquisition and processing that provides improvements in structural definition and signal to noise ratio in complex geologies.

The following discussion focuses on the application of 3D seismic data in the estimation of Reserve and Resource volumes as classified and categorized by PRMS. However, in some areas, 2D data may still play a crucial role when Prospective Resources are being estimated. Once a discovery is made, and as an individual asset or project matures, it has become the norm to acquire 3D seismic data, which provide critical additional information in support of the estimation of Contingent Resources and/or Reserves. Finally, once a field has been on production for some time, repeat seismic surveys may be acquired if conditions are suitable. The information from these

3.1 引言

以地震勘查为主的地球物理方法是石油行业用于评估一个油气田可开采油气数量的工具之一。根据地震数据解释和得到的认识，结合探井与评价井的测井、压力测试、岩心资料、地质沉积资料和其他信息的综合分析，可判断已知油气聚集体是否具有商业性，并制定初始油气田开发方案。当开发井完钻并投产，地震数据解释可利用新钻孔资料和生产历史进行修订和重新校正。当地震属性和油气田性质之间关系的不确定性降低，最初模棱两可的地震解释会变得更加可靠和详实。地震数据正发展为一个可持续利用和更新的、影响储量估算与开采方案的地下信息工具。

虽然二维地震测线可用于构造落实，但三维地震数据体的采集与处理会大大降低地震解释相关环节的不确定性。三维地震数据体的采集不仅提供了空间的全覆盖，而且其处理程序（尤其是地震偏移）可以更好地将反射归位到地下实际位置，从而大大提高地震图像的清晰度。此外，三维地震数据还可为油气藏在井控区域外的储层连续性预测提供更高置信度。三维地震使得地球科学家能够提取更复杂的地震属性组合来进一步改善对地下储层的描述。三维地震数据采集和处理技术正在不断提高；最近的一个例子是宽方位角（WAZ）地震采集和处理技术的发展，改善了复杂地质条件下的构造识别与信噪比。

下面将着重讨论三维地震数据在石油资源管理系统分类分级下储量与资源量估算中的应用。当然，在某些领域中，二维地震数据仍在远景资源量估算过程中发挥着至关重要的作用。一旦有了新发现，并且随着具体项目的逐渐成熟，通常会要求采集三维地震数据，其可以为条件资源量和 / 或储量的估算提供非常重要的补充信息。最后，一旦油气田生产了一段时间，若条件适合，可重新采集地震数据。时间推移地震（也称为四维地震），结合了生产动态信息，可用于储量与

time-lapse seismic surveys, also known as 4D seismic, are integrated with performance data and feed into the Reserves and Resource volumes estimates and updates to the field development plan.

3.2 Seismic Estimation of Reserves and Resources

The interpretations that a geoscientist derives from 3D seismic data can be grouped conveniently into those that map the structure and geometry of the hydrocarbon trap (including fault related aspects), those that characterize rock and fluid properties, and those that are directed at highlighting changes in the distribution of fluids and/or pressure variations, resulting from production.

3.2.1 Trap Geometry

Trap geometry is determined by the dips and strikes of reservoirs and seals, the locations of faults and barriers that facilitate or block fluid flow, the shapes and distribution of the sedimentary bodies that make up a field's stratigraphy, and the orientations of any unconformity surfaces that cut through the reservoir. A 3D seismic volume allows an interpreter to map the trap as a 3D grid of seismic amplitudes reflected from acoustic/elastic impedance ③ boundaries associated with the rocks and fluids in and around the trap. The resolution of 3D seismic typically ranges from 12.5 to 50 m laterally and 8 to 40 m vertically, depending on the depth and properties of the objective reservoir as well as the nature of the seismic survey acquisition parameters and the details of the subsequent processing. A geoscientist uses various interpretive techniques available on a computer workstation to analyze the seismic volume(s). A geoscientist can synthesize a coherent and quite detailed 3D picture of a trap's geometry depending on the seismic quality and resolution. Mapping travel times to selected acoustic/elastic impedance boundaries (geoscientists often call these boundaries seismic horizons), displaying seismic amplitude variations along these horizons, isochroning between horizons, noting changes in amplitude and phase continuity through the volume, and displaying time and/or horizon slices and volumetric renderings of the seismic data in optimized colors and perspectives all contribute to the detailed picture of the trap's geometry. Velocity data from wells, optionally supplemented with seismic velocity data, is used to convert the horizons picked in time into depth and thickness.

To fully analyze a trap, a geoscientist typically makes numerous cross sections, maps, and 3D visualizations of both the surfaces (bed

资源量的估算，以更新油气田的开发方案。

3.2 地震技术评估储量与资源量

地球科学家利用三维地震数据得到的解释结果可以包括：油气圈闭构造及其几何形态（包括断层要素）的图件，对岩石和流体性质的表征，以及反映由生产所引起的流体分布和 / 或压力的明显变化。

3.2.1 圈闭的几何形态

圈闭的几何形态取决于储层和盖层的倾角与走向、连通或阻碍流体流动的断层和隔夹层的位置、构成油气田地层的储层沉积体的形状和分布，以及切穿储层的不整合面方向等。利用三维地震数据体，地震解释人员可以将圈闭绘制为地震振幅的三维网格图，以反映与地下圈闭内部和周边岩石与流体相关的声波 / 弹性波阻抗的反射边界③。通常，三维地震的分辨率为横向 12.5m ～ 50m，纵向 8m ～ 40m，取决于目标储层的深度和物性，以及地震采集参数的性质和随后地震处理的具体情形。地球科学家可以在计算机工作站上用各种现有的解释技术来分析地震数据体；并根据地震数据的质量和分辨率，合成清晰连贯且细致的圈闭的三维几何图像。将旅行时间与所选声波 / 弹性波阻抗边界（地球科学家通常称之为反射层位）相关联，可显示沿反射层面的振幅变化，在反射层面之间作等时划分，可记录下数据体中振幅和相位的连续性变化，并显示地震数据体的时间和 / 或沿层切片，以及色彩和角度优化的体积透视图等，这些都有助于详细描述圈闭的形态。利用井的声波数据（选择性地补充地震速度数据）可将时间域的层面图转换为深度域的深度和厚度图。

为了全面分析一个圈闭，地球科学家通常需

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③ Acoustic impedance is the product of density and velocity. Since seismic reflection coefficients/strengths change with angle elastic impedance is sometimes used for oblique incidence.
声阻抗是介质密度与声传播速度的乘积，有时反射系数 / 强度随角度梯度弹性阻抗的变化可用于斜入射。

boundaries, fault planes, and unconformities) and thicknesses of the important stratigraphic units comprising the trap. In particular, the geometric configurations of the reservoirs and their adjacent sealing units are carefully defined. The displays ultimately are distilled to geometric renderings of the single or multiple pools that form the field. The final product of the trap analysis is a calculation of the reservoir bulk volume of these pools (which will later be integrated with reservoir properties such as porosity, net-to-gross, and hydrocarbon saturation to compute an estimate of the original oil and gas in place).

For fields interpreted to be faulted, it may be necessary to classify resource estimates differently for individual fault blocks. It is important to make a distinction whether the fault that separates the undrilled fault block from a drilled fault block can be considered a major, potentially sealing fault or not. This will depend on the analysis of the extent of the fault, the fault throw as well as an assessment of fault transmissibility. Seismic amplitudes and flat-spots (see 3.2.2) may be included in this assessment.

3.2.2 Rock and Fluid Properties

The second general application of 3D seismic analysis is predicting the rock and pore-fluid properties of the reservoir and sometimes its pressure regime. The reservoir properties that 3D seismic can potentially predict under suitable conditions are porosity, lithology, presence of gas/oil saturation as well as pressure. Predictions must be supported by well control and a representative depositional model. Depending on conditions predictions may be either qualitative or quantitative. Lithology, including net-to-gross, and porosity can be loosely estimated from a depositional model of the reservoir based on well data, 3D seismic facies analysis, and field analogs. By knowing whether the depositional system is fluvial, deltaic, deepwater, or another system, a geoscience team can apply general geologic understanding and predict reservoir porosity to within appropriate ranges from reservoir analogues.

In some situations more accurate and higher resolution predictions can be made based on seismic attributes such as amplitude. The use of such seismic attributes requires that:

(1) A relationship exists at log scale between these attributes and specific reservoir characteristics;

(2) This relationship still exists at seismic scale (which exhibits lower vertical resolution) ;

(3) The seismic quality is satisfactory;

(4) A reliable seismic to well tie exists.

The geoscientist should work through each of these: first, by demonstrating a relationship between a log-scale seismic attribute, such as p-wave or s-wave impedance or elastic impedance and a

要绘制大量剖面图、平面图，并对圈闭重要地层单元的层面（包括地层界面、断层面以及不整合面）和厚度进行三维可视化分析。特别是，要仔细确定储层及相邻盖层的几何形态。最后抽提出形成油气田的单个或多个油气聚集单体的几何空间展布图。圈闭分析的最终结果是计算这些油气聚集单体的储层总体积（随后将结合孔隙度、净毛比以及含烃饱和度等储层性质，来估算油气原始原地量）。

对于解释的断块油气藏，有必要按单个断块对资源进行评估。重要的是要辨别分隔未钻断块与已钻断块的断层是否为主要的潜在封堵断层。这取决于对断层长度、断距的分析以及对断层导流性的评估。该评估可包括地震振幅和平点的研究（参见第 3.2.2 节）。

3.2.2 岩石和流体性质

三维地震分析的第二个普遍应用是预测油气藏的岩石和孔隙流体性质，有时还包括压力场。在适当条件下，三维地震可以预测油气藏的属性包括孔隙度、岩性、含油气性以及压力。预测的结果必须由井控点和具代表性的地质沉积模型支持。根据情况，预测可以做到定性和定量。岩性（包括净毛比）和孔隙度，可根据井数据、三维地震沉积相分析和类比油气田得到油气藏地质沉积模型来进行粗略地评估。通过确定沉积体系是否是河流、三角洲、深水或其他沉积体系，地球科学研究团队就可以利用常规地质认识，根据类比油气藏在合理参数范围内预测储层的孔隙度。

在某些情况下，根据地震属性（如振幅）可进行更高精度和更高分辨率的预测。应用地震属性需满足以下要求：

（1）在测井尺度，这些地震属性与特定油气藏特征之间存在一定关联关系；

（2）在地震尺度（纵向分辨率较低），上述关系仍然存在；

（3）地震数据的质量满足要求；

（4）地震与井数据之间存在可靠关联关系。

地球科学家应开展以下工作：首先，论证测

reservoir property; second, by demonstrating that a useful relationship still exists at seismic resolution and for the anticipated geometries of the reservoir; third, the geoscientist should demonstrate that the data quality of the seismic at the reservoir level is good and that, for example, overburden effects do not obscure or distort the imaging of the reservoir; and finally, it should be demonstrated that well synthetics (modeled seismic derived from density and sonic logs) adequately tie the seismic data.

Qualitative predictions such as the stratigraphic extent of a reservoir may be based on relatively simple attribute extractions supported by well data and analogues. Quantitative predictions for example of porosity or net-to-gross will need more sophisticated approaches that compensate for the tuning ④ effects caused by the band-limited nature of the seismic data. These could be either 2D map based approaches or 3D seismic inversion based. They may involve either a direct calibration of the seismic attribute to a reservoir property or a two-stage approach by first estimating the impedance values. The risks and uncertainties of seismic inversion are discussed in 3.4.

Attributes may be extracted from conventional stacked volumes or, increasingly, from AVO attribute volumes such as intercept or gradient or linear combinations of the two. This can improve correlations between the seismic attribute and the reservoir property. Inversion algorithms make use either AVO volumes or prestack data. In all cases the quality of the track record and confidence ranges, either locally within the 3D volume or regionally, will need to be considered when determining the reliability of seismic based estimates.

The presence of hydrocarbons typically lowers the seismic velocity and density of unconsolidated to moderately consolidated sandstones and hence modifies the impedance contrast with surrounding shales relative to the contrast of water bearing sands with the same shales. Typically this will increase reflectivity but if brine sands are harder than shales, the reflectivity can be reduced or change polarity. The down-dip limit of this changed reflectivity will show up as a change of amplitude that conforms with a structural contour.

If the reservoir thickness is above seismic resolution, a reflection

井尺度地震属性（例如纵波或横波阻抗或者弹性波阻抗）与储层性质的关系；其次，论证在地震尺度下仍存在有效的关联关系，可用于预测油气藏的几何形态；第三，地球科学家应论证油气藏尺度的地震数据质量合格（例如，上覆地层的影响没有掩盖或歪曲储层的成像）；最后，应论证井的合成地震记录（根据密度和声波测井合成的模型化地震数据）能够充分约束地震数据。

在井数据和类比信息的支持下，可以提取简单属性来定性预测油气藏的地层范围。定量预测（例如孔隙度或净毛比）则需要更复杂的方法，补偿地震数据有限带宽造成的调谐效应④，可基于二维成图方法或三维地震反演。这些工作可能涉及用储层性质直接标定地震属性，或采用两步法，先评估波阻抗值。地震反演的风险和不确定性将在第 3.4 节讨论。

地震属性可以从常规叠后数据体中提取，或者更多地从 AVO 属性体（例如 AVO 截距和梯度或二者的线性组合）中提取，这可以提高地震属性与储层性质之间的相关性。反演运算使用的是 AVO 数据体或叠前数据体。无论在什么情况下，在确定地震方法评估的可靠性时，都需要考虑地震道记录的质量及其置信度范围（无论在三维地震数据体局部还是在区域范围内）。

烃的存在通常会降低疏松 - 中等固结程度砂岩的地震速度和密度，因而改变其与周边泥岩的波阻抗差（相对于含水砂岩和相同泥岩的波阻抗差）。通常这样会增加反射率，但如果含（盐）水砂岩比页岩硬，反射率会降低或改变极性。反射率变化的下倾边缘将展现出与构造等值线相一致的振幅变化。

如果储层厚度大于地震分辨率，则可以观测

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④ For thin reservoirs, the seismic reflections from the top and the base of the reservoir overlap and interfere constructively and destructively with each other to such an extent that the two interfaces have no individual expression; geophysicists call this effect "tuning." The tuning thickness is the bed thickness at which the two seismic reflections become indistinguishable in time. It is important to know this thickness before one starts interpreting seismic data. To this end, geophysicists produce tuning models for the relevant seismic data that can act as a guide for determining the tuning thickness.

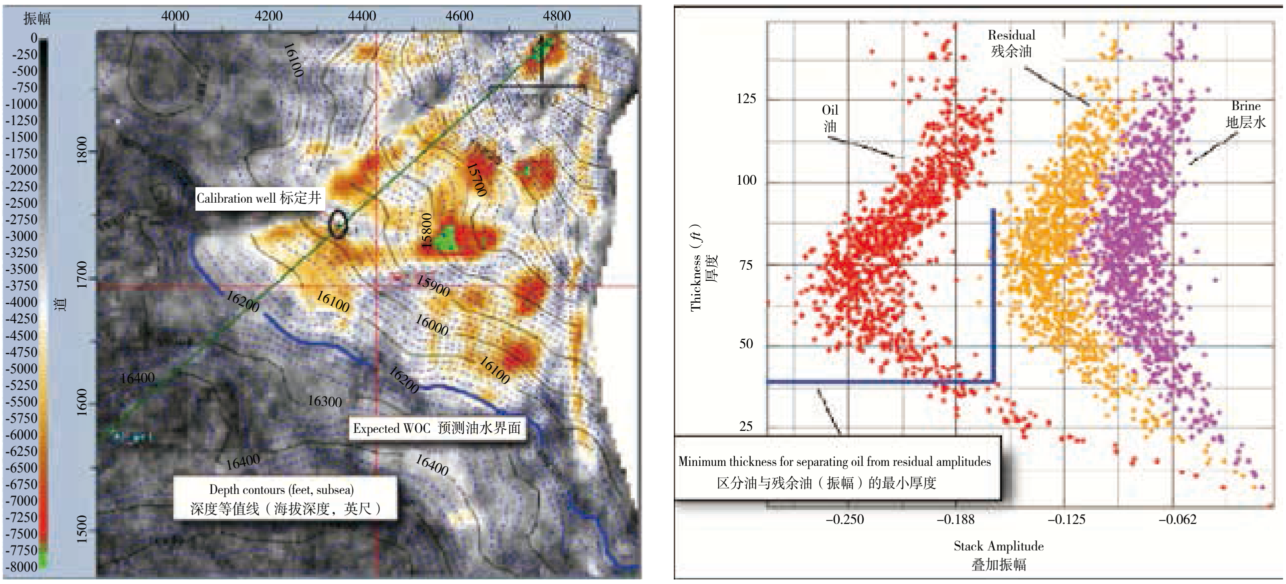
对于薄储层，其顶、底面的地震反射波的叠加与干涉严重，以致两个界面都得不到单独的地震响应；地球物理师称该现象为“调谐”。调谐厚度为储层厚度，若小于该厚度，则两个层面的地震反射波在时间上就无法再区分。所以在开始地震解释之前，调谐厚度的确定十分重要。地球物理师可建立地震调谐模型，为确定调谐厚度提供有用信息。

from the hydrocarbon/water contact may be visible as a reflection event known as a ”flat-spot.” Flat-spots are normally attributed to a depth (unless there is a lateral pressure gradient in the aquifer) but may not be flat in time.

The field in the example below shows a seismic expression of an apparent oil-water contract in a high quality oil sand. The normalized seismic amplitude map in Figure 3.1 a shows a good fit-to-structure of the amplitude change at the apparent oil-water contact. However, some amplitude variations are present as well at shallower levels, suggesting variability in the lithology. Key results are shown in the plot on the right in Figure 3.1 b. The impact of both reservoir thickness as well as pore-fill on the seismic response can be observed. The outcome to this analysis underpins the low, best, and high estimates that feed into the resource classification.

到来自烃 / 水界面的反射，即“平点”。平点通常是指深度上的现象（除非有水体引起的横向压力梯度），在时间域里可能不是“平点”。

下面的油田示例展示了地震在储层物性好的油砂中对清晰油水界面的描述。图 3.1a 是归一化的地震振幅图，显示出很好拟合了油水界面附近与振幅变化一致构造形态。尽管，一些振幅变化也出现在更浅的位置，但指示的是岩性变化。图 3.1b 绘制了主要解释结果，可以观察到储层厚度和孔隙充填对地震响应的影响。该分析结果为资源分类中低估值、最佳估值和高估值的评估提供了依据。



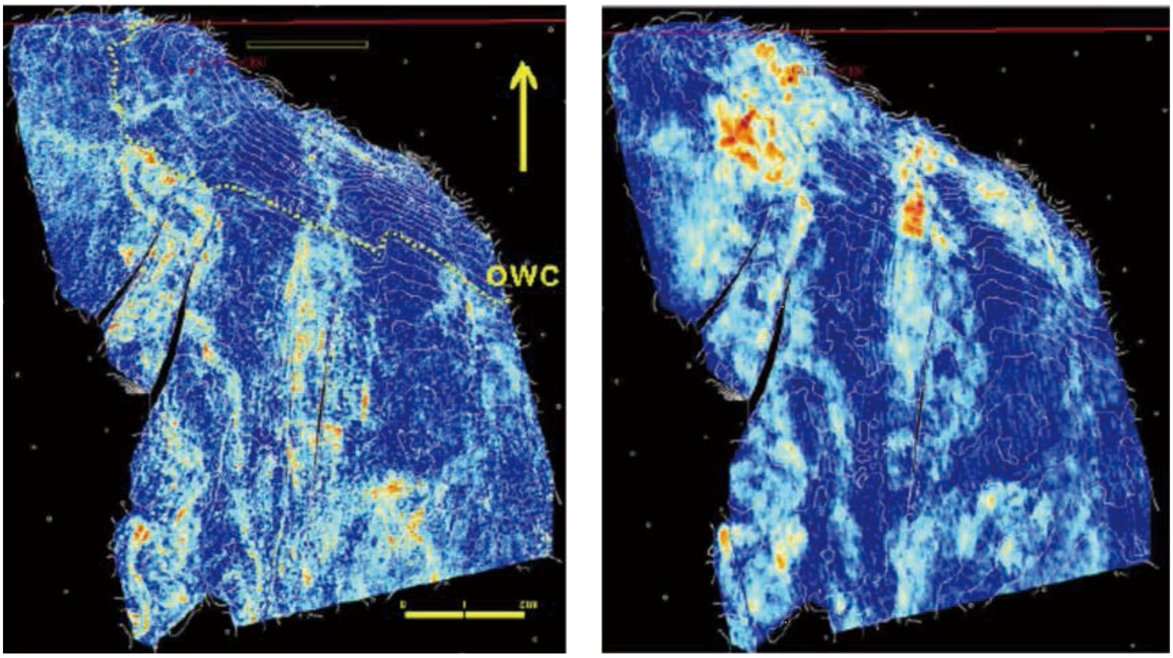
a.Normalized Seismic Amplitude Map
归一化振幅

b.Key Results
解释结果

Figure 3.1　Example of Using Seismic Technology to Assess Fluid Contacts.
The plot on the right shows the results of a Monte Carlo seismic modeling exercise in which the full range of key uncertainties (reservoir thickness, porosity, net-to-gross, rock and fluid properties, etc.) were evaluated.
图 3.1　利用地震技术评价流体界面的案例
右图为蒙特卡洛地震模拟的主要参数（储层厚度、净毛比、岩石和流体性质等）不确定性范围

The visibility of hydrocarbon-related amplitude conformance and flat-spots (Direct Hydrocarbon Indicators or DHIs) may be enhanced through the use of appropriate AVO volumes. In all cases, seismic rock property analysis should be provided to support the identification of an event as a DHI to ensure that the strength and polarity of reflections is consistent with expectations. DHIs must also be shown to be consistent with the trapping geometry (Figure 3.2).

利用适当的 AVO 数据体可以提高振幅对构造（与烃相关）的响应和平点（直接烃类指示，DHI）的识别。在任何情况下，应提供地震岩性分析来支撑 DHI 的识别，以确保反射强度和极性与期望结果是一致的，显示的 DHI 也必须与圈闭的几何形态一致（图 3.2）。



a. Near Offset Volume
近偏移地震数据体

b. Far Offset Volume
远偏移地震数据体

Figure 3.2 Amplitude Maps from A Deepwater Oil Field (hot colors are high negative amplitudes).

The oil accumulation is trapped against a fault to the northeast dipping to an oil-water contact (owc) to the southwest. The maps are from a near offset (left) and far offset (right) volume. The oil-water contact appears as an amplitude increase on the near offsets and an amplitude decrease on the far offsets. Both run along a structural contour. The response is consistent with the trap geometry, the depositional model and the seismic rock properties from the well data.

图 3.2 某深水油田地震振幅图（暖色为负振幅高值）

原油聚集体受东北部断层遮挡，向西南下倾至油水界面。左图为近偏移地震数据体，右图为远偏移地震数据体。油水界面在左图中表现为振幅增加，在右图中表现为振幅减小；均沿构造线延伸。该响应与圈闭几何形态、地质沉积模型和井数据解释的地震岩石性质一致

It is usually not possible to distinguish a fully saturated gas accumulation from a partially saturated column (residual gas) using full stack or conventional (two-term) AVO analysis, so this may remain as an unresolved risk. Direct estimation of density contrast using higher order AVO analysis can in principle distinguish between the two, but this is an emerging technology and would need to be supported by a historical track record.

It is noted that in many other examples, in which the seismic evidence itself is not as convincing, other data sources (e.g., pressure data, performance data, geologic deposition model) will also contribute as part of an integrated analysis to achieve comparable confidence of the recoverable volumes below the Lowest Known Hydrocarbons (LKH), as observed in the wells.

When a known hydrocarbon accumulation is being appraised, seismic flat-spots and/or seismic amplitude anomalies can be used to increase confidence in fluid contacts when the following conditions are met:

(1) The flat-spot and/or seismic amplitude anomaly is clearly

通常情况下，利用全道集叠加或常规（两阶）AVO 分析不可能区分完全饱和的天然气聚集体与部分饱和（残余气）的储层段，因此，仍存在没有解决的风险。原则上使用高阶 AVO 分析直接估计密度差可以对两者进行区分，但这是一个新兴技术，仍需要历史记录的支持。

需要注意的是，在许多其他案例中，地震信息依据本身并不令人信服，其他数据资源（例如压力数据、生产动态数据、地质沉积模型）也有助于开展综合分析，以相对可信地估算已知烃底（LKH）以下的可采量，正如在生产井中所观测到的情况。

一个已知油气藏在评价过程中，只要满足以下条件，则可利用地震平点和 / 或地震振幅异常来提高对流体界面判断的置信度。

（1）平点和 / 或地震振幅异常在三维地震数据体中清晰可见，并且与成像问题无关。

visible in the 3D seismic, and not related to imaging issues.

(2) Within a single fault block, well logs, pressure, and well test and/or performance data demonstrate a strong tie between the calculated hydrocarbon/water contact (not necessarily drilled) and the seismic flat-spot and/or down-dip edge of the seismic anomaly.

(3) The spatial mapping of the flat-spot and/or down-dip edge of the amplitude anomaly within the reservoir fairway fits a structural contour, which usually will be the down-dip limit of the accumulation.

Seismic amplitude anomalies may also be used to support reservoir and fluid continuity across a faulted reservoir provided that the following conditions are met:

(1) Within the drilled fault block, well logs, pressure, fluid data, and test data demonstrate a strong tie between the hydrocarbon-bearing reservoir and the seismic anomaly.

(2) Fault throw is less than reservoir thickness over (part of) the hydrocarbon bearing section across the fault and the fault is not considered to be a major, potentially sealing, fault.

(3) The seismic flat-spot or the seismic anomaly is spatially continuous and at the same depth across the fault.

If these conditions are met, the presence of hydrocarbon in the adjacent fault block above the seismic flat-spot or seismic amplitude anomaly may be judged sufficiently robust to qualify the hydrocarbon volumes as within the same known accumulation and thus qualify as reserves. If these conditions are only partially met, the interpreter must consider the increased level of uncertainty inherent in the data and appropriately classify the volumes based on the uncertainty components. Caution should be exercised in assigning reserves and resource classification categories. The levels of risk and uncertainty should be commensurate the quality of the data, velocity uncertainty, repeatability, and quality of supporting data.

3.2.3 Surveillance

The third general application of 3D seismic analysis is monitoring changes in pore-space composition, pressure, and temperature with fluid movement in the reservoir. This application is often called time-lapse seismic or more commonly as 4D seismic. Surveillance is possible if one

(1) Acquires a baseline seismic data-set

(2) Allows fluid flow to occur through production and/or injection with associated pressure/temperature changes

(3) Acquires additional 3D seismic data-sets sometime after the baseline

(4) Observes differences between the seismic character of the two data-sets in the reservoir interval

（2）在单一断块内，测井、压力、测试和 / 或生产动态数据显示所计算的烃水界面（不一定是钻遇）与地震平点和 / 或地震异常的下倾边缘之间存在很强的关联性。

（3）将平点和 / 或振幅异常的下倾边缘在油气藏层面进行空间成图，可以形成一个构造等高线，这通常就是油气聚集的下倾边缘。

地震振幅也可用于判断整个断块油气藏储层和流体的连续性，但前提条件是满足以下条件：

（1）在已钻断块内，测井、压力、流体和测试数据显示储层与地震异常之间存在很强的关联性。

（2）从整个（部分）过断层的含烃对比剖面看，断距小于储层厚度，且该断层不是主要封堵断层。

（3）地震平点或者地震异常的空间分布连续，且穿过断层的深度相同。

如果满足上述条件，则可以明确地判断相邻断块在地震平点或地震振幅异常（下倾边缘）以上的区域存在烃类，将含烃体积划归已知的同一个油气聚集体，并评价为储量。如果这些条件只是得到部分满足，则解释人员必须意识到数据内蕴的不确定性增加，并根据不确定性情况相应地将体积进行级别划分。在储量和资源量的级别划分时，要十分细心。风险和不确定性的水平应与地震数据质量和地震速度的不确定性、可重复性以及其他支持数据的质量相对应。

3.2.3 监控

三维地震分析的第三个普遍应用是监测随着油气藏流体的流动，孔隙空间中流体组分、压力和温度的变化情况。这一应用通常被称为时移地震或更普遍地称为四维（4D）地震。在以下情况可以开展地震监测：

（1）采集一套基准地震数据；

（2）通过开采和 / 或注水作业，使储层中的流体流动，并伴有压力 / 温度的变化；

（3）在采集基准数据体一段时间后，再采集一套三维地震数据；

（4）观察油气藏储层段对应的两套数据地震特征的差异；

(5) Demonstrates through seismic modeling and/or rock and fluid physics based on a relevant set of well log data that the differences are the result of physical changes related to the hydrocarbon recovery process

One must be careful not to vary seismic acquisition and processing parameters drastically between surveys and thereby introduce differences between the seismic data sets that can be mistaken for reservoir effects. One expects that the seismic character of horizons laterally distant would be virtually identical between the seismic data-sets because background geology would be much less affected by production/injection than the hydrocarbon interval. Hence, observing the difference between the data-sets highlights changes caused by depletion/injection in the reservoir interval (and possibly in the overburden if compaction occurs). Obviously one can acquire a third or fourth seismic survey and continue the surveillance by comparing successive data-sets to one another.

Time-lapse seismology impacts estimation of reserves when an extraction procedure changes a reservoir's properties sufficiently so that a robust response occurs in the seismic data. For example, gas injection to pressurize or flood a reservoir produces an expanding seismic amplitude anomaly around the injection well owing to the same rock physics that causes naturally occurring gas zones to appear as bright seismic amplitude anomalies. In this case, the expansion of the seismic bright spot is directly measurable on successive 3D volumes and clearly shows the movement of the front of the injected gas. Observing where the gas does not flow (i.e., where no seismic amplitude changes) highlights areas of the reservoir that are not being swept by the gas injection.

As a second example, bypassed oil reserves can be spotted on time-lapse seismic when a compartment (fault block or other discrete component of the trap) is unaffected by a drop in reservoir pressure below bubble point (i.e., there is no indication on the seismic of gas coming out of solution in that particular compartment at the time in the field's production life when overall field pressure is dropping below bubble point). When employed in this manner, time-lapse seismic identifies isolated pools that previously were believed to be part of the field's connected pool or pools.

As a third example, direct detection of the original versus current depth of the oil/water contact (OWC) in a producing field is easier on time-lapse seismic data-set than on a single data-set because changes of saturation in the interval swept by the water can noticeably alter the acoustic/elastic impedance of this part of the reservoir. This impedance change can be detected by time-lapse seismic comparisons. An example of this is given in Figure 3.3 below.

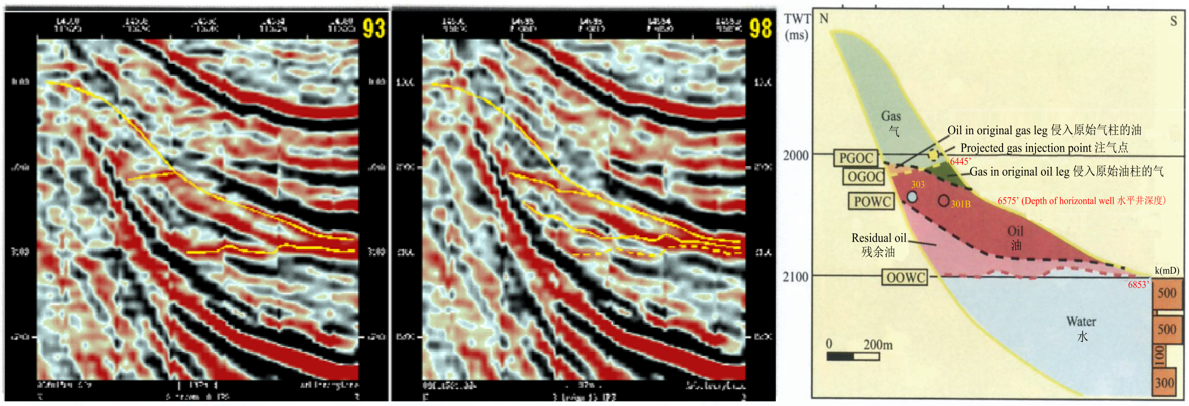
（5）通过地震建模和 / 或岩石与流体物理性质（依据相关测井数据）展现由于油气开采所引起的物理变化。

必须小心，不能大幅改变地震采集和处理的参数，造成地震数据体之间的差异，从而错误地判断对油气藏的影响。可以预期，横向延伸层位的地震特征在数据体之间几乎是相同的，因为地质背景比含油气层段受生产 / 注水作业的影响要小得多。因此，观察地震数据体之间的差异，可以凸显出储层段和上覆地层（若存在压实作用）因衰竭开发 / 注水开发而引起的变化。显然，也可以采集第三次或第四次地震数据，通过对比连续采集的数据体来持续监测油气藏的变化。

当开采过程显著改变油气藏性质，致使地震数据出现强反应时；因此，时移地震可以对储量的评估发挥作用。例如，注气或水驱会使得注入井周边的地震振幅异常现象扩大，由于岩石物性相同，自然引起含气层段出现明亮的地震振幅异常。在这种情况下，地震亮点的扩大可以通过连续采集的三维数据直接测量，并清楚地显现注入气的移动前缘。观察没有气体流动（即没有地震振幅变化）的区域，可以凸显油藏中未被注入气驱扫的区域。

例二，在油藏压力降至泡点之后，分隔区（未波及区域，即断块或圈闭范围的离散部分）不再受压降影响，未经驱替的石油储量可以在时移地震图中圈出（即在油田的生产期内没有任何地震现象显示有气体从该分隔区逸出，尽管油田的整体压力已降到泡点以下）。采用这种方式，时移地震可识别出孤立的油气藏，而以前它们被认为是与油田相连接的油气藏（一个或多个）的一部分。

例三，时移地震数据体比单次采集的地震数据更容易直接检测已投产油气田的油水界面（OWC）原始深度与当前深度，因为水驱之后储层段饱和度的变化可明显改变该区域的声波 / 弹性波阻抗。波阻抗变化可在时移地震的数据对比中检测出来。图 3.3 案例展示了这种情况。



a. Baseline Survey 基准地震剖面　　b. Repeat Survey 重复地震剖面　　c. Interpretation 解释结果

Figure 3.3　Example of Using Time-Lapse Seismic to Assess OWC Movement.

图 3.3　利用时移地震评估油水界面移动情况

These OWC changes as derived from the time-lapse seismic results can then subsequently be mapped out laterally and be used to update the static and dynamic reservoir models that underpin the Resources and Reserves volumes estimate.

In general, the seismic tool is useful in time-lapse mode as a check on the validity of the assumptions in the geologic model that is used in a reservoir simulation of fluid flow. Because seismic monitoring is more spatially specific than pressure monitoring, estimation and extraction of reserves can be optimized over time by using the seismic to guide detailed simulations of depletion and to resolve contradictions between the seismic and the reservoir model. In general, the incorporation of time-lapse seismic results prompt geologic model updates that usually improve production history matches.

An example to illustrate this is presented below. In this case, time-lapse seismic results revealed an area in the west of the F block without 4D sweep (Figure 3.4 a), different from what was expected. New spectrally boosted 3D seismic (Figure 3.4 b) shows evidence for a normal fault cutting the F block into two separate blocks. The 3D horizon (Figure 3.4 c) shows that the downthrown block corresponds to the same area seen to be unswept on the time-lapse seismic (Figure 3.4 a).

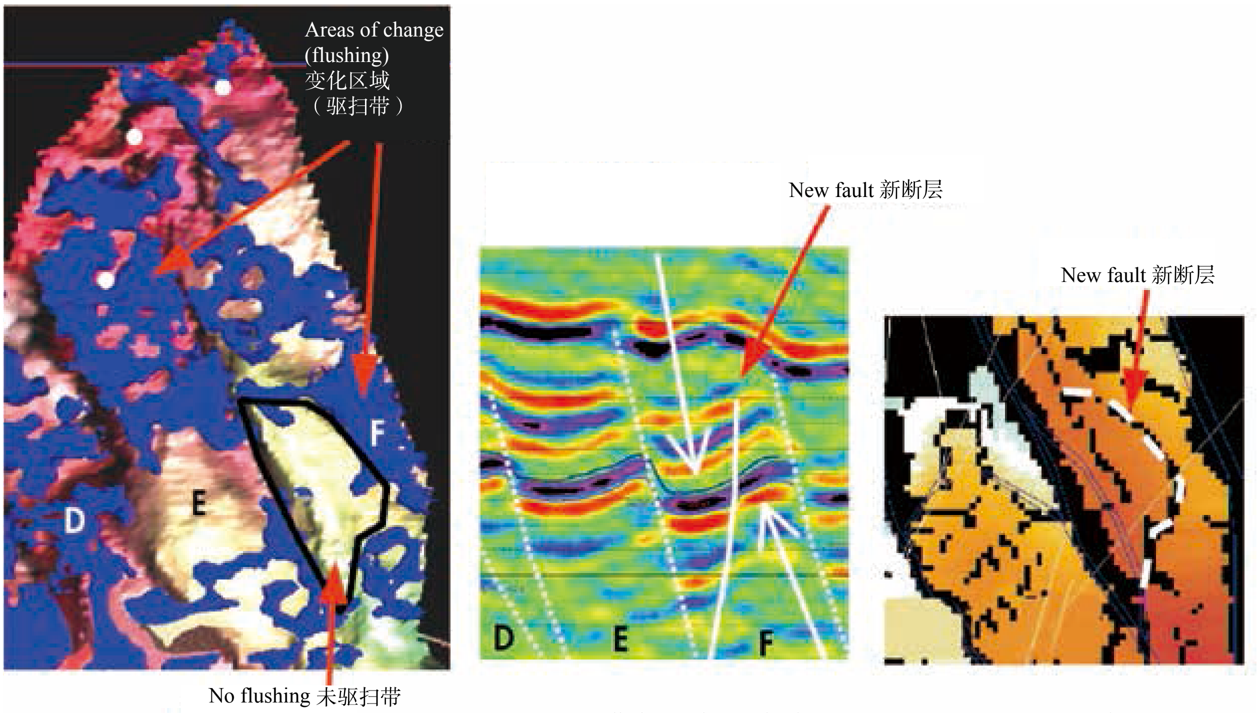
The new fault was incorporated in the model update, allowing for an improved history match by adjusting the fault seal properties. Simulated production data from the northern EF blocks prior to the time-lapse seismic results (Figure 3.5 d—solid lines) show a much later water breakthrough, as compared to actual production data (Figure 3.5 d—diamonds). Incorporating the new fault into the model, resulted in the bypassing the block (Figure 3.5 right panel) and greatly improved the timing of water breakthrough (Figure 3.5 d—dotted lines). As a result from incorporating the time-lapse seismic results, the bypassed volumes in the SW part of block F will have to be reclassified from Developed Reserves into Contingent Resources until further development activities are in place.

根据时移地震分析获得的油水界面变化可以绘制成平面图和用于更新静态和动态油气藏模型，为资源量和储量的评估奠定基础。

总的来说，采取时移方式的地震工具十分有用，可验证流体流动数值模拟所需地质模型中假设条件的有效性。由于地震监测比压力监测更具有空间（立体）性，可利用地震指导开发方案的精细数值模拟研究，解决地震和储层模型之间的矛盾，使储量的评估和开采随着时间推移逐步优化。一般来说，结合时移地震结果，促进地质模型的更新，通常会改善对生产历史的拟合效果。

下面介绍一个案例。在该案例中，时移地震显示 F 块西部的一个区域没有四维地震属性差信息（图 3.4a），与预期不同。拓频三维地震（图 3.4b）显示一个正断层将 F 块切分为两块；相应三维地震水平切面（图 3.4c）显示，断层的下盘与时移地震中的未波及区带相吻合（图 3.4a）。

新识别的断层用于了地质模型的更新，通过调整断层的封堵性质提高历史拟合的效果。在有时移地震结果以前，模拟预测的 EF 块北部生产数据（图 3.5d，实线）显示水突破时间比实际生产数据（图 3.5d，菱形）晚很多。将新识别断层纳入地质模型，使得流体流动绕过该区（图 3.5e），大大加快了水突破（图 3.5d，虚线）的时间。结合时移地震的结果，F 块西南部未波及体积必须重新由已开发储量划归为条件资源量，除非进一步实施开发作业。



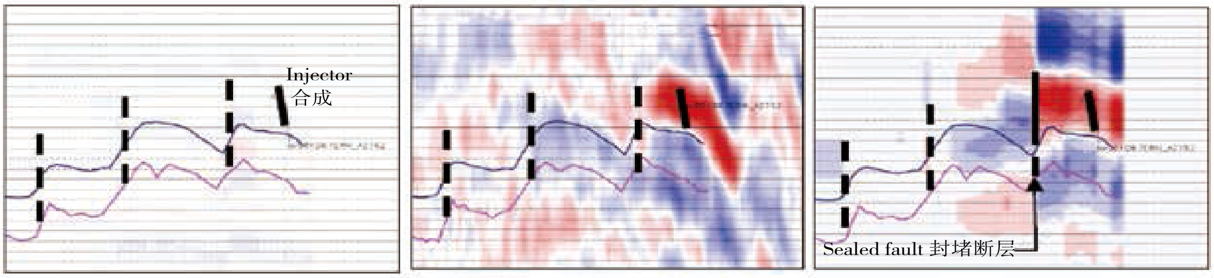
a. 4D Seismic 四维地震

b. Spectrally boosted 3D Seismic
拓频三维地震

c. 3D Horizon
三维水平切片

Figure 3.4 Time-lapse Seismic Results Indicate the Presence of A Sealing Fault.

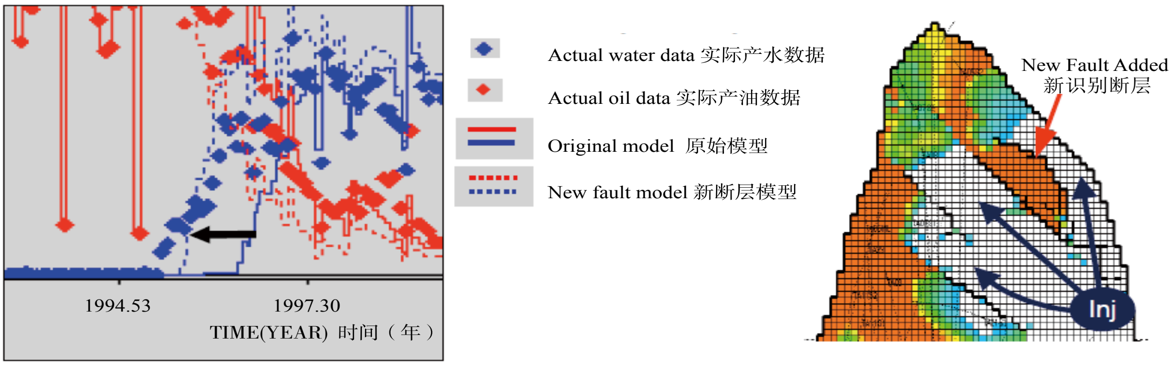
图 3.4 时移地震分析结果显示封堵断层的存在



a. Old Model Synthetic Seismic
旧模型合成地震记录

b. Actual 4D Difference Data
四维地震属性差

c. Updated Model Synthetic Seismic
新模型合成地震记录



d. Production Data
生产数据

e. New fault added
新识别断层

Figure 3.5 Integration of Time-lapse Seismic Results into Reservoir Simulation.

图 3.5 将时移地震分析结果融入油藏模拟研究

3.3 Uncertainty in Seismic Predictions

Predictions from 3D seismic data aimed at defining trap geometry, rock/fluid properties or fluid flow have an inherent uncertainty. The accuracy of a given seismic-based prediction is fundamentally dependent on the resulting interplay between

(1) The quality of the seismic data (bandwidth, frequency content, signal-to-noise ratio, acquisition and processing parameters, overburden effects, etc.)

(2) The uncertainty in the rock and fluid properties and the quality of the reservoir model used to tie subsurface control to the 3D seismic volume

A derived reservoir model that is accurately predicting a subsurface parameter or process as proven by drilling results from new wells has demonstrated a reduction in uncertainty and the current level of uncertainty can be revised accordingly after several successful predictions. Such a reservoir model is far more valuable than an untested reservoir model, even though the latter may be more sophisticated. Care should be taken extrapolating the results from new wells, if such programs targeted high amplitude or “sweet spot” and remaining targets are not in a similar setting. Appropriate consideration should be made regarding predictability.

It is useful to assess the track record of a given 3D seismic volume or of regional analogues in predicting subsurface parameters at new well locations before drilling. The predictive record is the best indicator of the degree of confidence with which one can employ the seismic to estimate reserves and resources as exploration and development proceeds in an area.

The following is a general quantification of the uncertainty in using 3D seismic to estimate reserves and resources. Specific cases should be analyzed individually with the geophysical and geology team members to determine if a project’s seismic accuracy is better or worse than this general quantification.

3.3.1 Gross Rock Volume (GRV) of a Trap

The gross rock volume of a field is defined by structural elements, such as depth maps and fault planes resulting from an interpretation based on seismic and well data. Uncertainties in the GRV, and hence in the in-place volumes, reserves and production profiles, can arise from

(1) The incorrect positioning of structural elements during the processing of the seismic

(2) Incorrect interpretation

(3) Errors in the time to depth conversion

An assessment of these uncertainties is an essential step in a field study for evaluation, development, or optimization purposes.

3.3 地震预测的不确定性

利用三维地震来预测圈闭的几何形态、岩石 / 流体性质或流体流动状况，难免存在不确定性。基于地震的预测精度从根本上依赖于以下因素的相互影响：

（1）地震资料的品质（带宽、频率、信噪比、采集和处理参数、覆盖效应等）；

（2）岩石与流体性质的不确定性和油气藏模型质量，后者可将地层控制信息与三维地震数据体进行关联。

获得的油气藏模型在准确预测地下参数或进程（为新井钻探结果所证实）后，可降低其不确定性，多次成功预测之后，不确定性程度将进一步修正。这种油气藏模型比未经检验的油气藏模型更具有价值，即使后者可能更复杂。若所追踪的高振幅、“ 甜点 ”以及剩余目标不具备类似背景时，外推新井结果时要小心，应适当地考虑可预测性。

新井开钻前，评估三维数据体或区域类比记录对预测地下参数很有用。地震预测记录是人们在勘探和开发进程中采用地震方法评估该区域储量和资源量的置信度最佳标志。

下面将介绍利用三维地震数据估算储量和资源量过程中不确定性的常规量化方法。具体情况应与地球物理和地质工作组一起进行单独地分析，确定项目的地震精度是否比常规量化方法更好，还是更差。

3.3.1 圈闭的岩石总体积（GRV）

油气田的岩石总体积由构造要素确定，例如根据地震和井数据解释的深度图和断层面。圈闭岩石总体积、原地量、储量和产量剖面的不确定性来源于：

（1）在地震数据处理过程中不正确地配置构造要素；

（2）不正确的解释；

（3）时深转换错误。

对这些不确定性的评估是油气田评价、开发或优化研究的重要步骤。

值得庆幸的是，一旦准确获得第一批井位的

It is important to appreciate that the relative uncertainty in predicting depth to a trapping surface at a new location, once the trap depth is precisely known at initial well locations, is much less than the errors in predicting trap depth in an exploration setting prior to the drilling of the first well. That uncertainty generally is tens to hundreds of meters because there is no borehole control on the vertical velocity from the earth's surface down to the trap. In addition to the uncertainties in the velocities, alternative interpretations of the seismic data are the major source of uncertainties in (green-field) exploration settings, affecting the evaluation of Prospective Resources.

3.3.2 Reservoir Bulk Volume

If the trap volume under the seal is completely filled with reservoir rock, the GRV of the trap is of course identical to reservoir bulk volume. Generally, this is not the case, and the thickness and geometry of the one or more reservoir units within the trap have to be estimated to derive reservoir bulk volume. The accuracy of the estimate of the thickness of each reservoir is a critical element in assessment of reserves.

Estimation of reservoir thickness is dependent on the bandwidth and frequency content of the seismic data and on the seismic velocity of the reservoir. Broadband, high-frequency seismic data in a shallow clastic section where velocity is relatively slow can resolve a much thinner bed than, for example, narrow- band, low-frequency seismic data deep in the earth in a fast, carbonate section. Fortunately, geoscientists can analyze seismic and sonic log data to estimate what thicknesses can reasonably be measured for particular reservoirs under investigation.

Stacked reservoirs in a trap can be individually resolved and separate reservoir bulk volumes can be computed if the reservoirs and their intervening seals can be interpreted separately and individually meet the minimum thickness derived from the relevant tuning model. Under these conditions, a deterministic estimate of reserves in each reservoir is possible. When the individual reservoirs and seals are too thin to satisfy these conditions, seismic modeling can be used to get a general idea of how much hydrocarbons might be present in a gross trapped volume. In some circumstances it may be possible to detune the seismic response of thin reservoirs to estimate the total net or gross reservoir. The reliability of these calculations will depend on a number of factors; bed thicknesses, spacing among beds, porosity variation, etc.

3.4 Seismic Inversion

Standard 3D seismic volumes display seismic amplitude in either travel time or depth. Conversion of seismic amplitude data to acoustic impedance (product of P-velocity and density) and shear impedance (product of S-velocity and density) volumes or related elastic parameters

圈闭层面深度，预测新井位圈闭深度的不确定性要比在勘探区块（钻第一口井之前）预测圈闭深度时出现的错误小得多。后者的不确定性通常是数十至数百米，这是因为钻井前没有井眼资料约束从地表到圈闭的垂向传播速度。除了速度的不确定性，勘探区域（绿色区）地震数据的多解性也是不确定性的主要来源，影响着对远景资源量的评估。

3.3.2 储层总体积

如果盖层以下的圈闭中全是储集岩，则圈闭的岩石总体积当然就等同于储层总体积。但通常情况并非如此，必须评估圈闭中（一个或者多个）储层单元的厚度和几何形状，然后获得储层总体积。每个储层厚度的评估精度都是储量估算的关键因素。

储层厚度的评估主要依靠地震数据的带宽和频谱，以及储层的地震传播速度。例如，宽带、高频、地震速度相对较低的浅层碎屑岩段的地震数据解释出的薄层厚度比窄带、低频、高速的深层碳酸盐岩层段的更薄。幸运的是，地球物理学家可以通过地震和声波测井数据分析来合理地测定被评价储层的厚度。

圈闭中的叠置储层可以逐个解释，分别计算储层体积，条件是这些储层及其控制盖层能分别识别，均达到相应调谐模型要求的最小厚度。在此条件下，每个油气藏的储量都可以采用确定法进行评估。当单个储层或其盖层太薄，不能满足上述条件时，则可通过地震建模来大致预测圈闭空间所存在的油气量。某些情况下，可能会解谐薄储层的地震响应，以评估储层的总厚度和净厚度。这些计算的可靠性将取决于许多因素：地层厚度、地层间距、孔隙度变化等。

3.4 地震反演

标准的三维地震数据体是按旅行时间或深度显示地震振幅。将地震振幅数据转换为声波阻抗（P 波速度和密度的产物）和横波阻抗（S 波速度和密度的产物）或相关弹性指标的技术仍在发

is still a growing field. The conversion process is called seismic inversion. There will typically be a relationship between acoustic and shear impedance and lithology, porosity, pore fill and other factors and hence estimates of these parameters may be derived from an analysis of these relationships (a rock property model) combined with inverted seismic.

Inverted seismic data focuses on layers rather than interfaces, and some features in the data may be more obvious or easier to interpret in the inverted format than the conventional format, so there can be value to analyzing the basic seismic information in both formats.

Inversion requires the seismic to be combined with additional data and hence good-quality impedance inverted volumes will contain more information than a conventional seismic volume. Specifically additional data is required to compensate for the lack of low frequencies in the seismic. However, there will rarely be enough data to fully constrain the low-frequency component so inversion results will be nonunique. Because of this uncertainty, a probabilistic approach can be followed to try to capture the full range of possible outcomes. The uncertainty analysis should cover the nonuniqueness of the inversion process and the uncertainties arising from the rock property model. The probabilities of the various outcomes can then subsequently be used as input to Reserves and Resource volume assessments. However, estimating all the uncertainties in the process is difficult. Use of this technology would need to be supported by a strong track record. Additionally, a relationship between acoustic impedance or elastic impedance and petrophysical properties must be established at log scale resolution. The type of inversion method should also be considered as well as the confidence in the well-based background model used for generating the low frequency component.

An example of probabilistic seismic inversion is given below. In this example, the key uncertainty for estimation of in-place volumes is the net sand thickness distribution. Porosity variation within a reservoir unit is small, although there is a general trend where deeper reservoir levels have slightly lower porosity. Likewise, variation in oil saturation is small. However, variation in reservoir thickness and sand percentage is large. Probabilistic inversion was used to provide a better estimate of net sand distribution, and also to quantify the range of uncertainty. The inversion works on a layer-based model, where all input data are represented as grids. The inversion combines in a consistent manner the petrophysical and geologic information with the seismic data. Probability density functions for reservoir parameters such as layer thickness, net-to-gross, porosity and fluid saturations are obtained from well and geologic data with soft constraints obtained from seismic

展。该转换过程被称作地震反演。通常情况下，声波阻抗和横波阻抗与岩性、孔隙度、孔隙填充物和其他因素之间存在相关关系；因此，分析这些相关性（岩性模型）联合反演后的地震数据就可以对这些参数进行评估。

反演后的地震数据主要针对层而不是界面，而且反演后一些地震数据特征可以比常规形式下更明显或更易于解释，因此，将两种形式的地震基础信息都进行分析是很有价值的。

地震反演需要将地震数据与其他的一些数据相结合，因此高品质声波阻抗反演数据体将比常规地震数据体蕴涵更多信息。对于缺少低频的地震数据，需要特别地弥补一些数据。当然，很少有足够的数据完全约束低频分量，所以反演结果可能不是唯一的。由于这种不确定性的存在，可尝试用概率方法捕捉可能结果的整个分布范围。不确定性分析应包括反演过程的不唯一性和岩性模型引起的不确定性。不同反演结果的概率随后可以用作储量和资源量评估的输入参数。当然，评价所有不确定性是十分困难的，采用这种技术需要有很好的记录跟踪作为支撑。此外，必须以测井尺度的分辨率构建声波阻抗或弹性波阻抗与岩石物理性质之间的相关关系。也应考虑该类反演的方法以及基于井网构建的用于生成低频分量背景模型的置信度。

下面是一个地震反演案例。在这个案例中，原地量评估的主要不确定性来源于净砂岩厚度分布。储层单元内孔隙度变化很小，尽管总的趋势是随着储层加深，孔隙度略微变小。类似地，含油饱和度的变化也不大，但是，储层厚度和砂体含量变化很大。概率反演被用来更好地评价净砂体的分布，量化不确定性的范围。反演基于层面模型，所有的输入数据整理为网格格式。反演将匹配的地球物理和地质资料与地震数据相结合。在地震振幅的软约束下，通过井和地质数据获得储层参数（如地层厚度、净毛比、孔隙度和流体饱和度）的概率密度函数。使用上述信息，可生

amplitudes. Using this prior information, the program then generates numerous subsurface models that match the actual seismic data within the limits set by the noise that is derived from the seismic data. The net sand maps in Figure 3.6 illustrate the probabilistic output from the inversion for low, mid, and high cases. Each map fits the well data used to constrain the model. The three net sand maps reflect the uncertainty in the net sand distribution and can be used to constrain three different “oil-in-place” scenarios in low, mid and high-case static models that can be carried through to reservoir simulation and are thus key input to the resource volume assessment and classification.

成大量地下模型，在噪声限制范围内与实际地震数据进行拟合。图 3.6 所示的净砂体分布图是概率法低、中、高反演方案的结果。每个图都与约束模型的井数据相吻合。这三张净砂体分布图反映了净砂体分布的不确定性，可用来约束低、中、高三个不同原地量计算方案的静态模型，并进一步开展油藏数值模拟；因而也是资源量评估和分级的关键输入参数。

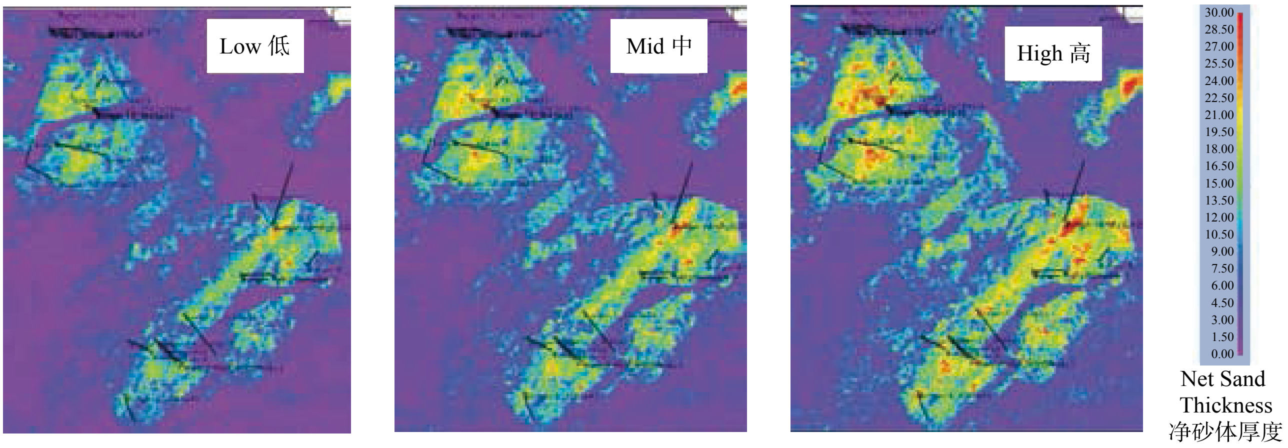


Figure 3.6 Model-based, Probabilistic Seismic Inversion Provides Low, Mid, and High Scenarios for Net Sand Distribution, which is the main driver for variation in oil in place estimates.

图 3.6 基于模型的概率法地震反演净砂体厚度分布图：低、中、高情景
上述情景分析结果是原油原地量估算中数据变化的主要依据

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第 4 章
CHAPTER 4

确定法石油资源评估
Assessment of Petroleum Resources Using Deterministic Procedures

Yasin Senturk 著， 杨 桦、罗 凯、李茜瑶 译

4.1 Introduction

This chapter provides additional guidance to the Petroleum Resources Management System (PRMS) Sec. 4.1 (SPE 2007) regarding the application of three broad categories of deterministic analytical procedures for estimating the range of recoverable quantities of oil and gas using (a) analogous methods, (b) volumetric methods, and (c) production performance analysis methods. During exploration, appraisal, and initial development periods, resource estimates can be "indirectly" derived only by estimating original in-place volumes using static-data-based volumetric methods and the associated recovery efficiency based on analog development projects, or using analytical methods. In the later stages of production, recoverable volumes can also be estimated "directly" using dynamic-data-based production performance analysis.

It must be recognized that PRMS embraces two equally-valid deterministic approaches to reserves estimation: the "incremental" approach and the "scenario" approach. Both approaches are reliable and arrive at comparable results, especially when aggregated at the field level; they are simply different ways of thinking about the same problem.

In the incremental approach, experience and professional judgment are used to estimate reserve quantities for each reserves category (Proved, Probable, and Possible) as discrete volumes. When performing volumetric analyses using the incremental approach, a single value is adopted for each parameter based on a well-defined description of the reservoir to determine the in-place, resources, or reserves volumes.

In the scenario approach, three separate analyses are prepared to bracket the uncertainty through sensitivity analysis (i.e., estimated values by three plausible sets of key input parameters of geoscience and engineering data). These scenarios are designed to represent the low, the best (qualitatively considered the most likely) and the high realizations of original in-place and associated recoverable petroleum quantities. Depending on the stage of maturity, these scenarios underpin the PRMS categorization of Reserves (1P, 2P, and 3P) and Contingent Resources (1C, 2C, and 3C) of the projects applied to discovered petroleum accumulations, or Prospective Resources (low, best, and high) of the undiscovered accumulations with petroleum potential.

The advantages of a deterministic approach are (a) it describes a specific case where physically inconsistent combinations of parameter values can be spotted and removed, (b) it is direct, easy to explain, and manpower efficient, and (c) there is a long history of use with estimates that are reliable and reproducible. Because of the last two advantages, investors and shareholders like the deterministic approach and it is widely used to report Proved Reserves for regulatory purposes. The major disadvantage of the deterministic approach is that it does not quantify the likelihood of the low, best and high estimates. Sensitivity analysis is

4.1 引言

《石油资源管理系统》（SPE- PRMS，2007）第 4.1 节介绍了油气可采量确定性评估的三大类方法：类比法、容积法和生产动态分析法，本章就此提供更多指引。在勘探、评价和开发初期阶段，资源的评估只能间接地通过基于静态数据的容积法计算原始原地量和通过类比法或解析法计算相应采收率。在生产后期，可采量也可通过基于动态数据的生产动态分析法“ 直接 ”得到。

一定要认识到，PRMS 认可两种同样有效的储量评估确定性方法：增量法和情景法。这两种方法都是可靠的，其结果具有可比性（尤其是在油田层次储量汇并时），它们只是考虑同一问题的不同途径。

在增量法中，对于每个储量级别（证实、概算和可能）的评估结果离散值，常常要根据经验和专业判断。当采用增量法进行容积法计算时，根据对油藏的明确描述，可采用单一的参数值确定原地量、资源量或储量。

在情景法中，要准备 3 个独立评估方案，通过敏感性分析归并其不确定性（即通过三套假定合理的主要地质与工程数据进行分析计算）。这 3 个情景分别代表原始原地量和对应可采量的低估值、最佳估值（定性认为是最可能估值）和高估值。依据项目的成熟度，这 3 种情景分别对应于已发现油气聚集体的 PRMS 储量级别 1P、2P 和 3P，条件资源量级别 1C、2C 和 3C，或含油气潜力未发现油气聚集体的远景资源量低估值、最佳估值和高估值。

确定法的优点在于：（1）描述了一个特定情景方案，物理意义上不一致的计算参数组合可能被发现并剔除；(2) 方法直接，易于解释且高效；（3）应用历史时间长、评估结果可靠，具有可重复性。因为后两个优点，投资者和持股人常采用确定法，并广泛应用于证实储量的监管报告。确定法的主要缺点是不能定量描述低、中和高估值的可能性。因此，需要进行敏感性分析（分析输入不同的关键地质和工程参数值）来评价估值

required to assess both the upside (the high) and the downside (the low) estimates by respectively using different values of key input reservoir parameters (geoscience and engineering data) to plausibly reflect that particular realization or scenario.

The guidance in this chapter is focused only on the deterministic methods where the range of uncertainty is captured primarily using a scenario approach. Chapter 5 provides guidance on applying probabilistic methods. The goal of this chapter is to promote consistency in reserves and resources estimates and their classification and categorization using PRMS guidelines.

Figure 4.1 shows how changes in technical uncertainty impact the selection of applicable resources assessment method(s) for any petroleum recovery project over its economic life cycle.

Figure 4.1 illustrates that the range of estimated ultimate recovery (EUR) of any petroleum project decreases over time as the accumulation is discovered, appraised (or delineated), developed, and produced, with the degree of uncertainty decreasing at each stage. Once discovered, the duration of each period depends both on the size of accumulation (e.g., appraisal period) and the development design capacity in terms of annual reservoir depletion rate (e.g., as % of reserves produced per year). For example, projects with lower depletion rates will support a relatively longer plateau period followed by a longer decline period, and vice versa. While the “best estimate” is conceptually illustrated as remaining constant, in actual projects there may be significant volatility in this estimate over the field appraisal and development life cycle.

增加（乐观结果）和估值降低（保守结果），以合理反映特殊实现或情景。

本章的指引重点仅为确定法，其不确定性范围的评估主要采用情景法。第 5 章将讨论概率法的应用。本章目标旨在促进储量和资源量评估，以及依据 PRMS 指南进行分类分级的一致性。

由图 4.1 显示了任何一个油气开发项目在其整个经济寿命周期内所适用的资源评估方法，及其技术不确定性变化的影响。

图4.1也说明了任何油气项目从油气藏发现、勘探评价（或开发评价）、开发到生产的各个阶段，随着不确定性程度的降低，其估算最终可采量 (EUR) 范围也减小。油气藏一经发现，每个阶段的持续时间（例如评价期）既取决于油气聚集体的规模大小，也取决于开发设计产能（以开采速度体现，如每年采出储量的百分比）的大小。例如，开采速度较低的项目会支撑相对长的稳产期和随后更长的递减期；反之亦然。图中，最佳估值在概念上是恒定的，但在实际项目评估中，该估值可能会在油气田的整个评价与开发生命周期大幅波动。

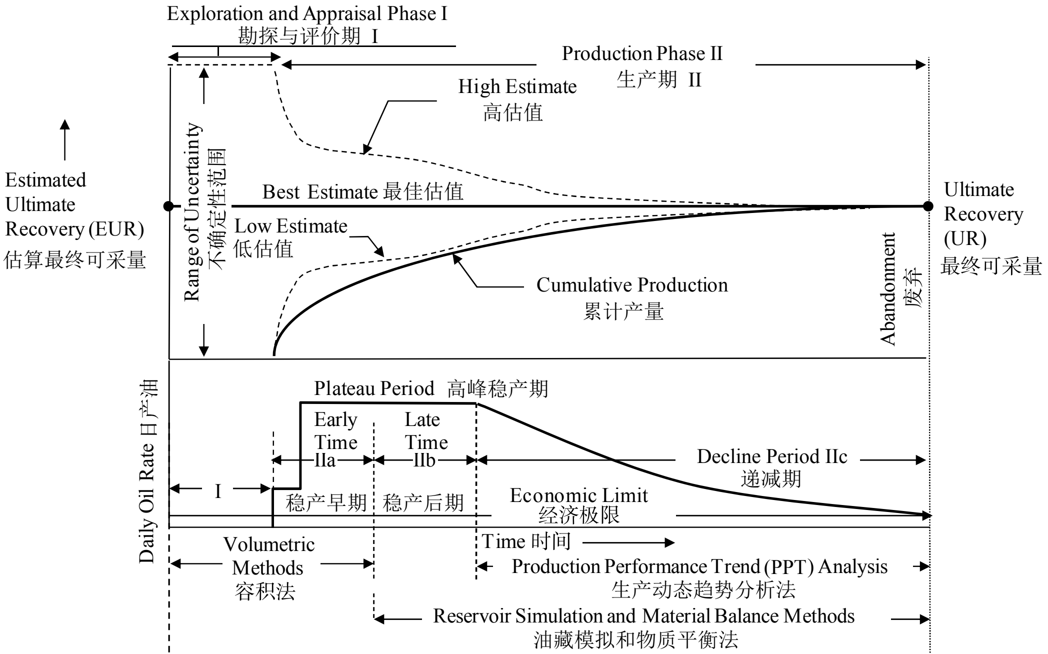


Figure 4.1 Changes in Uncertainty and Assessment Methods Over the Project's E&P Life Cycle
图 4.1 项目勘探与生产生命期内适用的资源评估方法与不确定性变化

Assessment of petroleum recoverable quantities (reserves and resources) can be performed deterministically by using both indirect and direct analytical procedures, involving the use of the volumetric-data-based "static" and the performance-data-based "dynamic" methods, respectively.

The selection of the appropriate method to estimate reserves and resources, and the accuracy of estimates, depend largely on the following factors:

(1) The type, quantity, and quality of geoscience, engineering, and economics data available and required for both technical and commercial analyses.

(2) Reservoir-specific geologic complexity, the recovery mechanism, stage of development, and the maturity or degree of depletion.

More importantly, reserves and resources assessment relies on the integrity, skill and judgment of the experienced professional evaluators.

4.2 Technical Assessment Principles and Applications

This section provides a technical summary description of the appropriate deterministic resource assessment methods applied to an example oil project in various stages of its maturity, retraced over its full E&P life cycle as depicted by phases and stages identified in Figure 4.1. In addition, an example of reserves assessment of a nonassociated mature gas reservoir is included to demonstrate the use of the widely practiced production performance-based material balance method of (p/z) vs. cumulative gas production relationship. The focus is on assessment of risk and uncertainty and how these are represented by PRMS classes and categories of petroleum reserves and resources.

4.2.1 Definition of the Example Oil Project—Setting the Stage

Since it is used to demonstrate the applications of each major assessment method using deterministic procedures, it is important to set the stage and describe the example oil reservoir and point out its distinguishing characteristics.

Figure 4.1a shows the time line and the assessment methods used to estimate the example project's in-place and recoverable oil and gas volumes at different stages of project maturity.

The example oil reservoir represents a typical accumulation in a mature petroleum basin containing extremely large structures with well-established regional reservoir continuity and numerous adjacent analog development projects. Therefore, the project scale and internal confidence in reservoir limits may not be typical for

油气可采量（储量和资源量）的确定性评估主要有间接和直接两种方法，分别包括基于容积数据的“静态法”以及基于生产数据的“动态法”。

储量和资源量评估合理方法的选择及其评估的精确度主要取决于以下因素：

（1）可用于技术和经济分析的地质、工程和经济参数的类型、数量与质量。

（2）具体油气藏的地质复杂程度、开采机理、开发阶段、开采程度或成熟度。

更重要的是，储量和资源量评估的可靠性还取决于资深专业评估师的职业道德、专业技能和经验判断。

4.2 技术评估理论与应用

本节提供了一个油气项目案例，对其不同成熟度阶段所采用的资源评估确定性方法进行了技术综述，并在图 4.1 中追溯了其与勘探开发生命期中不同时期与阶段的对应关系。另外，本节还增加了一个气藏储量评估案例，以阐述广泛应用并基于动态数据的物质平衡法（视地层压力（p/z）和累计产气量的关系）。本节重点是风险和不确定性评估，以及如何采用 PRMS 进行石油资源储量的分类与分级。

4.2.1 原油案例项目的定义——阶段设置

由于要诠释每一种评估技术的确定法流程，设定好案例油藏所处项目成熟度阶段，并进行适当的状态描述，识别其特征是十分重要的。

图 4.1a 展示了该案例项目在不同成熟度阶段所采用的油气原始原地量和可采量评估方法与时间轴的对应关系。

该案例油藏是成熟含油气盆地的一个典型油气聚集体。该盆地发育特大型构造，储层区域上连续性好，而且周边有大量可供类比的开发项目。因此，对于其他含油气盆地的资源评估而言，本

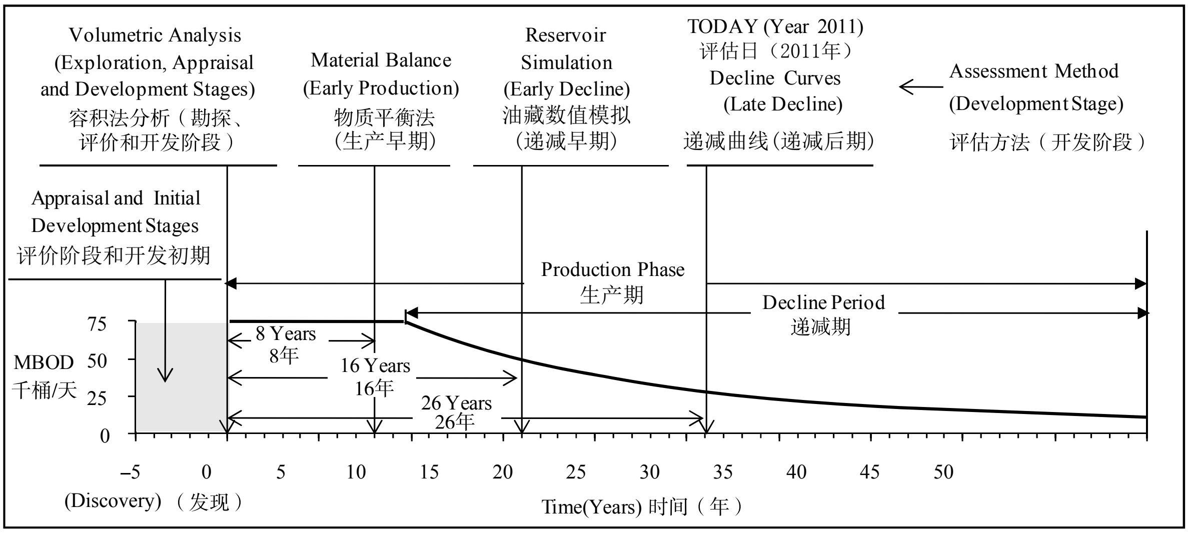


Figure 4.1a Timeline for example oil project maturity stages and assessment methods used

图 4.1a 原油项目案例成熟度阶段与采用的评估方法

assessments carried out in other petroleum basins. It is a very prolific carbonate reservoir located onshore. Analog projects with varying sizes have already produced over 60% of their respective EURs from the same geological formations in the same petroleum basin, all depleted under well-established and effective peripheral water injection schemes implemented initially at project start-ups.

In general, because of the leverage of having high-quality large oil reservoirs with excess development potential relative to market needs prevalent in the Middle East, the ways these reservoirs are developed and produced may be significantly different than those commonly practiced elsewhere. These reservoirs were developed at relatively low depletion rates, ranging from 2 to 4% of EUR per year, which means

(1) Low development size (e.g., level of daily plateau oil production rate) naturally necessitated reservoir development in stages. For example, instead of drilling most of the well-spacing units (WSU's) initially at once to achieve higher daily production rates, it was common to drill only a fraction (20 to 30%) of them to achieve the target rate. The number of producers depends on their established Productivity Indices (PIs). As a result, annual drilling continues over extended periods (sometimes exceeding 50 years) to sustain the target plateau production rate as long as possible to better manage decline and improve overall reservoir volumetric sweep efficiency.

(2) Longer plateau periods are followed by relatively low annual decline rates and longer decline periods and project economic lives, sometimes exceeding 100 years. In reality, the project lives will

案例项目的规模与油藏边界条件的置信度可能不具有代表性。案例油藏为富集油气的陆上碳酸盐岩油藏。不同规模尺度的类比项目位于同一油气盆地相同地层，估算最终可采量（EUR）的采出程度达到 60% 以上，项目开发初期均采用了成熟有效的边缘注水开发方式。

通常，由于中东地区许多大型优质油藏的开采潜力普遍超出市场需求，使得这些油藏的开发与生产情形同其他地区常规油藏显著不同，其估算最终可采量的采油速度相对较低，在 2% ～ 4% 之间。这意味着：

（1）开发规模小（如高峰日产油速度低），使得油藏需分阶段滚动开发。例如，通常在油藏开发初期只钻一部分（20% ～ 30%）井以实现目标产量，而不是按单位井距（WSU）集中完钻大部分开发井以追求早期高产。所需开发井的井数取决于井的产能指数 (PI)。这样，年度钻井工作会持续开展较长时间（有时超过 50 年），其目的是尽可能地长时间维持目标产量，更好地延缓递减和提高油藏整体波及效率。

（2）继较长的高峰稳产期之后是递减率低且周期长的递减期，以及项目经济寿命期（有时

eventually be shortened to 50–70 years as the approaching planned artificial lift and EOR projects are implemented to both accelerate production (e.g., higher depletion rates) and increase ultimate recovery. Moreover, longer project lives are very beneficial because:

① It allows the operator to take advantage of new technological applications that may not be available in other reservoirs with shorter lives and thus potentially benefiting from lower capital and operating costs. It also defers capital costs for delayed EOR projects.

② Growth in water production (or water-cut) is relatively low because of peripheral water injection and low depletion rates. Lower and slow growth in water-cuts help delay the need for installation of artificial lift facilities and again defers costs.

Note that for purposes of this oil example project, all associated raw gas volumes are deemed to be transferred to the host government at the wellhead before shrinkage for condensate recovery and/or subsequent processing to remove nonhydrocarbons and natural gas liquids (NGLs) to yield marketable natural gas. Thus, gas volumes are excluded from entitlement to the license holder. For more details, readers should refer to Chapters 9 and 10 on production measurements, reporting, and entitlement.

Many other important and more complex project-specific issues that may require different interpretations, judgments, and resolutions by the analysts are not addressed. The main objective of this chapter is to illustrate the applications of the major petroleum resources assessment procedures for estimating plausible ranges of project in-place and recoverable quantities that are deemed to be “reasonable,” “technically valid,” and are “compliant” with PRMS guidance.

4.2.2 Volumetric and Analogous Methods

Static data-based volumetric methods to estimate petroleum initially in-place (PIIP) and analogous methods to estimate recovery efficiencies are the indirect estimating procedures used during exploration, pre-discovery, post-discovery, appraisal, and initial development (or exploitation) stages of the E&P life cycle of any recovery project.

4.2.2.1 Technical Principles

These procedures may be called “indirect” because the EUR cannot be derived directly, but requires independent estimates of reservoir-specific PIIP volume and appropriate recovery efficiency (RE). It is generally expressed in terms of a simple classical volumetric relationship defined by

$$\text{EUR (STB or scf)} = \text{IIP (STB or scf)} \times \text{RE (fraction of PIIP)} \tag{4.1a}$$

长达 100 年以上）。在现实中，可以通过实施人工举升和提高采收率项目来加速生产（如开采速度更高）和提高最终可采量，使项目的经济寿命期最终缩减至 50 ～ 70 年。再者，项目经济寿命期长是有利的，因为：

①作业者可能有机会采用一些其它油气藏因寿命期短而未能应用的新技术，由此从更低的资本与操作成本中获利。这种情形，也可推延提高采收率项目的实施，进一步延缓资本投资。

②由于边缘注水和开采速度低，产水量（或含水率）上升相对缓慢，含水率低且上升缓慢有助于推迟实施人工举升措施，再次延缓投资。

需注意的是，根据本案例研究目的，所有伴生原料气被视为从井口直接输送给当地政府，而不是经回收凝析油和 / 或分离非烃组分与天然气液（NGL）之后得到销售气，因而不包含在合同者的净储量中。更多细节，可参考第 9 章和第 10 章有关产量计量、披露和份额确认的内容。

还有许多未提及的其他重要和更复杂、针对具体项目的问题，可能不同分析师会有不同解释、判断和解决方案。本章主要目的是阐述评估项目原地量与可采量合理范围的主要方法，这些方法应合理和技术可行，并与 PRMS 指南保持一致。

4.2.2 容积法和类比法

在任何开发项目勘探开发生命期的勘探、发现前、发现后、评价以及开发（或开采）初期阶段，采用基于静态数据的容积法和类比法分别间接估算石油原始原地量（PIIP）和采收率。

4.2.2.1 技术原理

这类方法被称为间接法，是因为估算最终可采量（EUR）不能直接得到，需要分别单独估算油藏的石油原始原地量（PIIP）和采收率（RE）。容积法通常用一个简单关系式表示：

$$\text{EUR (STB or scf)} = \text{PIIP (STB or scf)}\times\text{RE (\%PIIP)} \tag{4.1a}$$

基于以下参数的平均值：面积（A）、有效厚度（h）、

In terms of average variables of area (A), net pay (h), porosity (ϕ), initial water saturation (S_{wi}) and hydrocarbon formation volume factor (FVF) (B_{hi}) for oil (RB/STB) or gas (Rcf/scf), the generalized classic volumetric equation for the PIIP (oil initially-in-place (OIIP) or gas initially-in-place (GIIP)) is given by

$$\text{PIIP (STB or scf)} = A\,h\,\phi\,(1- S_{wi}) / B_{hi} \qquad (4.1b)$$

where oil or gas volumes are in barrels or cubic feet, abbreviated as STB and RB or scf and Rcf, representing the measurements at standard surface (s) and reservoir (R) conditions, respectively, based on respective pressures and temperatures.

For each petroleum resource category, the estimates of PIIP are determined volumetrically using Eq. 4.1b. However, an independently estimated RE is necessary to calculate project EUR. Recovery efficiency may be assigned from appropriate analogs, using analytical methods or, as a last resort, using published empirical correlations.

PRMS encourages the use of available analogs to assign RE. The rationale for the selection of analogous reservoirs are well provided for in Cronquist (2001) and Harrell et al. (2004) and in the PS-CIM publications (2004, 2005, and 2007). Technical principles of natural and supplementary oil recovery mechanisms and analytical procedures to estimate recovery efficiency may be found in many references, including Cronquist (2001), Walsh and Lake (2003), and Dake (1978 and 2001) (for natural reservoir drives); Craig (1971), Smith (1966), and Sandrea and Nielson (1974) (immiscible water and gas injection schemes for pressure maintenance); Taber and Martin (1983) [enhanced oil recovery (EOR) screening]; Prats (1982) and Boberg (1988) (thermal processes); Lake (1989) and Latil (1980) (polymer flooding); and Dake (1978), Stalkup (1983), Klins (1984), Lake (1989), Green and Willhite (1998), and Donaldson et al. (1985) (miscible processes and chemical methods of micellar-polymer and alkaline-polymer flooding). For a quick review, PS-CIM (2004) and Carcoana (1992) are recommended. Finally, the published empirical correlations to estimate RE can be found in many references, including Cronquist (2001), Walsh and Lake (2003), and Craig (1971). However, it should be emphasized that even a rough estimate of recovery efficiency from a near-analog or determined by using a physically based analytical method is preferable to using empirical correlations.

With the availability of computational power and integrated work-processes, these analytical procedures may be supplemented

孔隙度（φ）、原始含水饱和度（S_{wi}）和烃地层体积系数（B_{hi}，油 :RB/STB 或气 :Rcf/scf），通用的石油原始原地量（PIIP）（原油原始原地量：OIIP；或天然气原始原地量：GIIP）的经典容积法计算公式如下：

$$\text{PIIP (STB or scf)} = \text{Ah}\,\phi\,(1-S_{wi})/B_{hi} \qquad (4.1b)$$

这里油或气的体积单位是桶或立方英尺，缩写为 STB（或 RB）或 scf（或 Rcf），分别对应地面标准状态（s）和油藏状态（R）下的压力与温度计量条件。

不同级别石油资源的原始原地量均采用容积法公式（4.1b）进行估算。但是项目的采收率需要另行评估，以估算项目的最终采出量；可采用的方法包括合理类比、解析法，或最后一种方式——公开发表的经验公式。

PRMS 鼓励应用类比油气藏信息来核定采收率。Cronquist（2001）和 Harrell 等（2004）和 PS-CIM 的刊出文献（2004，2005 和 2007）详细提供了选择类比油气藏的理论依据。根据天然开采和二次采油机理评估采收率的技术原理与分析方法也可以在很多文献中找到，包括 Cronquist（2001），Walsh 和 Lake（2003），Dake（1978 和 2001）——油气藏天然开采；Craig（1971），Smith（1996）及 Sandrea 和 Nielson（1974）——保持地层压力注水和注气非混相驱；Taber 和 Martin（1983）——提高采收率筛选；Prats（1982）和 Boberg（1988）——热力采油；Lake（1989）和 Latil（1980）——聚合物驱；Dake（1978），Stalkup（1983），Klins（1984），Lake（1989），Green 和 Willhite（1998）及 Donaldson 等（1985）——混相驱和化学驱（如凝胶聚合物和碱聚合物驱）。为了快速回顾，推荐参考文献 PS-CIM（2004）和 Carcoana（1992）。公开发表的采收率经验公式可以在许多文献中找到，包括 Cronquist（2001），Walsh 和 Lake（2003）及 Craig（1971）。但应强调，通过类比邻近油气藏数据或物理分析得到的采收率估值比经验公式法

by recovery process-specific reservoir simulation model studies. Rigorous models may effectively predict not only any reservoir-specific recovery performance including EOR, but also incorporate the ever-changing recovery enhancing practices resulting from the successful application of field-tested drilling and completion (e.g., multilateral, extended-reach and smart wells with inflow-control devices, etc.), reservoir development and production engineering technologies that optimize the overall flow system starting from reservoir through well completions, wellbore and the surface facilities and pipelines.

4.2.2.2 Applications to Example Oil Project During Its Exploration and Appraisal Phase and Initial Development Stage

Geological maps for an example petroleum project during these phases and different stages within each phase (see Figures 4.2 through 4.5) were re-created through a look-back process. These maps were developed and associated net reservoir rock volumes were estimated by Wang (2010). However, the appraisal and development plans described estimates of PIIPs and recoverable volumes including the assignment of different categories of reserves and resources were made by the author.

Excellent guidance on how to construct better maps and minimize mapping errors is provided by Tearpock and Bischke (1991). Moreover, Harrell et al. (2004) provides an excellent review on the complex nature of the reserves assessment process, the use of analogs, and recurring mistakes and errors, including subsurface mapping.

Based on the PRMS definitions and guidelines, assessment and assignment of different categories of resources and reserves for the example oil project during its E&P life cycle stages are presented below.

4.2.2.2.1 Prediscovery Stage

In the prediscovery stage, the range of Prospective Resources is estimated based on a combination of volumetric analyses and use of appropriate analogs. The geological realization of this “exploratory prospect” shown in Figure 4.2a was developed based on a combination of seismic and geological studies that defined the shape and closure for potential petroleum accumulation. The 2D seismic defined a structural spill point, but provided no indication of fluid contacts. Based on the analog carbonate reservoirs, it was assumed that this exploratory petroleum prospect would most likely contain light crude with gravity 30 to 33ºAPI.

计算的更可靠。

随着计算能力的日益提高和工作流程一体化，针对开采过程的油藏模拟模型研究可进一步补充分析方法。精确的模型不仅可以有效地预测油藏的开采动态（包括提高采收率效果），也可以反映不断变化的开发成效，包括成功实施现场测试的钻完井技术（如多分支井和带流入控制装置的大位移智能井等），以及优化整个流体流动系统（从油气藏到完井层段、井筒、地面设施以及输送管线）的油气藏开发与生产工程技术。

4.2.2.2 在原油项目勘探评价期与开发初期的应用

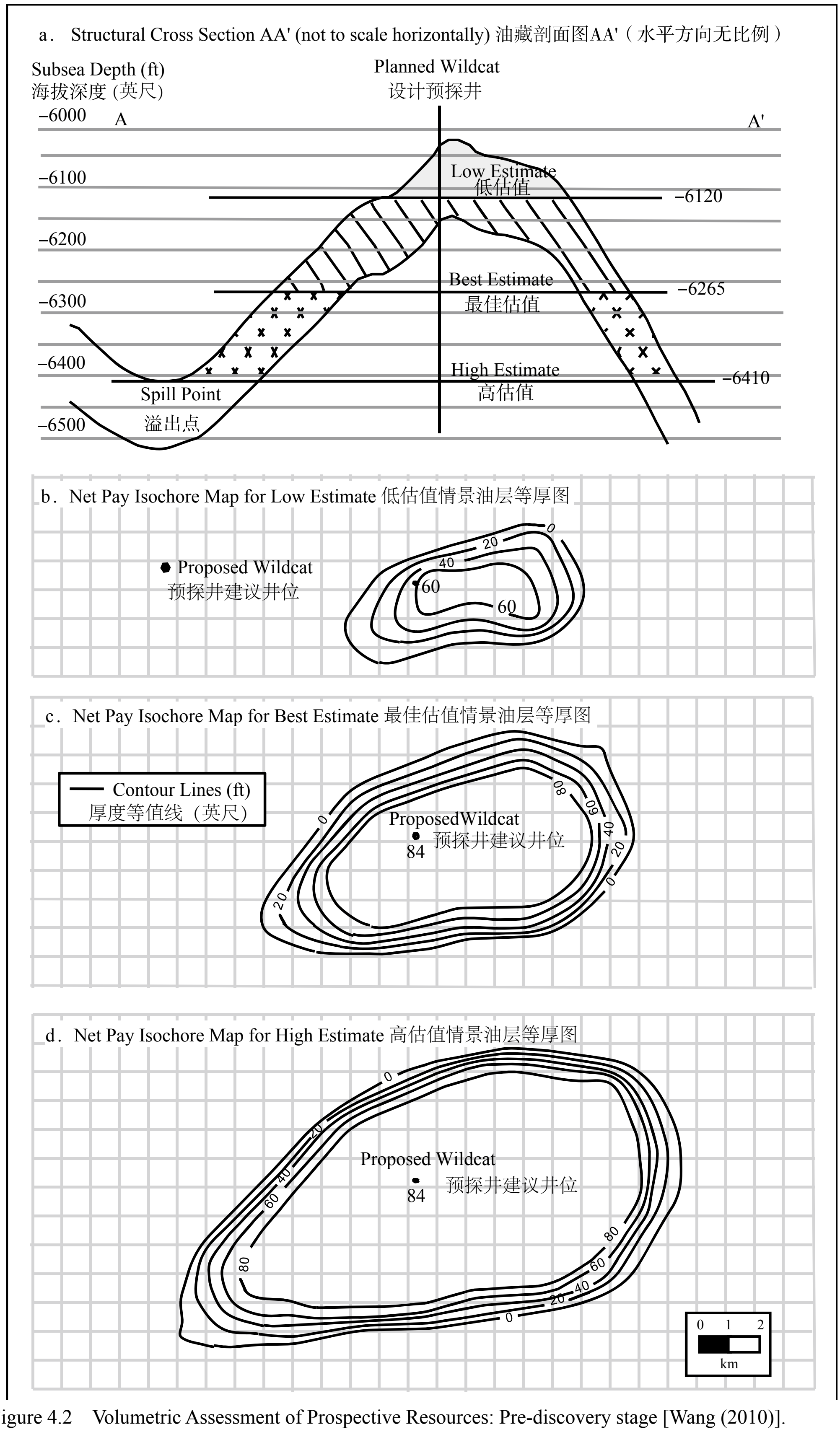
通过追溯方式，可以重新绘制案例项目在各勘探开发时期及其不同阶段的相应地质图件（图 4.2- 图 4.5）。本指南的这些图件是由 Wang（2010）绘制，并由其估算的相应净储层岩石总体积。但基于评价和开发方案的石油原始原地量与可采量评估，包括不同级别储量与资源量的核定是由本章作者完成的。

关于如何更好绘制地质图件和减少作图误差，Tearpock 和 Bischke（1991）提供了很好指引。另外，Harrell 等人（2004）针对储量评估的复杂特点、类比油气藏的使用，以及人为原因（包括地质图件绘制过程中）造成的二次错误与误差等提供了很好的借鉴意见。

根据 PRMS 定义和准则，案例项目在其勘探开发生命周期各阶段的不同级别资源量和储量评估情况如下。

4.2.2.2.1 发现前

在发现前阶段，远景资源量范围的评估是基于容积法与类比法的结合。图 4.2a 为案例项目勘探目标的地质实现示意图。其潜在油气聚集体的形状和闭合高度基于地震和地质研究所确定。该区二维地震确定了构造溢出点，但尚不能提供流体界面信息。根据类比碳酸盐岩油藏，可假定该勘探目标很可能蕴藏重度在 30 ～ 33° API 之间的轻质原油。


a. Structural Cross Section AA' (not to scale horizontally) 油藏剖面图AA'（水平方向无比例）

b. Net Pay Isochore Map for Low Estimate 低估值情景油层等厚图

c. Net Pay Isochore Map for Best Estimate 最佳估值情景油层等厚图

d. Net Pay Isochore Map for High Estimate 高估值情景油层等厚图

Figure 4.2 Volumetric Assessment of Prospective Resources: Pre-discovery stage [Wang (2010)].

图 4.2 容积法评估远景资源量（发现前）（据 Wang，2010）

The volumetric assessment process starts with the estimate of gross reservoir rock volume depicted by the cross section presented as Figure 4.2a. Based on regional analogs, the high estimate assumed the structure to be fully charged to its spill point at 6,410 ft subsea. The volume above 6,120 ft subsea was assigned conservatively to represent the low estimate and the vertical limit for the best estimate was set at an intermediate depth of 6,265 ft subsea. Typically, information on regional and local geology are used to construct net-to-gross (NTG) maps (obtained from the nearby analog reservoirs after applying parameter cutoffs to exclude portions of the reservoir that do not meet the minimum criteria to support production), and integrated with gross reservoir volume to yield net pay maps. In this case, analysts applied a constant average NTG ratio of 0.70. The net pay isochore maps depicted as Figures 4.2b, 4.2c, and 4.2d were developed, representing the reservoir pay volumes for low, best, and high estimate scenarios, respectively. The vertical and areal extent associated with each scenario is illustrated in these maps.

Furthermore, the chance of discovery was estimated at 40% based on independent assessments of source rock, trap integrity, reservoir adequacy, and regional migration paths. The chance of such a technical success being commercially developed, or the chance of development, is estimated at 60% based on analysis of economic scenarios and assessment of other commercial contingencies. Hence, the overall chance of commerciality of this exploratory prospect, defined as the product of these two risk components is estimated to be 24%.

Assuming a discovery, Table 4.1 documents the estimates of average reservoir parameters (i.e., rock and fluid properties, and a range of recovery efficiencies expected from peripheral water injection projects already implemented and well-established in several similar nearby reservoirs), and the resulting estimates of oil and gas volumes of these yet undiscovered Prospective Resources. As poorer reservoir quality in peripheral areas was included in the volumes of each successive resource category, the expected average value of porosity (or initial water saturation) was decreased (or increased).

4.2.2.2.2 Post-Discovery Stage

The wildcat well was drilled and encountered a significant oil column sufficient to declare a “discovery.” The geologic model was updated as Figure 4.3 for the discovered structure and well-based reservoir data with an estimated average NTG ratio of 0.75, translating into a net pay of 89 ft.

The discovery Well 1 flowed oil, but insufficient pressure data were retrieved and gradient analysis could not be performed, thus the low estimate of technically recoverable volume could not be allocated below the lowest known hydrocarbon (LKH) at 6,155 ft subsea.

容积法评估，可先根据图 4.2a 所示的剖面图来估算油藏岩石总体积。根据区域类比，可乐观估计整个构造全充满（至溢出点海拔深度 -6410ft）。保守估计的低估值为海拔深度 -6120ft 以浅的体积，最佳估值的垂向界限为高估值和低估值的中部深度——海拔深度 -6265ft。通常，可根据区域和该目标区的地质资料来构建净毛比（NTG）分布图——通过邻近类比油藏，可获取净厚度截止值，以剔除不能满足最低生产能力的无效储层，再结合总油藏体积分布，即可得到有效厚度等值线图。在本例中，评估师采用恒定的平均净毛比 0.70。图 4.2b、4.2c 和 4.2d 所示有效厚度等值线图分别代表低估值、最佳估值、高估值情景的油藏有效储层厚度图。这些图展示了每个情景在纵向和平面上的砂体展布。

此外，根据对烃源岩、圈闭完整性、油藏充注度以及区域油气运移途径的单独评价，估算发现几率为 40%。基于对经济条件情景的分析和其他商业或有因素的评价，该目标技术成功之后商业开发的几率（或开发几率）为 60%。因此，该勘探目标的整体商业几率为上述两个风险因子的乘积，即 24%。

表 4.1 列出了一个假定发现的平均油藏参数估值（包括岩石和流体性质，以及邻近类似油藏成熟应用边缘注水技术开发的采收率范围），以及尚未发现的油气远景资源量估值。由于油藏边部品质变差，在评估每个资源量级别时，油藏平均孔隙度估值减小，和 / 或平均原始含水饱和度估值增加。

4.2.2.2.2 发现后

预探井钻遇大段油层，宣布“发现”。已发现构造的地质模型由此进行更新，如图 4.3 所示；根据井资料估算平均净毛比为 0.75，折算 1 井有效储层厚度为 89ft。

发现井（1 井）出油，但没有获取足够压力数据，未能进行压力梯度分析，因此其技术可采量的低估值不能考虑已知烃底（海拔深度 -6155ft）以下的部分。

Table 4.1 Volumetric Assessment of Prospective Resources (Pre-discovery Stage): Estimates of Project PIIPs and EURs
表 4.1 容积法评估远景资源量（发现前）：项目原始原地量和最终可采量

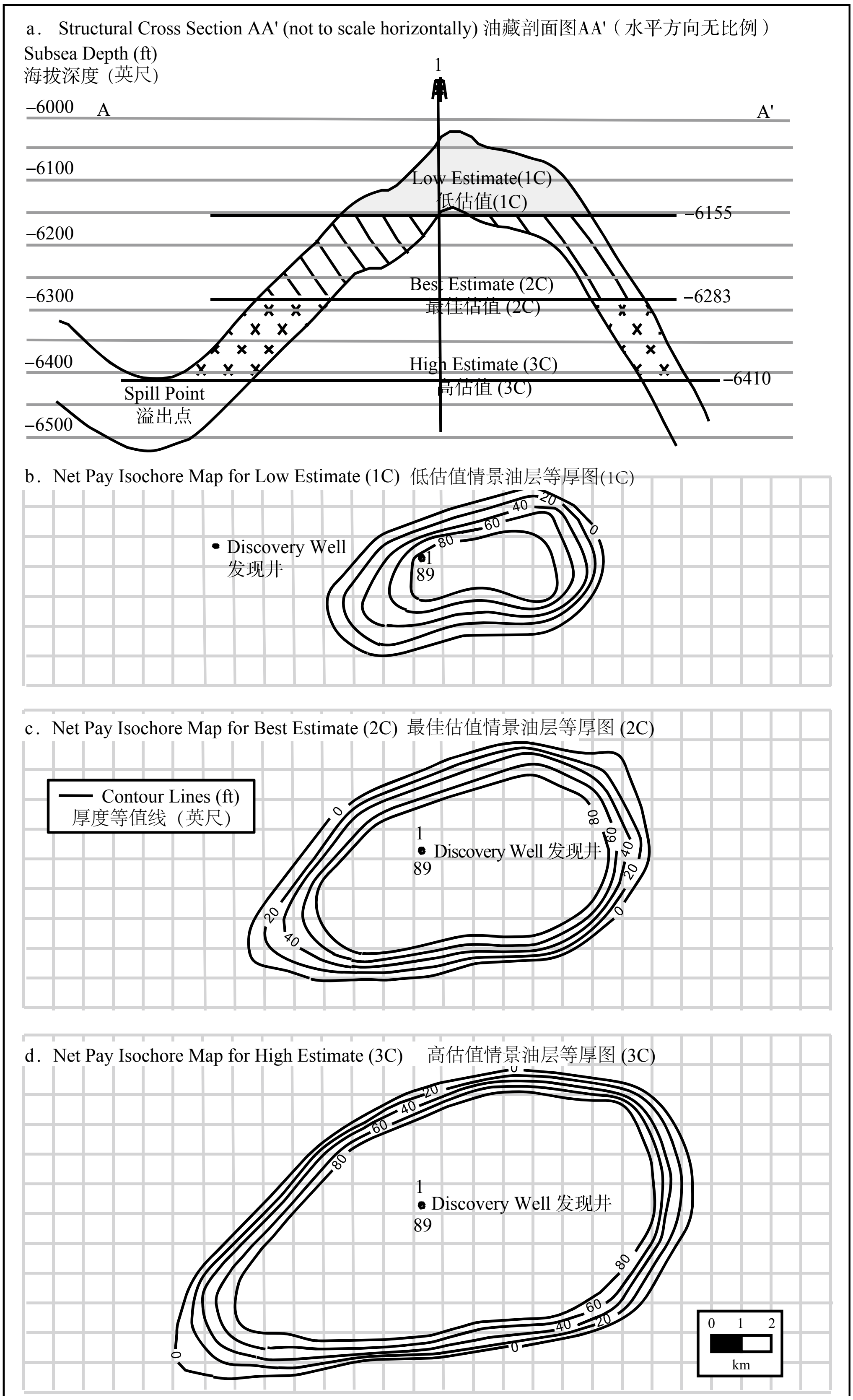
Estimated Parameters 估算参数	Units 单位	Bases and Categories of Prospective Resources 基础数据和远景资源量		
		Low Estimate 低估值	Best Estimate 最佳估值	High Estimate 高估值
Bulk Reservoir Pay Volume 储层总体积	M ac·ft	241.4	1055.6	2134.7
Average Porosity 平均孔隙度	%	17	16	15
Pore Volume（PV） 孔隙体积	M ac·ft	41.0	168.9	320.2
Average Initial Water Saturation 平均原始含水饱和度	%	18	19	20
Hydrocarbon Pore Volume (HCPV) 烃孔隙体积	M ac·ft	33.7	136.8	256.2
Average FVF（B_{oi}） 平均原始地层体积系数	RB/STB	1.4	1.4	1.4
Oil Initially-In-Place（OIIP） 原油原始原地量	MMSTB[1]	186.5	758.1	1419.5
Recovery Factor[2] 采收率	% (OIIP)	35	40	45
Recoverable Oil（EUR）[4] 原油估算最终可采量	MMSTB	65.3	303.2	638.8
Initial Solution Gas-Oil Ratio(R_{si}) 原始溶解气油比	scf/STB	500	500	500
Gross-Heationg Value of Raw Solution Gas 溶解气总热值	Btu/scf	1200	1200	1200
Gas Initially-In-Place（GIIP） 溶解气原始原地量	Bscf	93.2	379.0	709.8
Recoverable Raw Gas（EUR）[4] 原料气估算最终可采量	Bscf	32.6	151.6	319.4
	MMBOE[3]	6.8	31.4	66.1

[1] Calculated by using the conversion factor of 7,758 bbl/acre-ft.
使用转换系数 7758bbl/acre•ft 进行计算。

[2] Under peripheral Water injection,already well-established in several nearby analog reservoirs and projects.
采用边缘注水，该开发方式已在邻近的类比油藏和项目成熟应用。

[3] Calculated using an average conversion factor of 5.8 MMBtu per BOE.
使用平均转换系数 5.8MMBtu/BOE 进行计算。

[4] Estimated oil and gas Prospective Resources categories of Low, Best and High, respectively.
原油和天然气远景资源量的低估值、最佳估值和高估值。



a．Structural Cross Section AA' (not to scale horizontally) 油藏剖面图AA'（水平方向无比例）

b．Net Pay Isochore Map for Low Estimate (1C) 低估值情景油层等厚图(1C)

c．Net Pay Isochore Map for Best Estimate (2C) 最佳估值情景油层等厚图 (2C)

d．Net Pay Isochore Map for High Estimate (3C)　高估值情景油层等厚图 (3C)

Figure 4.3　Volumetric Assessment of Contingent Resources: Post-discovery stage [Wang (2010)]

图 4.3　容积法评估条件资源量（发现后）（据 Wang，2010）

Although preliminary economics of a proposed development plan were encouraging, there was still significant uncertainty, and the chance of its commercial development was estimated to be only 60%. Therefore, estimates of technically recoverable volumes of this discovered accumulation could only be reclassified as Contingent Resources. Even though the chance of an updip gas cap above the highest known hydrocarbon (HKH) could not be ruled out, the majority of analog reservoirs are undersaturated and hence, for simplicity, it was neglected while developing these maps and until the detailed pressure/volume/temperature (PVT) analysis and pressure-gradient data became available for confirmation.

High estimate (3C) assumed that the structure is full with oil to its spill point, and alternative geologic maps indicated a larger closure and higher recovery efficiency. Lacking any further control than the LKH, which defined the 1C limit, regional analogs supported the forecast that the vertical limit for the best estimate (2C) could be set at an intermediate depth of 6,283 ft subsea and that the recovery efficiency is slightly above that assumed for the 1C scenario. Based on the discovery well structure and log data, and an average oil gravity of 32ºAPI measured from the oil samples collected, the volumetric weighted average reservoir parameters were revised accordingly, but recovery factors were kept the same at this stage.

Table 4.2 documents average reservoir rock and fluid properties, and resulting estimates of relevant volumes of oil and gas for Contingent Resources. Note again that the “average” porosity is lower in the 2C and 3C scenarios, reflecting decreasing porosity (and increasing water saturation) in the peripheral areas included in the higher estimates of bulk reservoir pay volume.

At this stage, remaining uncertainty in the project’s commercial development was still considered significant, and without the benefit of additional data (e.g., from further delineation, bottomhole PVT samples, pressure-gradient and definitive production tests and associated analysis), the owners were not willing to commit funds to a development project. To better ascertain its commercial potential, an appraisal program designed to further evaluate the discovery was deemed necessary.

4.2.2.2.3 Appraisal (or Delineation) Stage

An appraisal program was designed and implemented, including (1) drilling of two additional wells with well testing and PVT analysis, and (2) acquisition and interpretation of 3D seismic data. It took two years to execute the Appraisal Program and complete the necessary analyses and interpretations.

Both Wells 2 and 3 penetrated and established new LKH depths, thereby extending the base for the low estimate to 6,240 ft subsea. PVT analysis of bottomhole fluid samples showed that oil was undersaturated. Undersaturated oil, supported also by pressure-gradient measurements, eliminated the potential for a gas cap. It was further determined that,

尽管开发（概念）设计的初步经济评价结果令人振奋，但仍存在很大不确定性，评估商业开发的几率只有 60%。因此，该油藏的技术可采量估值只能重新划归为条件资源量。即使在已知烃顶（HKH）以上，也不排除存在气顶的可能性，但由于绝大多数类比油藏是未饱和的，所以简便起见，制图时先忽略气顶。后续获得更多详实的压力 / 体积 / 温度（PVT）分析和压力梯度数据之后，再进一步确认。

高估值（3C）情景假设油在整个构造全充满至溢出点，更新后的地质图显示构造闭合面积更大，采收率更高。已知烃底（LKH）是低估值情景（1C）的深度下限。在没有更多限制性条件存在情况下，最佳估值（2C）情景的深度界限基于区域类比认识取 1C 情景和 3C 情景的中值，为海拔深度 -6283ft，其采收率也略高于 1C 情景的采收率。根据发现井的构造和测井解释资料，以及取样测得的原油平均重度 32° API，可按照体积加权方式相应地更新平均油藏参数，但该阶段的采收率保持不变。

表 4.2 给出了平均油藏岩石和流体参数，以及相应的油气条件资源量估算结果。请再次留意，2C 和 3C 情景所用的“平均”孔隙度略低，反映了更大的油藏体积估算量中增加了边部低孔隙度（和高含水饱和度）的储层。

在该阶段，项目商业开发的其他不确定性仍然较大，且没有更多资料（例如，进一步的开发评价、井底 PVT 取样、压力梯度、系统生产测试及相关分析），业主尚还不愿承诺项目开发的资金。为了进一步确认商业开发潜力，有必要实施评价工作来进一步评估该发现。

4.2.2.2.3 评价（或开发评价）阶段

设计和实施的评价工作方案包括：（1）新钻 2 口井，开展试井和 PVT 分析；（2）采集三维地震数据并解释。实施上述评价工作和完成必要的分析与解释，用了 2 年时间。

井 2 和井 3 均钻遇储层，获取了新的已知烃底 (LKH)，将低估值情景的深度基准线推至海拔深度 -6240ft。井底流样 PVT 分析显示油藏未饱和。压力梯度测试也证实了油藏是未饱和状态，从而排除了气顶的存在。另外，还进一步确定了以下

Table 4.2 Volumetric Assessment of Contingent Resources （Post-Discovery Stage）: Estimates of Project PIIPs and EURs
表 4.2 容积法评估条件资源量（发现后）：项目石油原始原地量和最终可采量

Estimated Parameters 估算参数	Units 单位	Bases and Categories of Contingent Resources 基础数据和条件资源量		
		Low Estimate 低估值	Best Estimate 最佳估值	High Estimate 高估值
Bulk Reservoir Pay Volume 储层总体积	M ac·ft	448.4	1258.7	2287.1
Average Porosity 平均孔隙度	%	19.1	18.9	18.7
Pore Volume（PV） 孔隙体积	M ac·ft	85.6	237.9	427.7
Average Initial Water Saturation 平均原始含水饱和度	%	14.5	14.8	15.2
Hydrocarbon Pore Volume （HCPV） 烃孔隙体积	M ac·ft	73.2	202.7	362.7
Average FVF（B_{oi}） 平均原始地层体积系数	RB/STB	1.4	1.4	1.4
Oil Initially-In-Place（OIIP） 原油原始原地量	MMSTB[1]	405.8	1123.2	2009.8
Recovery Factor[2] 采收率	% (OIIP)	35	40	45
Recoverable Oil（EUR）[4] 原油估算最终可采量	MMSTB	142.0	449.3	904.4
Initial Solution Gas-Oil Ratio（R_{si}） 原始溶解气油比	scf/STB	500	500	500
Gross-Heationg Value of Raw Solution Gas 溶解气总热值	Btu/scf	1200	1200	1200
Gas Initially-In-Place（GIIP） 溶解气原始原地量	Bscf	202.9	561.6	1004.9
Recoverable Raw Gas（EUR）[4] 原料气估算最终可采量	Bscf	71.0	224.6	452.2
	MMBOE[3]	14.7	46.5	93.6

[1] Calculated by using the conversion factor of 7,758 bbl/acre-ft.
使用转换系数 7758bbl/acre•ft 进行计算。

[2] Under peripheral water injection, already well-established in several nearby analog reservoirs and projects.
边缘注水开发，已在邻近的类比油藏和项目成熟应用。

[3] Calculated using an average conversion factor of 5.8 MMBtu per BOE.
使用 5.8MMBtu/BOE 平均转换系数计算。

[4] Estimated oil and gas Prospective Resources categories of 1C,2C and 3C, respectively.
原油和天然气条件资源量的低估值、最佳估值和高估值。

(1) The carbonate reservoir had an initial pressure (p_i) of 3,230 psia, temperature of 200°F, estimated average porosity of 18.7%, 15% initial water saturation, and 400 md permeability.

(2) The wells tested at rates (rounded to the lower 100) ranging from 2,500 to 5,000 BOPD, with an average stabilized oil rate of 3,500 BOPD, oil gravity of 33°API, and viscosity of 0.7 cp.

(3) The reservoir had a bubblepoint pressure (p_b) of 1,930 psia, initial solution gas/oil ratio (GOR), or R_{si}, of 550 scf/STB, and initial (B_{oi}) and bubblepoint (B_{ob}) FVFs of 1.33 RB/STB and 1.35 RB/STB, respectively.

Figure 4.4 illustrates the revision made for additional data obtained from this appraisal program. Based on the net reservoir distribution (via NTG ratios) in Well 1 (0.75), Well 2 (0.70), and Well 3 (0.55), a NTG surface was generated and used to develop the map views (Figure 4.4b to 4.4d), illustrating the interpreted areal extent and net reservoir volume for each reserves category.

An initial development program including pressure maintenance by means of peripheral water injection was applied. This recovery method is a well-established and common depletion method in several analog reservoirs and projects. With favorable project economics, the owners committed investment funds to the project and gave approval to proceed with the next development stage. No market, legal, or environmental contingencies were foreseen. Therefore, consistent with PRMS, the new estimates of recoverable quantities from the applied project are now reclassified as Reserves.

1P Reserves were assigned to the PIIP volume above the LKH established at 6,240 ft subsea. Although seismic amplitude analysis indicated potential extending below the LKH, it was insufficient to support extending Proved Reserves below this LKH depth. 2P Reserves were allocated to the total PIIP volume above 6,325 ft subsea. In the absence of original oil/water contact (OWC), 3P Reserves were assigned to the total PIIP volume above 6,410 ft subsea (or spill point). Three wells and 3D seismic data provided increased structural control. Based on similar regional analogs, there was reasonable potential that the structure was filled with oil to the spill point.

It may be important to note that in deterministic analysis, both scenario and incremental approaches (allowed by PRMS) generate the materially equivalent estimates. Based on the bulk reservoir pay volume associated with each incremental category obtained from the difference between the relevant maps, the incremental approach can also be used to directly calculate the Proved, Probable and Possible Reserves. Estimates should be very consistent with those obtained from the cumulative (scenario) approach provided that care is taken in estimating reasonable average values of porosity and initial water saturation for each incremental volume to yield correct the PIIPs. For simplicity in presentation, incremental analyses are not included here.

认识：

（1）该碳酸盐岩油藏的原始地层压力 (P_i) 为3230psia，原始地层温度200℉，平均孔隙度18.7%，原始含水饱和度15%，渗透率400mD。

（2）井的测试产能（取整到百位）在2500～5000BOPD之间，平均稳产量为3500BOPD，原油重度33° API，原油黏度0.7cp。

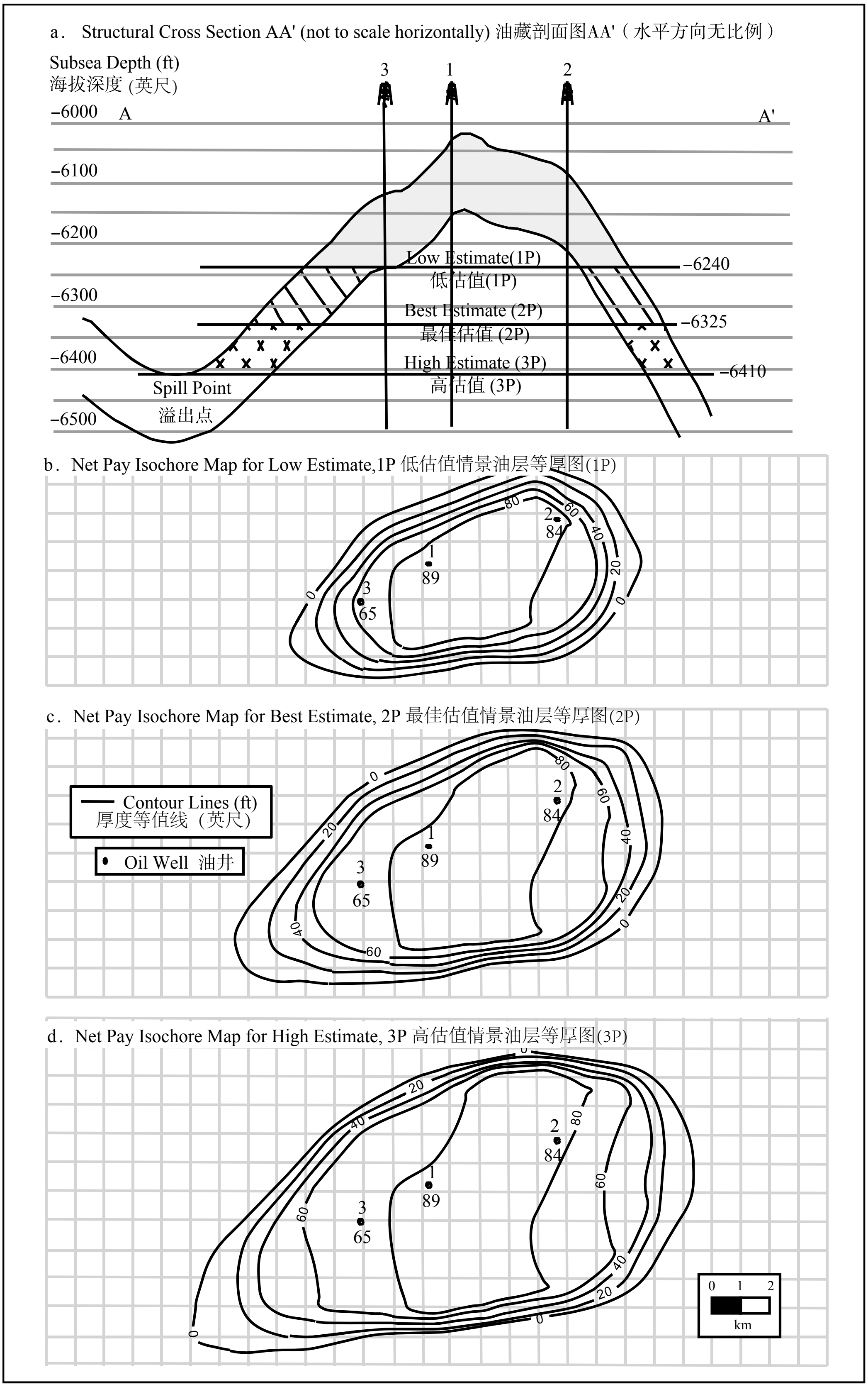
（3）油藏的泡点压力（P_b）为1930psia，原始溶解气油比（GOR）或 R_{si} 为550scf/STB，原油原始地层体积系数为1.33RB/STB，泡点压力下的原油地层体积系数为1.35RB/STB。

图4.4根据评价阶段获取的新资料进行了更新。根据有效油藏厚度分布图（净毛比，1井0.75，2井0.70，3井0.55），可生成新的净毛比平面分布并绘制成图（图4.4b至4.4d），以展示各级别储量的面积分布与有效储层厚度分布。

实施了初始开发方案，包括采用边缘注水保持油藏压力。该开采方式是类比油藏和项目普遍应用的成熟技术。由于项目经济性良好，项目业主承诺投资，并批准实施下一阶段的开发工作量。项目不存在市场、法律和环境方面的或有因素。因此，根据PRMS，该项目新评估的可采量现在可重新划归为储量。

1P储量的石油原始原地量（PIIP）位于已知烃底海拔深度-6240ft以浅。尽管地震振幅分析显示已知烃底以下可能含油，但其作为证实储量划分依据还不充分。2P储量的总原始原地量深度界限为海拔深度-6325ft。由于未钻遇原始油水界面(OWC)，3P储量的总原始原地量以海拔深度-6410ft（溢出点）为界。三口井的资料和三维地震数据提高了对构造的控制程度。根据区域类比，构造全充满至溢出点，存在合理可能性。

值得注意的是，确定法中的情景法与增量法（PRMS允许采用的方法）评估结果是等效的。基于相关图件的数据差异所得到的各级增量体积，可直接用于估算证实、概算和可能储量。如果每个增量相应原地量的估算都采用了合理的油藏平均孔隙度和原始含水饱和度，那么增量法与情景法的评估结果应该是高度一致的。为简洁起见，增量法分析在本节不作阐述。



a．Structural Cross Section AA' (not to scale horizontally) 油藏剖面图AA'（水平方向无比例）

b．Net Pay Isochore Map for Low Estimate,1P 低估值情景油层等厚图(1P)

c．Net Pay Isochore Map for Best Estimate, 2P 最佳估值情景油层等厚图(2P)

d．Net Pay Isochore Map for High Estimate, 3P 高估值情景油层等厚图(3P)

Figure 4.4　Volumetric assessment of Reserves: appraisal stage [Wang (2010)]
图 4.4　案例油藏容积法评估储量（评价阶段）（据 Wang，2010）

Table 4.3 documents the revised average reservoir rock and fluid properties, and resulting estimates of relevant oil and gas volumes for each reserves category. The project is located close to existing infrastructure; therefore, an overall development plan was prepared for immediate implementation.

表 4.3 列出了油藏岩石与流体参数的平均值以及各级别油气储量的评估结果。由于该项目附近已建有生产设施，其整体开发方案完成后，立即实施。

Table 4.3 Volumetric Assessment of Reserves （Appraisal Stage）: Estimates of Project PIIPs and EURs
表 4.3 容积法评估储量（评价阶段）：项目石油原始原地量和估算最终可采量

Estimated Parameters 估算参数	单位 Units	Bases and Reserves Categories 基础数据和储量		
		Low Estimate 低估值	Best Estimate 最佳估值	High Estimate 高估值
Bulk Reservoir Pay Volume 储层总体积	M ac·ft	821.0	1370.8	1917.9
Average Porosity 平均孔隙度	%	18.9	18.7	18.5
Pore Volume（PV） 孔隙体积	M ac·ft	155.2	256.3	354.8
Average Initial Water Saturation 平均原始含水饱和度	%	14.8	15.0	15.3
Hydrocarbon Pore Volume （HCPV） 烃孔隙体积	M ac·ft	132.2	217.9	300.5
Average FVF（B_{oi}） 平均原始地层体积系数	RB/STB	1.330	1.330	1.330
Oil Initially-In-Place（OIIP） 原油原始原地量	MMSTB[1]	771.2	1271.0	1753.0
Recovery Factor[2] 采收率	%(OIIP)	35	40	45
Recoverable Oil（EUR）[4] 原油估算最终可采量	MMSTB	269.9	508.4	788.8
Initial Solution Gas-Oil Ratio (R_{si}) 原始溶解气油比	scf/STB	550	550	550
Gross-Heationg Value of Raw Solution Gas 溶解气总热值	Btu/scf	1200	1200	1200
Gas Initially-In-Place（GIIP） 溶解气原始原地量	Bscf	424.1	699.0	964.1
Recoverable Raw Gas（EUR）[4] 原料气估算最终可采量	Bscf	148.4	279.6	433.9
	MMBOE[3]	30.7	57.9	89.8

[1] Calculated by using the conversion factor of 7,758 bbl/acre-ft.
使用转换系数 7758bbl/acre•ft 进行计算。

[2] Under peripheral water injection,already well-established in several nearby analog reservoirs and projects.
采用边缘注水，该开发方式已在邻近的类比油藏和项目成熟应用。

[3] Calculated using an average conversion factor of 5.8 MMBtu per BOE.
使用平均转换系数 5.8MMBtu/BOE 进行计算。

[4] Estimated oil and gas Reserves categories of 1P, 2P and 3P, respectively.
原油和天然气的 1P、2P 和 3P 储量估值。

The total area, about 60 1-km WSUs, defined as Proved by three wells in this example reflects an extremely high confidence in the lateral continuity of the productive reservoir. Such continuity of a high-quality reservoir with average permeability of 400 m was also supported by numerous surrounding analogs. Thus, it meets PRMS criteria for reasonable certainty. 1P reserves are considered Proved Undeveloped (PUD) status for now. However, based on a well drainage area of 1 km^2 (or about 250 acres) derived from single-well simulation studies, at least three 1-km WSUs (out of a total Proved of about 60) penetrated by these three productive wells represent a portion of approximately 5% of the total Proved volume (or about 38.5 MMSTB of the OIIP), which can be carried under Proved Developed (PD) status immediately after the installation of necessary equipment.

4.2.2.2.4 Initial Development (or Exploitation) Stage

Similar to well-established development and production practices in several nearby analogs producing from the same reservoir, a single recovery project integrating the primary and secondary waterflood development programs was recommended and approved for immediate implementation. The project was designed with an initial plateau production rate of 75,000 BOPD targeting an annual depletion of 5.4% of 2P reserves of 508.4 MMSTB (from Table 4.3) and supported by peripheral water injection with an injection rate of 100,000 BWPD. Pressure maintenance by peripheral water injection had been established to be a very effective depletion method in several nearby analog projects where the water injected into a partially active edgewater aquifer displaces the oil column updip thereby achieving oil recoveries, in some cases, exceeding 60% OIIP.

Based on an assumed conservative average well production rate that may vary between 2,500 and 3,000 BOPD, the initial development project required a total of 34 producers (including the three existing productive wells) to establish a balanced withdrawal fieldwide. The time line accounted for an operating factor in production rate considering annual downtime for preventive maintenance of surface facilities, including inspection, repairs, and testing. The project also required eight water supply wells from a local shallow aquifer and 19 peripheral water injectors (to inject produced plus externally supplied water) to maintain reservoir pressure and to provide balanced updip displacement. The project included pertinent surface production and injection facilities and associated pipelines. Based on this well-defined development plan, the production profile and required initial capital investment (for drilling and well completions, well flowlines, surface production and injection facilities and pipelines), and future capital (for future wells and flowlines) and operating expenditures required during the project's economic life, the recovery project's economic viability was reconfirmed. The approval

3 口井圈定的证实储量面积约有 60 个 1-km 井距，有效储层的横向连续性在该范围内置信度很高。储层物性好（平均渗透率 400mD）和连续性佳的特征也在邻近的大量类比油藏中得到印证。因此，满足 PRMS 关于合理确定性的条件要求。现阶段，1P 储量的状态可考虑为证实未开发（PUD）。然而，根据单井数值模拟的研究结果，1 口井的泄油面积约为 1km^2（大约 250acre），那么现有 3 口井的井控面积约占总证实体积（60 个井距面积，或原油原始原地量 38.5MMSTB）的 5%。必要的生产设施安装启动之后，3 口井的储量可划归为证实已开发（PD）。

4.2.2.2.4 开发初期阶段

与邻近相同储层的成熟类比油藏类似，推荐以一次采油和二次注水相结合的开发方式实施单一开发项目。项目获得批准后立即实施。项目设计初始高峰产量为 75,000BOPD，2P 储量 508.4MMSTB（见表 4.3）的年采油速度为 5.4%，日注水量为 100,000BWPD。边缘注水保持油藏压力的开采方式，在邻近的几个类比项目中非常有效；在部分活跃的边水区域注水，驱替原油向上倾方向流动，从而提高采收率（某些项目的采收率超过了原始原地量的 60%）。

保守估计，平均单井日产量 2500 ~ 3000 BOPD，初始开发方案共需要 34 口开发井（包括 3 口可投产的老井），以保持油田注采平衡。在配产中考虑了油田的生产时效——即考虑由于作业因素造成的无效生产时间，如年度地面设施保养（包括检查、维修和检测）而关井停产的时间。项目还需要 8 口水源井（从当地浅水层获取水源）和 19 口边缘注水井（注入油田产出水和外部供给水）以保持油藏压力与注采平衡。另外，项目还包含相关地面生产与注入设施，以及输送管线。根据已确定的开发方案、产量剖面、所需初始投资（用于钻井与完井、生产管柱、地面生产和注入设施，以及管线）、未来投资（未来新钻井及其生产管柱）和项目经济生命期内的操作费，可再次确认该开发项目的经济可行性。项目获得批

was given to include the project in the company's capital budget.

The project development took 3 years to complete and bring on stream in the fourth year (or just 3 years after appraisal and 5 years after the initial discovery). First, a total of 8 water supply wells (from a shallow and large regional aquifer already proven to be productive and supporting water injection in several other fields) and 34 additional oil wells in this example oil reservoir were drilled that included three dry holes (Wells 4, 7, and 15). It was followed by drilling the 19 water injectors at the periphery. The example oil reservoir was significantly delineated by these 56 wells. The original OWC was established at 6,340 ft subsea by well logs and supported by analysis of pressure-gradient data.

Figure 4.5a represents the cross section based on the revised interpretation. Wells illustrated by dashed lines on this cross section are projected. The net pay isochore map (Figure 4.5b) was developed with NTG ratios ranging from 0.3 to 0.9 (with majority greater than 0.7) obtained from the well logs and available cores, and supported further by full production tests conducted in six more strategically placed wells. Measured stabilized well rates and estimated reservoir permeability from buildup tests had ranged from 1,500 to 5,000 BOPD, and 150 to 500 md, respectively, with overall reservoir averages estimated to be about 2,500 BOPD and 350 md.

The reservoir parameters entered for each polygon are the volume-weighted averages. Because several wells penetrated the original OWC at 6,340 ft subsea, the entire enclosure was judged to represent a single most likely OIIP estimate of about 1,430 MMSTB. Based on similar nearby analog reservoirs with minor changes in reservoir structure and average reservoir parameters (and their distributions), developing separate OIIP for each reserves category was considered unwarranted by analysts at the time. It is recognized that this may not be typical of other developments where significant uncertainty associated with in-place volumes persists into late stages of development. In all cases, uncertainty should decrease over time as the amount and quality of data improves, including periodic updates of PIIPs using performance-based methods.

It may be important to note that Figure 4.5b depicts the well requirements (in black dots) for initial development only, representing just over one-third of the total WSUs available. Additional drilling of oil producers (and a few water injectors) was carried out during the later stages of the production phase (e.g., 16 producers, not numbered but shown in hollow circles were actually drilled during the first 8 years of production) to extend the plateau production rate, to help improve volumetric sweep, and to better manage the production decline. More wells were drilled during the later stages to fully develop the reservoir.

准，列入公司投资预算计划。

该项目的产能建设期为3年，第4年投产（或评价期之后3年和首次发现之后5年）。首先，新钻了8口水源井（从区域性的浅层水源层取水——该水源层已证实水源充足，正为其他油田的注水开发提供水源）和34口油井（其中井4、7和15三口井为干井）。随后，在油藏边部完钻了19口注水井。该案例油藏通过56口井的资料得到了详细评价。测井解释和压力梯度分析表明原始油水界面为海拔深度-6340ft。

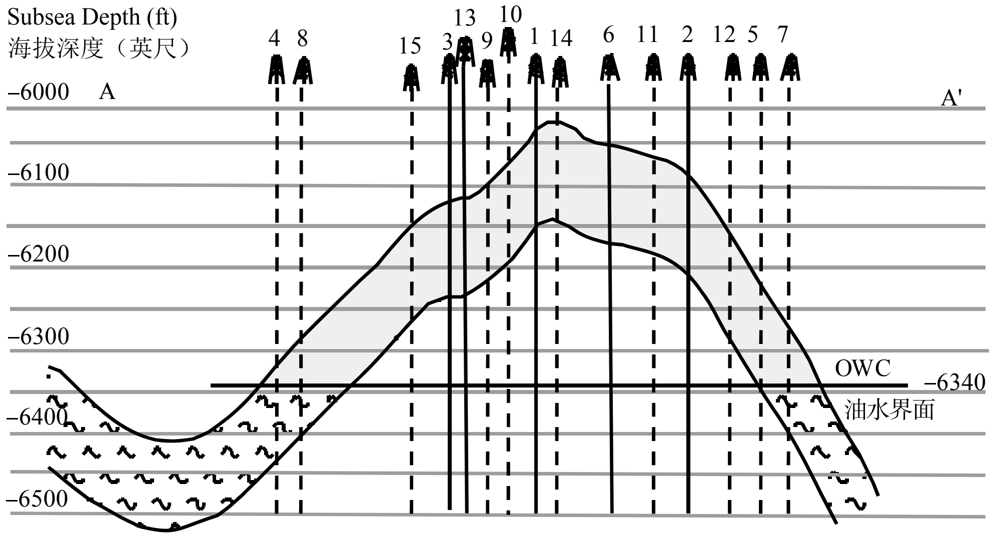
图4.5a是根据新解释结果绘制的油藏剖面图。图中虚线代表井的投影线。储层有效厚度等值线图（图4.5b）是根据测井解释、岩心分析和6口关键井生产测试结果绘制的，其净毛比范围为0.3～0.9（多数大于0.7）。依据压力恢复试井解释结果，单井稳定产量为1500~5000BOPD，有效渗透率150～500mD；油藏平均单井日产量为2500BOPD，平均渗透率为350mD。

绘制等值线的油藏参数是经体积加权的平均值。由于几口井钻遇的油水界面深度均为海拔深度-6340ft，所以整个圈闭的石油原始原地量调整为单一最可能估值1430MMSTB。基于邻近类比油藏的构造和油藏参数（及其分布）变化不大，评估师认为此时为不同级别储量分别确定单独的原始原地量依据不足。但这对于开发后期原地量仍存在较大不确定性的项目而言，不具备代表性。总之，随着项目生命期内数据信息的数量增加及品质提高，不确定性应该不断减小，可采用的途径包括动态法阶段性更新石油原始原地量。

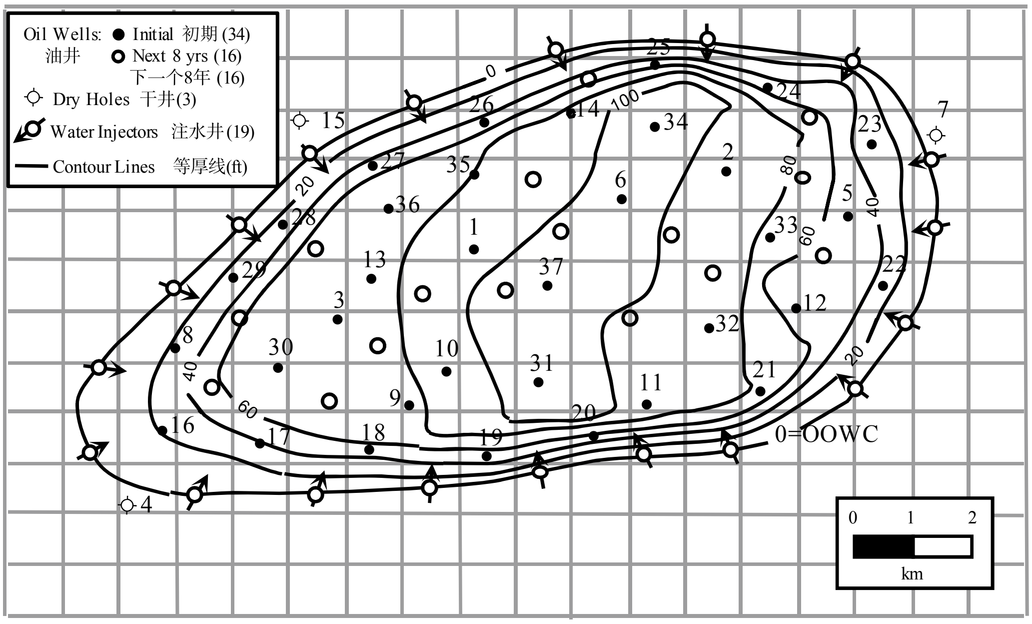
值得注意的是，图4.5b绘出的只是项目开发初期的生产井位（黑点），仅占了总井距单元的三分之一。在稳产期的后期，补钻了生产井（和少量注水井）——如16口油井（未标井号的空心圆点，钻于油藏生产的第一个8年期间），以维持高峰产量，提高体积波及效率，延缓产量递减。后期，又钻了更多井以全面开发该油藏。

As compared with its appraisal stage, the reservoir was significantly delineated, and analyses of an additional 31 productive oil well logs and tests indicated a better average reservoir quality than that seen in analogs. Thus, the recovery efficiencies for all reserves categories were increased modestly by 5% OIIP from their respective levels in the appraisal phase, bringing the high estimate to 50% OIIP. However, these estimates would be revised in future re-assessment studies as additional production data was obtained and new wells were drilled.

与评价阶段相比，该油藏在开发初期得到了充分地评价，31 口井的测井及测试资料显示，该油藏的品质好于类比油藏。因此，各级别储量的采收率比评价期适度提升 5%，高估值情景达到了石油原始原地量的 50%。当然，随着生产数据和新井数量的增加，该估值还将在后续评估中进一步修正。



a． Structural Cross Section AA' (not to scale horizontally) 油藏剖面图AA'（水平方向无比例）



b． Net pay isochore map and depiction of wells for initial development plan and beyond
油层等厚图及初始开发方案和后期开发方案井位部署图

Figure 4.5　Volumetric assessment of Reserves (initial development stage).
图 4.5　容积法评估储量（开发初期）

Reservoir average rock and PVT data were revised and documented in Table 4.4. With the revised OIIP (1,429.6 MMSTB) and increased reserves, the initial plateau production rate of 75,000 BOPD represented an annual depletion rate of only 4.3% of 2P reserves.

Analysis of six additional well tests and several single-well simulation studies have further supported the validity of 1 km^2 (or about 250 acres) average well spacing. There were approximately 98 1-sq-km WSUs in the area described by the original OWC. Although wells were not necessarily drilled in the center of each WSU (Figure 4.5b), about 35 WSUs (or about 36% of total) may be allocated to the Proved Developed (PD) reserves status. Therefore, under PRMS guidelines and as described in the Appraisal Stage earlier, based on the developed OIIP portion of 514.7 MMSTB (refer to Table 4.4), 25.7 MMSTB (= 514.7 ×0.05) oil and 14.7 Bscf raw gas from the recoverable volumes assigned to both 2P and 3P can be allocated to Developed status in Table 4.4, but were not shown separately here to keep the table as simple as possible.

Finally, the example oil project's EOR potential is supported by the results of a miscible CO_2 pilot project from an analog reservoir with incremental recovery of 20% OIIP. Based on the same single project OIIP estimate, three categories of Contingent Resources were assigned for this potential project using conservative incremental recovery efficiencies of 5%, 10%, and 15% OIIP and summarized in Table 4.5.

4.2.2.3 Use of Geocellular Models in Estimating Petroleum In-Place Volumes

While not illustrated in this particular example oil recovery project, given the 3D seismic and early well control, conventional geologic mapping is often supplemented by 3D geologic modeling. Advances in computer technology have facilitated the widespread applications in building multimillion-cell digital geocellular models populated cell by cell with the static geological, geophysical, petrophysical, and engineering data characterizing the subsurface reservoir structure in 3D, similar to the depiction in Figure 4.6.

In a gridded mapping process, the parameters in the original hydrocarbon in-place (OHIP) equation change from cell to cell, and the total OHIP is obtained by the sum of the individual values assigned to, calculated for, and/or matched for each cell. Based on early well performance, modifications to the development program including supplemental secondary and enhanced recovery projects can be designed using streamline and/or finite-difference simulation models with such multimillion-cell reservoir characterization models, including several cases of "what-if" scenarios represented by different plausible realizations. However, refinement and verification of these large geocellular models with actual analogs and thus the degree of certainty in the resulting estimates to a large extent is dependent on both the quantity and quality of geoscience, engineering, and, more importantly, the performance data.

表4.4列出了更新后的油藏岩石和PVT参数。原油原始原地量修正为1429.6MMSTB，使储量有所增加，初始高峰产量75,000BOPD对应的2P储量年度采油速度仅为4.3%。

6口井的新测试分析和几口单井数值模拟研究成果进一步证明了平均单井控制面积为1km^2（约250acre）是合理的。在原始油水界面圈定的含油面积范围内，约有98个井控单元。尽管35口已钻井无需也未钻于井控单元中心位置（图4.5b），其储量（约占总量36%）状态仍可划归为证实已开发（PD）。因此，根据PRMS规则和前面评价阶段所述，基于已开发动用原始原地量514.7MMSTB（参见表4.4）的2P与3P原油最终可采量25.7MMSTB（=514.7×0.05）和原料气最终可采量14.7Bscf可核定为已开发状态。但为了尽量简洁，表4.4未单独列出这一内容。

最后，依据类比油藏实施CO_2混相驱先导性试验成功提高采收率20%，支撑了该案例油藏提高采收率的潜力。基于相同单一开发项目的原油原始原地量估值，潜在提高采收率项目所对应的三个级别条件资源量可保守依据原始原地量的采收率增量5%、10%和15%来分别估算，参见表4.5。

4.2.2.3 地质建模估算石油原地量

虽然该原油开发项目案例介绍地质建模技术的应用，但若有三维地震数据和早期的控制井资料，三维地质建模通常可用于辅助常规地质制图。受益于计算机技术的发展，数百万网格节点的数值建模技术已广泛应用。模型中每个网格节点包含了油藏三维构造层面的静态地质、地球物理、岩石物理和工程数据的代表值，如图4.6所示。

在网格化过程中，烃原始原地量计算公式的参数在每个网格结点都产生变化，总原始原地量由单个网格结点匹配、计算和/或拟合的数据进行加合。结合早期生产动态，可在百万结点地质模型基础上，利用流线模拟和/或有限差分数值模拟调整开发方案，包括设计二次采油与提高采收率补充方案和进行不同假设条件的情景分析。当然，用实际类比油藏细化和论证这些大型地质模型及其评估结果的不确定性，可靠性很大程度上取决于地质、工程和更重要的生产动态资料的数量与质量。

Table 4.4 Volumetric Assessment of Reserves (Initial Development Stage): Estimates of Project PIIPs and EURs
表 4.4 容积法评估储量（开发初期）：项目石油原始原地量和估算最终可采量

Estimated Parameters 估算参数	Units 单位	Bases and Reserves by Category and Status 基础数据和储量的级别与状态				
		Proved 证实	Reserves Status 储量状态		Best Estimate 最佳估值	High Estimate 高估值
		Low Estimate 低估值	Proved Developed (PD) 证实已开发	Proved Undeveioped (PUD) 证实未开发		
Bulk Reservoir Pay Volume 储层总体积	M ac·ft	1523.3	548.4	974.9		
Average Porosity 平均孔隙度	%	19.0	19.0	19.0		
Pore Volume（PV） 孔隙体积	M ac·ft	289.4	104.2	185.2		
Average Initial Water Saturation 平均原始含水饱和度	%	15.0	15.0	15.0		
Hydrocarbon Pore Volume（HCPV） 烃孔隙体积	M ac·ft	246.0	88.6	157.4		
Average FVF（B_{oi}） 平均原始地层体积系数	RB/STB	1.335	1.335	1.335		
Oil Initially-In-Place（OIIP） 原油原始原地量	MMSTB[1]	1429.6	514.7	915.0	1429.6	1429.6
Recovery Factor[2] 采收率	%(OIIP)	40	40	40	45	50
Recoverable Oil（EUR）[4] 原油估算最终可采量	MMSTB	571.9	205.9	366.0	643.3	714.8
Initial Solution Gas-Oil Ratio (R_{si}) 原始溶解气油比	scf/STB	570	570	570	570	570
Gross-Heationg Value of Raw Solution Gas 溶解气总热值	Btu/scf	1350	1350	1350	1350	1350
Gas Initially-In-Place（GIIP） 天然气原始原地量	Bscf	814.9	293.4	521.5	814.9	814.9
Recoverable Raw Gas（EUR）[4] 原料气估算最终可采量	Bscf	326.0	117.3	208.6	366.7	407.4
	MMBOE[3]	75.9	27.3	48.6	85.4	94.8

[1] Calculated by using the conversion factor of 7,758 bbl/acre-ft.
使用转换系数 7758bbl/acre•ft 进行计算。

[2] Under peripheral water injection, already well-established in several nearby analog reservoirs and projects.
采用边缘注水，该开发方式已在邻近类比油藏和项目成熟应用。

[3] Calculated using an average conversion factor of 5.8 MMBtu per BOE.
使用平均转换系数 5.8MMBtu/BOE 进行计算。

[4] Estimated oil and gas Reserves categories of 1P, 2P and 3P, respectively.
原油和天然气 1P、2P 和 3P 储量估值。

Table 4.5 Volumetric Assessment of Contingent Resources (Initial Development Stage): Estimates of Project EURs
表 4.5 容积法评估条件资源量（开发初期）：项目估算最终可采量

Estimated Parameters 估算参数	单位 Units	Bases and Categories of Contingent Resources 基础数据和条件资源量		
		Low Estimate 低估值	Best Estimate 最佳估值	High Estimate 高估值
Oil Initially-In-Place（OIIP） 原油原始原地量	MMSTB	1429.6	1429.6	1429.6
Incremental Recovery Factor [1] 提高采收率	% (OIIP)	5	10	15
Recoverable Oil（EUR）[3] 原油估算最终可采量	MMSTB	71.5	143.0	214.4
Initial Solution Gas-Oil Ratio（R_{si}） 原始溶解气油比	scf/STB	570	570	570
Gross—Heationg Value of Raw Solution Gas 溶解气总热值	Btu/scf	1350	1350	1350
Gas Initially-In-Place（GIIP） 天然气原始原地量	Bscf	814.9	814.9	814.9
Recoverable Raw Gas（EUR）[3] 原料气估算最终可采量	Bscf	40.7	81.5	122.2
	MMBOE[2]	9.5	19.0	28.5

[1] Under a CO_2 Miscible Flood based on the results of an already implemented nearby analog CO_2 pilot project.
CO_2 混相驱，类比邻近已实施 CO_2 混相驱先导试验结果。

[2] Calculated using an average conversion factor of 5.8 MMBtu per BOE.
使用平均转换系数 5.8MMBtu/BOE 进行计算。

[3] Estimated Oil and Gas Contingent Resources categories of 1C, 2C and 3C, respectively.
原油和天然气的 1C、2C 和 3C 条件资源量估值。

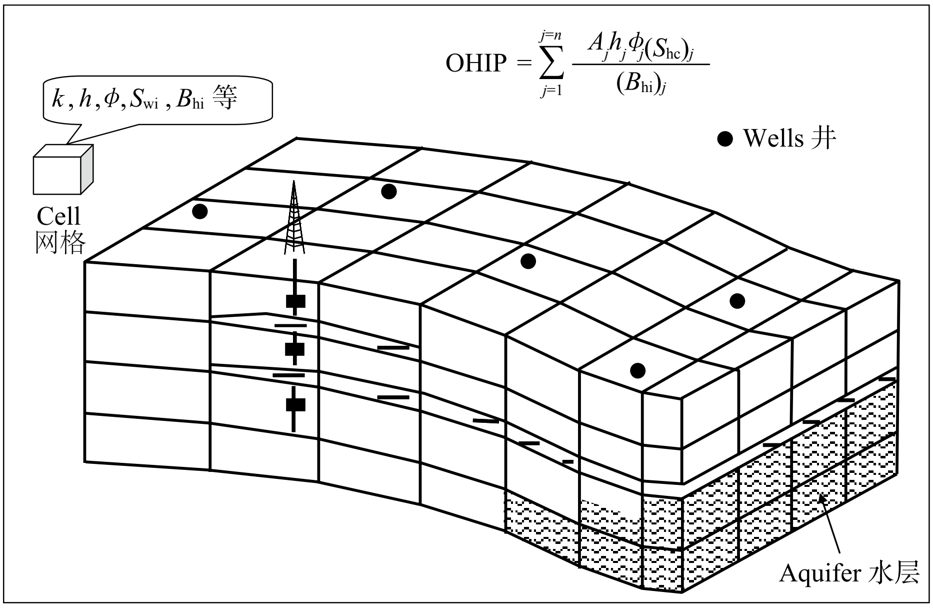


Figure 4.6 3D Multi-cell Geological Model [adapted from PS-CIM (2004)]
图 4.6 三维多节点地质模型 [摘自 PS-CIM,（2004）]

4.2.3 Performance-Based Methods

As illustrated in Figure 4.1, the Production Phase can be divided into three producing stages (or periods) of Early Time (IIa), Late Time (IIb), and Decline (IIc), which show the increasing project maturity and changing of applicable resources assessment methods over time. Depending on the amount and quality of historical pressure, production and other reservoir performance data available, a combination of reservoir simulation, material balance, and production performance trend (PPT) analysis (or decline curve analysis) can be used not only to directly estimate the recoverable petroleum, but also the petroleum in-place quantities (by the first two methods only), and thereby provide a useful second check and validation of estimates obtained earlier by volumetric methods.

4.2.3.1 Material Balance Methods

Material balance methods are part of performance-based dynamic analyses. The performance data include production and injection profiles, volume-weighted average reservoir pressures, and reservoir-specific relevant fluid and rock properties (c_o, c_g and c_w; B_o, B_g, R_s, R_v, and B_w) all as a function of reservoir pressure and temperature. Independent of the volumetric methods, the material balance methods can be used to directly and simultaneously estimate PIIP, the size of its gas-cap (m), or its in-place volume (gas cap initially-in-place (GCIIP)), and/or the water influx (W_e). The results of material balance analysis are considered more reliable with longer performance histories and high-quality production data, both measured and interpreted. A well-established and reasonable assumption is that use of the material balance analysis to estimate PIIP is often considered valid if the cumulative production exceeds 10% PIIP providing the development of the accumulation is such that the pressures used in the analysis represent an average over the entire reservoir. Uncertainty in the estimate is expected to decrease over time as historical production performance data cover at least the early production period (IIa) and beyond.

4.2.3.1.1 Application to Example Oil Project in Its Early-Production Stage

(1) Technical Principles.

Technical principles and definition of terms involved in developing the conventional material balance equation (MBE) applicable to any oil and gas reservoir (i.e., black or volatile oil and retrograde or nonretrograde gas) and applications may be found in Walsh and Lake (2003), and Towler (2002). Modern flowing and dynamic material balance analyses developed by Mattar and McNeil (1998) and Mattar and Anderson (2005) may also be used.

4.2.3 动态法

如图 4.1 所示，油藏的生产期可以划分为三个阶段：稳产早期（Ⅱ a）、稳产后期（Ⅱ b）和递减期（Ⅱ c）。图中，项目成熟度随时间增加，评估适用的方法也相应变化。基于油藏历史压力、产量和其他动态资料的数量与质量，综合应用数值模拟、物质平衡和生产动态趋势 (PPT) 分析 (或递减曲线分析）等方法，不仅可以直接估算可采量，还可以估算石油原地量（仅限前两种方法），因而可对前期容积法的评估结果进行二次校验和确认。

4.2.3.1 物质平衡法

物质平衡法是生产动态分析方法之一。生产动态数据，包括产量和注水剖面、油藏体积加权平均压力、油藏流体和岩石性质（c_o，c_g，c_w；B_o，B_g，R_s，R_v 和 B_w）等，均为压力和温度的函数。不受容积法评估影响，物质平衡法可同时直接估算石油原始原地量（PIIP）、气顶大小（m）或气顶原始原地量 (GCIIP)，和 / 或水侵量（W_e）。在生产动态历史较长和生产数据计量与解释质量好的情形下，物质平衡方法的分析结果更为可靠。通常认为，当石油原始原地量的采出程度超过 10% 时，应用物质平衡法来估算原始原地量是有效的。物质平衡分析所采用的压力为整个油藏的平均压力；当生产历史数据至少跨越稳产早期（IIa）和后续阶段时，评估结果的不确定性会随着时间不断减小。

4.2.3.1.1 原油项目稳产早期的应用

（1）技术原理

有关各种油气藏（如黑油或挥发油，以及反凝析气或非反凝析气）适用常规物质平衡方程 (MBE) 的技术原理与术语定义，以及相关应用可以在 Walsh 与 Lake（2003）和 Towler（2002）的文献中找到。也可以采用 Mattar 和 McNeil(1998) 以及 Mattar 和 Anderson（2005）所建立的现代渗流和动态物质平衡分析方法。

本案例项目为一黑油油藏，原始状态未饱和

The example oil project represents a black-oil reservoir, initially undersaturated (i.e., no gas cap) with partially active water influx, which was developed by peripheral down-dip water injection to supplement reservoir energy and to help maintain a constant reservoir pressure 100 to 200 psia above the bubblepoint pressure. Furthermore, above the bubblepoint ($R_s = R_{si} = R_p$), all gas produced at the surface would be dissolved in the oil. The straight line Havlena-Odeh-type (Havlena and Odeh 1963 and 1964) MBE for this particular case can be written as

$$F_p = N[(B_o-B_{oi})+((c_wS_{wi}+c_f)/S_{oi})\Delta pB_{oi}]+(W_e + W_{inj}B_w) \qquad (4.2)$$

It can be further simplified and re-written in terms of effective reservoir compressibility (c_e) as follows:

$$F_p = N(B_{oi}\, c_e\, \Delta P) \;=\; (W_e + W_{inj}B_w) \qquad (4.3)$$

where the variables and terms given are defined by the following relationships:

① Left side of Eq. 4.3 represents cumulative net reservoir withdrawal (F_p) defined by

$$F_p = N_pB_{oi} + W_p\, B_w \qquad (4.3a)$$

② Right side of E_q. 4.3 represents cumulative net reservoir expansion terms (E_p) and the water influx (W_e), which is given in terms of the van Everdingen and Hurst (1949) unsteady solution by

$$W_e=U\sum_{j=0}^{k=1}\Delta p_{j+1}\, W_D(r_D,\Delta t_{Dj}) \qquad (4.3b)$$

where j = 0 indicates initial reservoir conditions when $P_i = P_0$ and k = 1, 2,…., n and n is the number of time intervals for which the historical pressure, production, and injection data are available.

The effective, saturation-weighted compressibility of the reservoir system (oil, water, and the formation or reservoir rock pore volume) in Eq. 4.3 is defined by

$$c_e = (c_oS_{oi} + c_w\, S_{wi} + c_f)/S_{oi} \qquad (4.3c)$$

Eq. 4.3 can also be re-arranged as

$$F_p/(B_{oi}\, c_e\Delta p)=N+\left[W_e+W_{inj}B_w\right]/(B_{oi}c_e\Delta p) \qquad (4.4)$$

This MBE represents reservoir depletion under a combined waterdrive (i.e., water influx and/or down-dip water injection into the aquifer) that is effective and strong enough to maintain average reservoir pressure above the bubblepoint pressure. Because water is injected into the aquifer at the periphery, it is treated as part of the water aquifer irrespective of how much of the water actually enters the oil zone and helps displace oil or how much of it enters the aquifer.

Eq. 4.4 suggests that a plot of the left-hand side vs. the second term of the right-hand side should yield a straight line of unit slope intercepting the ordinate at N (or OIIP). Data necessary for this plot can be generated at each timestep as follows: At any time period with an

（即无气顶），部分区域水侵活跃，在下倾方向采用边缘注水开发以补充油藏能量，保持油藏压力稳定在泡点压力以上 100 ～ 200psi。另外，在泡点压力 (R_s=R_{si}=R_p) 之上，地面的产出气均为原油溶解气。该案例采用的 Havlena-Odeh 直线物质平衡方程 (Havlena 与 Odeh，1963 和 1964) 如下：

$$F_p = N[(B_o-B_{oi})+((c_wS_{wi}+c_f)/S_{oi})\Delta pB_{oi}]+(W_e + W_{inj}B_w) \qquad (4.2)$$

用油藏有效压缩系数 (c_e)，该方程可进一步简化为：

$$F_p = N(B_{oi}\, c_e\, \Delta P) \;=\; (W_e + W_{inj}B_w) \qquad (4.3)$$

其中，变量和术语由以下关系式确定：

①方程式 4.3 左边是油藏累计净采出量 (F_p)，由 4.3a 确定。

$$F_p = N_pB_{oi} + W_p\, B_w \qquad (4.3a)$$

②方程式 4.3 右边为油藏累计净膨胀量 (E_p) 和水侵量 (W_e)，可根据 van Everdingen 和 Hurst(1949) 的非稳态流水侵量计算方法求解：

$$W_e=U\sum_{j=0}^{k=1}\Delta p_{j+1}\, W_D(r_D,\Delta t_{Dj}) \qquad (4.3b)$$

式中：j=0 表示 P_i=P_0 时的原始油藏条件，k=1, 2, …, n，n 为有压力、产量和注入量历史数据的时间段数量。

式 4.3 中，油藏系统（油、水和储层或油藏岩石孔隙体积）的饱和度加权有效压缩率由下式计算：

$$c_e = (c_oS_{oi} + c_w\, S_{wi} + c_f)/S_{oi} \qquad (4.3c)$$

式 4.3 还可改写为：

$$F_p/(B_{oi}\, c_e\Delta p)=N+\left[W_e+W_{inj}B_w\right]/(B_{oi}c_e\Delta p) \qquad (4.4)$$

该物质平衡方程描述了油藏采用复合水驱的开发过程（天然水侵或下倾方向边缘注水）。复合水驱是有效的，足以维持油藏的压力高于泡点压力。由于是在油藏边部的水体注水，注入水被视为水层的一部分，不管实际上有多少水进入了油层有利于驱油或注进了水层。

用方程式 4.4 左边与右边第二项作图可生成一条直线，其在 Y 轴上的截距为 N（或原油原始原地量 OIIP）。绘制此图所需的数据可按以下步骤计算：对任一时间段压差Δp，① F_p、c_e 可采

appropriate Δp, (1) the F_p, c_e data can be calculated using the relevant relationships and measured production and injection data, (2) the unsteady-state water influx theory of van Everdingen and Hurst (1949) may be used to estimate dimensionless influx rates (W_D), and (3) Eq. 4.3b can be used to calculate water influx (W_e).

(2) Application

The oil reservoir evaluated in this application example is a prolific carbonate reservoir with undersaturated oil, developed and producing with very effective down-dip water injection that has maintained the reservoir pressure over the bubblepoint. An additional 16 new oil producers and one water injector were also drilled during this 8-year production period (bringing the total to 50 and 20 wells, respectively) to maintain plateau rate and help improve overall recovery efficiency. The project produced 220.8 MMSTB of oil (15.4% OIIP of 1,429.6 MMSTB estimated and reported earlier in Table 4.4), 126 Bscf of solution gas and 80 MMSTB of water and injected 385 MMSTB of produced and supply water into the aquifer below the original OWC.

Based on the average reservoir pressure observed, production and injection performance data recorded over an 8-year period (the first-year data were erroneous, out of scale, and excluded), the terms in Eq. 4.4 were calculated and plotted in Figure 4.7.

用计量的产量与注入量关系式进行计算；② van Everdingen 和 Hurst（1949）的非稳态流水侵理论可用于估算无因次水侵量（W_D）；③用方程（4.3b）计算水侵量（W_e）。

（2）应用

案例油藏是一个富集的碳酸盐岩未饱和油藏，采用了非常有效的下倾边缘注水进行开发与生产，油藏压力维持在泡点压力以上。在 8 年的生产早期阶段又新钻了 16 口油井和 1 口注水井（共计 50 口油井和 20 口注水井），以维持高峰产量和提高整体采收率。项目已采出原油 220.8MMSTB（为原始原地量 1429.6MMSTB 的 15.4%，参见前面表 4.4 中估算和报告的数据）、溶解气 126Bscf，以及水 80MMSTB；在原始油水界面以下的水体中共注入了产出水和水源供给水 385MMSTB。

根据 8 年生产期监测的油藏平均压力、产量和注入量数据（第一年数据误差大，超出坐标刻度，未包含在图中），可计算得到方程式 4.4 的各项参数，并绘制图 4.7。

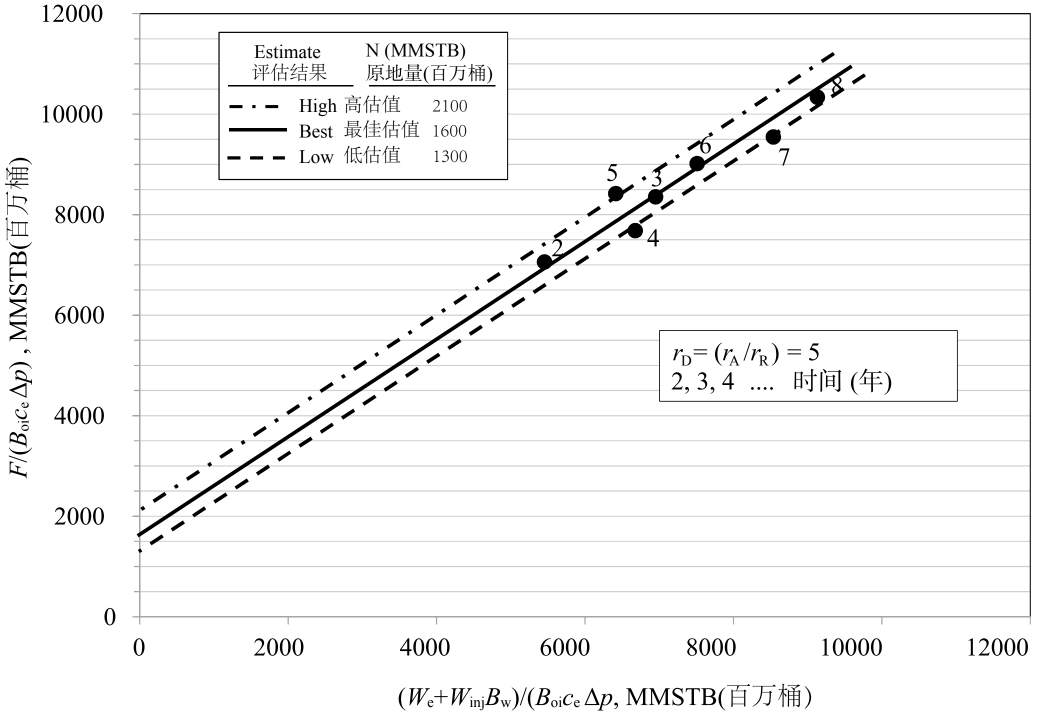


Figure 4.7　Assessment of OIIP by Material Balance Methods (Early-production Stage).
图 4.7　物质平衡法评估原油原始原地量（稳产早期阶段）

With the variations shown in the plotted data, it was possible to draw three parallel straight lines with a unit slope confirming the correct value of the dimensionless radius, $r_D= 5$ (defined as a ratio of the aquifer radius and reservoir radius) and bracketing the degree of uncertainty in the measured and interpreted data and thus the resulting estimates of in-place volumes. These minimum, most likely, and maximum interpretations of OIIP (or N) values of 1,300, 1,600, and 2,000 MMSTB were assumed to represent the low, best, and high estimates, respectively. These OIIP estimates were judged to be a valid basis for assigning 1P, 2P, and 3P Reserves categories because (1) the project produced more than 10% OIIP (or about 17% of low and 14% of best OIIP), (2) a reasonably good match was obtained in Figure 4.7 and deviations are accounted for, and (3) it was supported by a new volumetric in-place estimate of 1,567 MMSTB reported by analysts updating the old estimate (versus 1,430 MMSTB after completion of initial development) by incorporating additional data from 16 new producers drilled over this 8 years of production.

Over the past 8 years, the ongoing peripheral waterflood project confirmed similar performance to the analogs nearby and a second CO_2 pilot was also implemented showing similar initial performance to the first one already completed. However, to further ensure reasonable confidence in the estimates, the recovery efficiencies were not changed at the time and kept the same as the initial development stage 8 years earlier. Based on these low, best, and high estimates OIIPs, the respective EURs and Reserves (under the ongoing Peripheral Waterflood Project) and the Contingent Resources (under a proposed CO_2 Miscible Project) were calculated and summarized in Table 4.6.

Moreover, it was recommended that these estimates be updated in the future based on the results of new re-assessment studies expected to incorporate data from additional wells drilled and production performance data observed and recorded. It is recognized that this type of traditional material balance analysis using analytical procedures has routinely been performed by reservoir simulation studies, which are discussed next under Reservoir Simulation Methods.

4.2.3.1.2 Application to a Volumetric Gas Reservoir in Its Late Production and Early Decline

(1) Technical Principles

In volumetric gas reservoirs there is no (or insignificant) aquifer water influx, and the volume of initial HCPV will not significantly decrease and remain constant during reservoir pressure depletion. Therefore, with no adjoining aquifer or water influx ($W_e = 0$), no water production ($W_p = 0$), and injection of gas ($G_{inj} = 0$), the generalized conventional MBE for a volumetric gas reservoir reduces to (Lee and Wattenbarger 1996):

$$G_p B_g= G (E_g + B_{gi} E_w + B_{gi} E_f) \tag{4.5}$$

根据图中数据点的变化，可以作 3 条相同斜率的平行线，确认无因次半径 r_D（水体半径与油藏半径之比）的合理值为 5，从而确定对应的原地量。该方法的不确定性为产量计量和解释数据的不确定性。原油原始原地量的最小、最可能和最大估值为 1300MMSTB、1600MMSTB 和 2100MMSTB，分别对应低估值、最佳估值和高估值，它们是 1P、2P 和 3P 储量级别核定的有效基础，因为：①项目原始原地量的采出程度超过 10%（或原始原地量低估值的 17%，最佳估值的 14%）；②图 4.7 进行了合理拟合，并考虑了偏差；③与容积法新估算的原地量 1567MMSTB 吻合，该结果是评估师在开发初期估值 1430MMSTB 基础上，结合 8 年生产期内新钻的 16 口生产井数据更新估算结果所得到的。

在过去 8 年里，案例油藏持续边缘注水开发的生产动态特征和邻近类比油藏是相似的。该类比油藏正在实施第二个 CO_2 驱先导试验，其早期动态特征与已完成的第一个先导试验也是相似的。但为了进一步确保评估结果的合理可靠性，采收率在现阶段不变，仍然与 8 年前开发初期的数值保持一致。基于低估值、最佳估值和高估值的原油原始原地量，相应的估算最终可采量、储量（继续实施边缘注水项目的情形）以及条件资源量（考虑实施 CO_2 混相驱项目的情形）估算结果汇总于表 4.6。

此外，建议未来结合更多新井和生产数据进一步更新评估结果。通常，油藏模拟研究已包含这种通过解析流程进行的传统物质平衡分析。油藏模拟研究将在油气藏模拟方法一节继续讨论。

4.2.3.1.2 定容气藏稳产后期和递减早期的应用

（1）技术原理

定容气藏无水体水侵（或很小），其原始含烃孔隙体积（HCPV）不会明显减小，并在气藏的开采过程中保持不变。因此，没有毗邻水体或水侵（$W_e=0$），无产水量（$W_p=0$）和注气量（$G_{inj}=0$），定容气藏的广义常规物质平衡方程（Lee 和 Wattenbarger，1996）如下：

$$G_p B_g= G (E_g + B_{gi} E_w + B_{gi} E_f) \tag{4.5}$$

Table 4.6　Assessment using Material Balance Methods (Early-Production Stage):
Estimates of Project PIIPs, EURs, Reserves and Contingent Resources
表 4.6　物质平衡法评估（稳产早期）：项目石油原始原地量、估算最终可采量、储量和条件资源量

Measured and Estimated Parameters 计量和估算参数		Units 单位	Bases and Estimates by Reserves Category 基础数据和各级储量		
			Low Estimate 低估值	Best Estimate 最佳估值	High Estimate 高估值
Cumulative Production 累计产量	Oil 原油	MMSTB	220.8	220.8	220.8
	Raw Gas 原料气	% (OIIP)	17.0	13.8	11.0
		Bscf	125.9	125.9	125.9
Oil Initially-In-Place (OIIP) 原油原始原地量		MMSTB	1300	1600	2000
Recovery Factor[1] 采收率		% (OIIP)	40	45	50
Recoverable Oil（EUR）原油估算最终可采量	Original 原始	MMSTB	520.0	720.0	1000.0
	Remaining[4] 剩余	MMSTB	299.2	499.2	779.2
Initial Solution Gas-Oil Ratio（R_{si}）原始溶解气油比		scf/STB	570	570	570
Gross-Heationg Value of Raw Solution Gas 溶解气总热值		Btu/scf	1350	1350	1350
Gas Initially-In-Place（GIIP）溶解气原始原地量		Bscf	741	912.0	1140.0
Recoverable Raw Gas（EUR）原料气估算最终可采量	Original 原始	Bscf	296.4	410.4	570.0
		MMBOE[2]	69.0	95.5	132.7
	Remaining[4] 剩余	Bscf	170.5	284.5	444.1
		MMBOE[2]	39.7	66.2	103.4
			Bases and estimates by Contingent Resources Category 基础数据和 各级条件资源量		
			Low Estimate 低估值	Best Estimate 最佳估值	High Estimate 高估值
Incremental Recovery Factor [3] 提高采收率		% (OIIP)	5	10	15
Recoverable Oil（EUR）[4] 原油估算最终可采量		MMSTB	65.0	160.0	300
Recoverable Raw Gas（EUR）[4] 原料气估算最终可采量		Bscf	37.1	91.2	171.0
		MMBOE[2]	8.6	21.2	39.8

[1] Under peripheral water injection scheme that maintains reservoir pressure above the bubble point.
边缘注水开发，油藏压力保持在泡点压力之上。

[2] Calculated using an average conversion factor of 5.8 MMBtu per BOE.
使用平均转换系数 5.8MMBtu/BOE 进行计算。

[3] Under a CO_2 Miscible Flood based on the results of one CO_2 pilot already implemented and a positive response from a second pilot being applied in another nearby analog reservoir.
CO_2 混相驱开发，基于邻区一个已实施的 CO_2 先导试验类比项目结果，以及第二个先导试验获得的良好反应。

[4] Estimated oil and gas Reserves categories of 1P, 2P and 3P and Contingent Resources of 1C,2C and 3C.
原油和天然气 1P、2P 和 3P 储量估值，以及 1C、2C 和 3C 条件资源量估值。

Except for the special case of abnormally pressured gas reservoirs, relative to significantly high gas compressibility (or c_g approximately equal to the inverse of reservoir pressure), the formation water (E_w) and formation or pore-volume compression (E_f) terms can be neglected because $E_g >> (B_{gi} E_w + B_{gi} E_f)$, and the Eq. 4.5 will further reduce to:

$$G_p B_g = G E_g = G (B_g - B_{gi}) \quad (4.6)$$

and the gas formation factor (B_g) can be calculated using

$$B_g = 5.0435(10^{-3})zT/p, \text{ in RB/scf; or } = 2.8269(10^{-2})zT/p, \text{ in Rcf/scf} \quad (4.6a)$$

where standard surface pressure (p_{sc}) and temperature (T_{sc}) conditions are 14.7 psia and 60°F.

It is common practice to express this relationship in terms of average reservoir pressure by combining Eqs. 4.6 and 4.6a and rearranging to yield this well-known material balance equation applicable only to volumetric gas reservoirs:

$$(p/z) = (p_i / z_i) - [(p_i / z_i)/G]G_p \quad (4.7)$$

Where

p_i, p = average reservoir pressure (psia) at reservoir datum and “i” stands for initial,

T = average reservoir temperature at reservoir datum (°F),

z_i and z = gas compressibility factors evaluated at p_i and T_i and any p and T, respectively,

G = GIIP (scf), and

G_p = cumulative gas production (scf) at any reservoir pressure (p).

Eq. 4.7 simply asserts that in volumetric gas reservoirs, the gas production, and therefore the ultimate recovery under natural pressure depletion is a direct function of the expansion of the free gas initially-in-place. The lower the economic limit (or abandonment pressure), the higher the EUR. Furthermore, Eq. 4.7 suggests that a plot of (p/z) vs. G_p should yield a straight line with an intercept (p_i / z_i) and a slope of $[-(p_i / z_i)/G]$ from which the GIIP = G and EUR at the economic limit (p/z) can be estimated.

(2) Application to Example Gas Project.

A deep carbonate, normally-pressured and volumetric reservoir with wet gas has been on production for the past 22 years and produced about 316 Bscf of raw natural gas and 9 MMSTB of condensate. Based on several analog onshore projects producing from the same formation in different nearby gas fields, it has been determined that the gas exhibits borderline retrograde behavior. However, several laboratory tests and compositional model study results verified that condensate dropout in the reservoir during depletion drive below dewpoint pressure is not significant enough to justify gas cycling. This minor loss has been reflected by the use of lower condensate recovery confirmed by the analogs. The measured initial condensate gas ratio (CGR_i) of 30 STB/MMscf was confirmed during production above its reservoir dewpoint

除异常高压气藏这一特殊情况外，相对于很高的天然气压缩系数（或 c_g，近似等于油藏压力的倒数），地层水压缩性（E_w）和地层或孔隙体积的压缩性（E_f）可忽略不计，因为 $E_g >> (B_{gi} E_w + B_{gi} E_f)$，则方程（4.5）可进一步简化为：

$$G_p B_g = G E_g = G (B_g - B_{gi}) \quad (4.6)$$

天然气地层体积系数 (B_g) 由下式计算：

$$B_g = 5.0435\times10^{-3}zT/p，\text{(RB/scf)}$$

$$[\text{或} = 2.8269\times10^{-2}zT/p，\text{(Rcf/scf)}] \quad (4.6a)$$

其中标准地面压力（p_{sc}）和温度（T_{sc}）分别为 14.7psia 和 60 ℉。

通常，将方程（4.6）和方程（4.6a）合并，用气藏平均压力来表达物质平衡方程：

$$(p/z) = (p_i/z_i) - [(p_i/z_i)/G]G_p \quad (4.7)$$

式中 p_i，p—基准深度平均气藏压力（psia），i 代表原始值；

T—基准深度平均气藏温度（° F）；

z_i 和 z—在 p_i 和 T_i 以及任意 P 和 T 条件下的天然气偏差因子；

G—GIIP，天然气原始原地量（scf）；

G_p—任意气藏压力 (p) 对应的累计产气量（scf）。

根据方程（4.7）可简单判定，定容天然气藏衰竭开采的产量（以及最终可采量）是游离气原始原地量膨胀状态的直接函数。气藏的经济极限（或废弃压力）越低，最终可采量就越高。另外，方程（4.7）提示了（p/z）和 G_p 呈直线关系，截距为（p_i/z_i），斜率为 $[-(p_i/z_i)/G]$。根据该图版，则可估算经济极限 (p/z) 条件下的原始原地量 (G) 和估算最终可采量（EUR）。

（2）天然气项目应用案例

某碳酸盐岩定容湿气藏，埋藏深、正常压力系统，投产 22 年，累计生产天然气量 316Bscf、凝析油 9MMSTB。经类比邻近不同气田中储层相同的在产陆上项目，可确定该气藏具有临界反凝析特征。然而，实验室测试分析和组分模型研究结果表明，该气藏在低于露点压力的衰竭开采过程中凝析油的析出不明显，不足以支撑循环注气的必要性。类比气藏证实了凝析油的采收率低，损失不大。经测试，原始凝析油气比（CGR_i）为 30STB/MMscf，该数据在高于露点压力的生产过

pressure, declining only to 27 STB/MMscf at a reservoir pressure of about 5,500 psia (compared to 7,000 psia initial). The small loss was taken into account by the use of a lower condensate recovery efficiency confirmed by the analogs.

Figure 4.8 depicts the p/z vs. G_p performance plots for this example wet-gas reservoir. Because of variations in the observed data under pressure depletion, it was possible to draw three different straight lines bracketing the potential degree of uncertainty in the measurement and interpretation of the historical data. These minimum, most likely, and maximum interpretations of GIIP estimates from Figure 4.8 were judged to represent the valid basis for assigning different reserves categories of 1P, 2P, and 3P, respectively, based on an estimated (p/z) economic limit of 1,500 psia. The resulting implied volumetric recovery efficiency is calculated to be about 75 to 76% of GIIP. Estimates are further supported by and considered reasonable because (1) the reservoir has been established to be volumetric with nonretrograde gas, (2) it is fully delineated and developed with a best estimate GIIP of 1,800 Bscf using volumetric methods, (3) it has already produced 316.2 Bscf, which is more than 17.6% of this volumetric GIIP or 21.1% of the low GIIP estimate from Figure 4.8, and (4) the project economics based on these three different scenarios are all determined to be viable with discounted cash flow rates of return (DCF-RORs) exceeding 20%. The reserves status is considered Developed.

程中得以证实；当气藏压力降至5500psia（原始压力为7000psia）时，凝析油气比仅降至27STB/MMscf。这一部分小损失在选用类比气藏较低凝析油采收率时已有所考虑。

图4.8绘制了该湿气藏p/z和G_p动态关系图。根据压力衰竭过程的监测的数据变化情况，可绘制3条不同直线，以体现历史数据在计量和解释过程中的不确定性程度。由图4.8可估算天然气原始原地量的最小、最可能和最大估值，分别作为经济极限压力（1500psia）下1P、2P和3P储量估算的基础。基于上述估算结果，意味着定容开采的采收率约为原始原地量（GIIP）的75%～76%。该评估结果认为是合理的，并得到进一步支持，因为①该气藏已确认为非反凝析定容气藏；②该气藏已全面评价并开发，容积法估算其原始原地量的最佳估值为1800Bscf；③已累计产气316.2Bscf，超过容积法原始原地量的17.6%，或图4.8获得的原始原地量低估值的21.1%；以及④三种不同情景的项目经济评价均可行，其贴现现金流收益率（DCF-ROR）均超过20%。储量的状态为已开发。

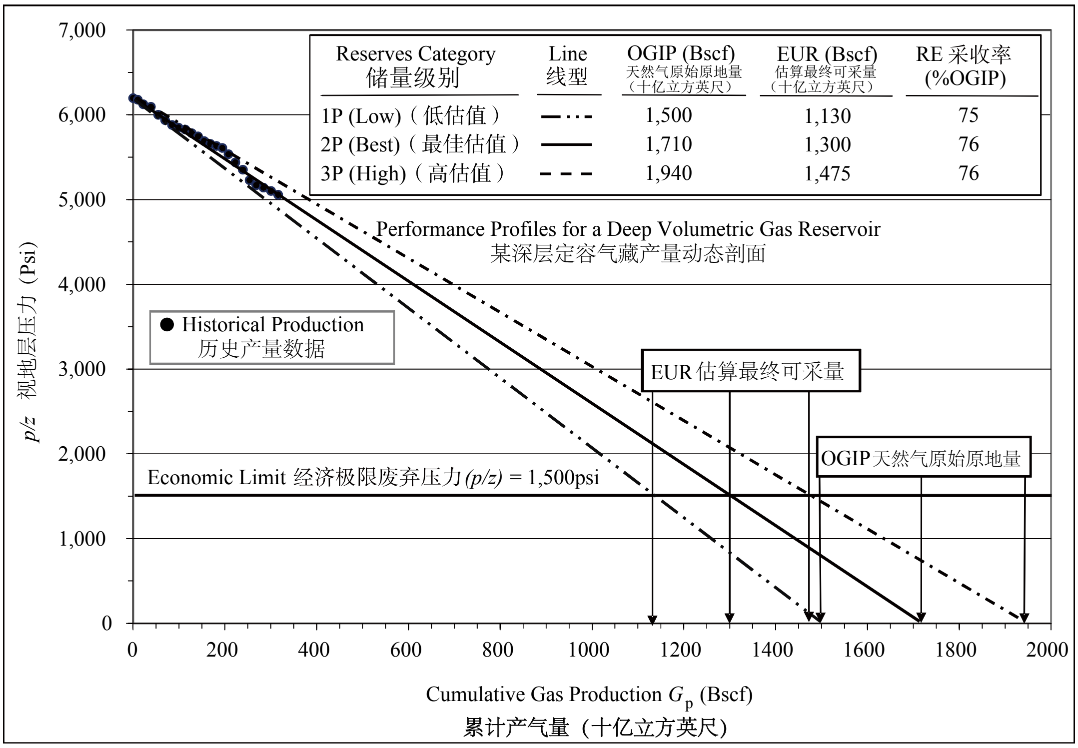


Figure 4.8　Gas reserves assessment by material balance methods (Late-Production Stage).
图4.8　物质平衡法评估天然气储量（稳产后期）

Based on the initial condensate gas ratio (CGR_i) of 30 STB/MMscf raw gas (with a gross heating value of 1,100 Btu/scf) and a recovery factor of 60% original condensate in-place (OCIP) from the nearby analog reservoirs, the in-place and reserves estimates for this gas

根据原始凝析油气比 CGR_i 数值 30STB/MMscf（总热值为 1100Btu/scf），邻近类比气藏凝析油采收率 60%（OCIP），该气藏的原地量和储量评估结果汇总于表 4.7。请注意，表中的原

Table 4.7 Gas Reserves Assessment by Material Balance Methods (Late-Production Stage): Estimates of Project GIIPs, CIIPs, EURs and Reserves

表 4.7 物质平衡法评估天然气储量（稳产后期）：天然气原始原地量、凝析油原始原地量、最终可采量和储量

Measured and Estimated Parameters 计量和估算参数		Units 单位	Bases and Estimates by Reserves Category 基础数据和储量		
			Low Estimate 低估值	Best Estimate 最佳估值	High Estimate 高估值
Cumulative Production 累计产量	Raw Gas 原料气	Bscf	316.2	316.2	316.2
	Condensate 凝析油	% (GIIP)	21.1	18.5	16.3
		MMSTB	9.4	9.4	9.4
Gas Initially-In-place （GIIP）[1] 天然气原始原地量		Bscf	1500	1710	1940
Gross-Heating Value of Raw Gas 天然气总热值		Btu/scf	1100	1100	1100
Recoverable Raw Gas（EUR）[1] 原料气估算最终可采量	Original 原始	Bscf	1130	1300	1475
		MMBOE[2]	214.3	246.6	279.7
	Remaining[4] 剩余	Bscf	813.8	983.8	1158.8
		MMBOE[2]	154.3	186.6	219.8
Implied Recovery Factor 采收率		% (GIIP)	75	76	76
Initial Condensate-Gas Ratio (CGR_i) 原始凝析油气比		STB/MMscf	30	30	30
Condensate Initially-In-Place（GIIP） 凝析油原始原地量		MMSTB	45.0	51.3	58.2
Condensate Recovery Factor[3] 凝析油采收率		% (GIIP)	60	60	60
Recoverable Condensate（EUR） 凝析油估算最终可采量	Original 原始	MMSTB	27.0	30.8	34.9
	Remaining[4] 剩余	MMSTB	17.6	21.4	25.5

[1] Estimated directly from Figure 4.8 based on (P/Z) values of 0 and 1500 psia (economic limit), respectively.
根据图 4.8 直接估算视地层压力分别为 0 psia 和 1500 psia（经济极限）时对应的估值。

[2] Calculated using an average conversion factor of 5.8 MMBtu per BOE.
使用平均转换系数 5.8MMBtu/BOE 进行计算。

[3] Based on several nearby analog reservoirs and accounts for condensate dropout in the reservoir, if any.
基于邻近类比气藏，考虑凝析油的析出损失（若存在凝析油损失）。

[4] Estimated Gas and Condensate Reserves categories of 1P, 2P and 3P, respectively.
天然气和凝析油的 1P、2P 和 3P 储量估值。

reservoir are summarized in Table 4.7. Note that the recoverable raw gas volumes (in terms of both scf and therefore the barrels-oil-equivalent, BOE) summarized in Table 4.7 must be reduced by approximately 20% for the surface loss to yield their residue sale gas equivalents or reserves (EUR), consisting of 3.2% for the shrinkage of condensate reserves and 16.8% for the subsequent processing to remove nonhydrocarbons (8.1%) and recovery of C_2 plus NGLs (8.7%). For more detail, readers should refer to Chapters 9 and 10 on production measurements, reporting, and entitlement issues.

It is a common practice to determine whether “gas compression” is economically viable and can be used to lower wellbore backpressure to help gas wells produce at lower average reservoir abandonment pressures (or associated p/z economic limits) and thus provide additional reserves.

The wellbore backpressure is the sum of the backpressure imposed by the sales gas pipeline and the pressure drops in the gas gathering system at the surface and the tubing string in the wellbore. A gas well will stop flowing when the average reservoir pressure drops to and equals this wellbore backpressure. This “no flow” average reservoir pressure and therefore its (p/z) value does not necessarily represent the economic limit because the wellbore imposed backpressure can be reduced by designing and installing an optimal gas compression facility (with an optimum compression ratio) at the point of sales (or plant feed) to significantly reduce the sales gas pipeline imposed backpressure.

The economic limit (p/z) of 1,500 psia for this example deep gas reservoir represents a point where the value of production is just equal to the operating cost of producing the project under pressure depletion without compression. It is a deep gas reservoir and although gas compression is expected to reduce the economic (p/z) limit to as low as 1,000 psia, it is uneconomic because the value of incremental gas reserves realizable is determined to be less than the capital and operating costs of installing and running the compression facility. Thus the incremental volumes associated with compression are considered as Contingent Resources (but not reported here) pending future updates for cost reduction and/or higher gas prices.

4.2.3.2 Reservoir Simulation Methods (RSM)

4.2.3.2.1 Technical Principles.

The body of scientific knowledge on the development and use of integrated reservoir simulation models is extensive and may be reviewed in many books, including Aziz and Settari (1979), Mattax and Dalton (1990), Ertekin et al. (2001), Fanchi (2006), and many others. PS-CIM (2004) provides a brief and concise review of the subject, including the different phases of a typical reservoir simulation study.

A reservoir simulation model characterizes the reservoir by integrating the static geological model (similar to that in Figure 4.6) and the dynamic flow model populated with actual reservoir performance data (pressures, tests, production rates, inter fluid-rock characteristic

料气最终可采量（单位分别为 scf 和桶油当量）须扣减 20% 的地面损失之后计算剩余的销售气量或储量，这部分损失包含了 3.2% 的凝析油收缩率和后续加工处理的损失率 16.8%（其中去除非烃组分占 8.1%，乙烷和天然气液回收占 8.7%）。更多详细信息，请参阅第 9 章和 10 章有关产量计量、报告和份额核定的相关内容。

在天然气开发实践中，通常需要考虑启用天然气压缩机的经济可行性。气体压缩机可降低井底回压，有利于气井在更低的平均气藏废弃压力（或相应经济极限视地层压力 p/z ）条件下生产，从而增加储量。

井底回压是销售气管线回压、天然气地面集输系统以及井筒生产管串压降的总和。当平均气藏压力降至井底回压时，气井不再生产。“ 停流 ”时，气藏压力及其 p/z 值并不代表经济极限，因为若在销售点（或处理厂入口）设计与安装天然气压缩设施（优化压缩比率）则可以显著降低销售气管线的回压，从而降低井底回压，恢复生产。

本案例深层气藏的经济极限压力（p/z）为 1500psia，这表明项目衰竭开发并不考虑增加压缩设施情形下，该废弃压力下的产量价值刚好等于生产操作费。由于本案例气藏埋藏深，尽管新增压缩设施可降低经济极限压力（p/z）至 1000psia，但由此增加的天然气储量不足以回收压缩设施安装和运行的资本与操作成本，即新增压缩设施项目没有经济可行性。所以，启用压缩设施增加的天然气可采量可划归为条件资源量（本案例未报告此数量），待未来成本降低和 / 或气价更高时再进行更新。

4.2.3.2 油藏数值模拟方法（RSM）

4.2.3.2.1 技术原理

有关一体化油藏数值模拟技术研发及应用的科技信息非常多，在许多著作中均有介绍，包括 Aziz 和 Settari（1979）、Mattax 和 Dalton（1990）、Ertekin 等（2001）、Fanchi（2006）等人著作和许多其他书籍。PS-CIM（2004）对不同阶段的典型油藏模拟研究进行了简洁论述。

一个油藏数模模型整合了其静态地质模型（类似于图 4.6 所示）和建立在实际生产动态数据（如压力、测试、产量、表征流体 - 岩石特征

curves characterized by the capillary and relative permeability curves, PVT data, etc). Moreover, the results of integrated reservoir simulation models can be used with increased confidence as the amount and quality of static geoscientific and dynamic reservoir performance data increase. Reservoir simulation can be used during any production stage (or period) to directly estimate both the original in-place and the recoverable quantities of petroleum or the EUR for any oil and gas recovery project. Estimates may be derived for any petroleum recovery project under any recovery method, including primary drive mechanisms, secondary pressure maintenance and displacement schemes (crestal immiscible gas injection, and down-dip peripheral and pattern waterfloods), and various potentially applicable EOR processes.

Developing a meaningful reservoir model capable of generating reliable results with reasonable certainty requires a multidisciplinary team with appropriate technical skills and broad experience. Once a reasonably good history match is obtained, the model can be used to predict production and injection profiles, infill wells, well workovers, stimulation, and other requirements according to specified prediction guidelines (related to drilling, well completions, production engineering and reservoir management, including vertical flow and surface flow systems) under various “what-if” conditions for reservoir development, production and management strategies. Based on a comparative economic analysis, the optimum development and producing strategy can be selected for implementation. Depending on the amount and quality of performance data available, the projected cumulative production to the economic limit with this optimum strategy should establish the most likely EUR.

Determination and assignment of different reserves categories, however, must be consistent with PRMS definitions and therefore would depend on the degree of uncertainty the evaluator determined to exist in these estimates. Irrespective of the assessment method, it is good practice to consider the following two key points:

(1) The degree of uncertainty in the estimates (or the range of outcomes) is expected to decrease as the amount and quality of geoscience, engineering and production performance data increase.

(2) Compare the estimates obtained using several different methods (e.g., volumetric, material balance, reservoir simulation and/or production performance trend analyses) and the analog projects, if available, before booking reserves.

There are no published generally accepted rules, but several key observations can be made regarding best practices employed in the assessment of petroleum in-place and recoverable volumes using reservoir simulation studies. With limited data (geoscience and engineering), the model is best suited to make sensitivity scenario projections to bracket what is possible around the best estimate defined as the base case. The uncertainty in the range of estimates is expected

的毛管压力曲线与相渗曲线、PVT 性质等）基础上的动态流动模型。此外，一体化油藏数值模拟研究结果的置信度是随着静态地质资料和生产动态资料数量和质量的提升而增加。油藏数值模拟方法可以在任何生产阶段（或时期）应用，以直接评估任一油气开采项目的石油原始原地量和可采量（或估算最终可采量）。该方法适用于各种开采方式下的油气开采项目，包括一次开发、二次保压驱替开发（如顶部注气非混相驱、下倾边缘注水和面积注水等），以及各种可能的提高采收率项目。

建立一个具有合理确定性、结果可信的油藏模型，需要一个有技术能力、经验丰富的多学科专家团队。一旦完成高质量的历史拟合，油藏模型就可以用于产量与注水剖面预测，加密井、修井作业和增产措施效果评价，以及基于油藏开发、生产和管理策略的条件优化研究开展其他所需的预测分析（如钻井、完井、开采工程和油藏管理，包括垂直管流和地面流动系统）。根据经济分析对比，可优选开发与生产策略以指导生产实践。依据可利用动态资料的数量和质量，根据优化开发策略，油藏模拟方法所预测的累计产量（截至经济极限）应视为最可能的估算最终可采量。

当然，不同级别储量的核定须与 PRMS 的定义保持一致，这取决于评估师对评估结果不确定性的研判。不管采用什么评估方法，好的实践做法是考虑以下两个关键点：

（1）评估结果的不确定性（或评估结果分布范围）随着地质、工程和生产动态数据数量和质量的提升而减小。

（2）在申报储量之前，要对比不同方法（如容积法、物质平衡法、油藏模拟法和 / 或生产动态趋势分析法）和类比项目（若有的话）的评估结果。

在油藏数值模拟法研究中，没有公开发表的通用规则，但有几条可用于石油原地量和可采量评估的最佳实践认识。当地质和工程基础数据有限时，最好应用模型进行方案设计敏感性分析，然后将最佳估值情景作为基础方案。评估结果的不确定性范围应比数据更多情形的不确定性范围大。如 PRMS 所述，根据项目的经济性评估和所

to be larger than those estimated using more data. As specified in the PRMS, based on the respective project economics and whether or not all project contingencies are met, resulting estimates may be assigned to different categories of Reserves and/or Contingent Resources. As the amount and quality of data increases, the range of estimates of in-place and recoverable volumes obtained using these integrated reservoir simulation models (matched using long observed production performance data) will decrease. In actual practice, one may have the following two extreme cases in which to assess and categorize the estimates using simulation models:

(1) Case 1. One may have three different geological realizations (representing the low, best, and high scenarios) and associated reservoir simulation models that can be used to directly estimate the respective in-place volumes, EURs, Reserves (e.g., the EURs reduced for cumulative production realized, if any), and/or Contingent Resources categories. This is definitely preferred, but not a common practice given the time and expense to develop several rigorous models.

(2) Case 2. One may only have a single integrated reservoir simulation model, which can be used to directly estimate a single most likely (or best) value of project PIIP, EUR, Reserves, and/or Contingent Resources. In deterministic analysis, it is common practice to run sensitivity predictions to understand the range of uncertainty and assign the 1P and 3P categories accordingly.

Irrespective of the assessment method used and amount and quality of necessary data available, the estimates must fulfill the premise stated in Point 2 above before booking.

Expertise gained over many years of working with the reservoir simulation models and the ability to select the model most appropriate for the oil and gas reservoir (or recovery project) under evaluation are critically necessary skills required to complement a thorough understanding and application of PRMS guidelines for the classification and categorization of petroleum resources. However, it is absolutely critical to be realistic and pay attention to the following wise and cautionary statement by Thiele (2010) that applies to all analyses, but specifically the reservoir simulation: “The industry has long recognized the importance of quantifying uncertainty. As a result, computational resources are being directed more toward simulating large ensembles of models rather than adding ever increasing levels of detail and physics to a single representation of the subsurface. For multimillion-dollar capital investments, it is far more important to acknowledge the possibility of catastrophic outliers and invest in reducing uncertainty by guided data acquisition than to tweak a single reality to excess.”

4.2.3.2.2 Application to Example Oil Project

This application represents an oil recovery project at its mature late-production and early-decline stages. The example oil reservoir was developed and produced under a very effective down-dip water injection

有或有因素是否已满足，可将评估结果划分为不同级别的储量和 / 或条件资源量。随着数据数量和质量的提升，应用一体化油藏模拟模型（经长时间历史生产动态数据拟合）评估的原地量和可采量估值范围将缩小。在实际应用油藏模拟进行评估与分级时，可能会遇到以下两种极端情形：

情形 1：有三组不同地质实现（分别代表低估值、最佳估值和高估值情景）及相应的油藏模拟模型，可以直接用于评估原地量、估算最终可采量、储量（估算最终可采量减去累计产量，若有的话）和 / 或条件资源量。这当然很好，但在给定时间和费用情况下，建立多个精确模型显然是不实际的。

情形 2：只有一个一体化油藏模拟模型，可以直接用于评估项目的石油原始原地量、估算最终可采量、储量和 / 或条件资源量的单一最可能估值（或最佳值）。在确定法分析中，常用做法是进行敏感性预测分析以了解不确定性的范围，并相应地核定 1P 和 3P 储量估值。

无论采用哪种评估方法、所用数据的数量与质量如何，评估结果在申报之前必须按前面提及的第二关键点进行校验。

多年油藏数模工作经验和选择油气藏（或开采项目）最佳评估模型的能力，是深化对 PRMS 石油资源分类分级指南的理解与应用的重要必备技能。尽管如此，Thiele (2010) 提出以下告诫“石油行业很早就认识到量化不确定性的重要性。结果，计算资源更多地将引向大量模型计算，而不是持续增加地层模型数据的详实程度和物理意义。对于数百万美元的投资而言，了解发生灾难性异常情况的可能性以及进一步投资有意识地补充采集可降低不确定性的数据，远比过分纠结于某单一现实重要得多。”Thiele 的告诫适用于所有的分析研究（尤其是油藏数值模拟），具有很重要的现实意义。

4.2.3.2.2 原油项目应用案例

该应用案例的原油开发项目处于成熟稳产阶段后期和递减早期。该案例油藏采用非常有效的下倾边缘注水开发方式生产了 16 年。期间，新

scheme over the past 16 years. During that time, 36 new oil producers and 3 water injectors were also drilled (bringing the total to 70 and 22 wells, respectively) to better manage production decline and to help further improve overall recovery efficiency.

Based on the extensive log, core, and testing data obtained over the past 19 years (discovery year, 2-year appraisal period followed by a 3-year initial development and a 16-year of production periods depicted by Figure4.1a), a 0.5 million-cell geocellular model (similar to that depicted in Figure 4.6) was built and used to estimate an OIIP of about 1,525 MMSTB with a reported single statement that “the results of sensitivity runs, using this geological model, showed about a 6% downside (meaning 1,434 MMSTB) and a 14% upside (meaning 1,739 MMSTB) in the OIIP estimate.” It is important to note that since the Material Balance Analysis of this example oil project was conducted 8 years ago, the range in the OIIP estimates were reduced to a ratio of 1.21 (=1,739/1,434) from 1.54 (=2,000/1,300), a 21% reduction in the range for both in OIIP and the EURs (because of using the same recovery factors). Hence, the relative degree of uncertainty in these estimates should also have been reduced.

Based on this most likely or best 3D geological realization (with an OIIP estimate of 1,525 MMSTB), a related integrated 3D and three-phase reservoir simulation model was developed by a multidisciplinary team and used to match this extensive reservoir performance history covering a period of 16 years with 399 MMSTB (26.2% OIIP) produced.

This history-matched black-oil model was used to predict future reservoir performance under the ongoing base-case operations using peripheral waterflood, including economically justified well workovers, infill drilling, and well completions to better manage the decline. The historical and predicted profile for the Best Scenario (Base Waterflood) is presented in Figure 4.9. As shown in Figure 4.9, an EUR of 686.3 MMSTB (45% OIIP) at an economic limit of about 2,700 BOPD was predicted. It represented the most likely or the “best” scenario for the ongoing waterflood performance already confirmed by the excellent performance observed over the past 16 years. It confirmed the 45% OIIP recovery factor assigned 8 years earlier in Material Balance Analysis.

Based on the reported low and high estimates of OIIP from the sensitivity analysis and using the respective same REs, the project EURs and Reserves were calculated. The results are summarized in Table 4.8.

The same black oil model was used to study a “what-if” reservoir performance scenario of installing a fieldwide artificial lift facility using electrical submersible pumps (ESPs) in all oil producers by the Year 21. Based on a conservative economic limit of about 3,000 BOPD, an EUR of 793 MMSTB (or about 52% OIIP) was predicted for the combined project of peripheral waterflood with artificial lift using ESPs. The

完钻了 36 口油井和 3 口注水井（总油井数和注水井数分别达到 70 口和 22 口），以更好地延缓产量递减和进一步提高整体采收率。

基于过去 19 年（如图 4.1a 所示，发现年与 2 年评价期之后是 3 年开发初期和 16 年生产期）期间所获取的测井、岩心和测试资料，建立了一个 50 万网格节点的地质模型（类似于图 4.6 所示），评估原油原始原地量约 1,525MMSTB，并在报告中作出单独声明 :“ 根据该地质模型的敏感分析，表明原油原始原地量的波动范围为下浮 6%（1,434MMSTB）和上浮 14%（1,739MMSTB）。” 值得注意的是，由于该案例油藏在 8 年前采用物质平衡法评估过原油原始原地量，其不确定性分布范围比率从 1.54（2,000/1,300）降至本次评估的 1.21（1,739/1,434）。原始原地量和估算最终可采量（采用相同采收率）的估值范围均减小了 21%。由此可见，评估的不确定性已降低。

基于这个最可能或最佳三维地质实现模拟模型（原油原始原地量为 1,525MMSTB），多学科研究团队建立了一个三维三相油藏模拟摸型，拟合了 16 年生产动态历史（累计产量 399MMSTB，OIIP 采出程度 26.2%）。

经过历史拟合校验的黑油模型对正实施的基础方案（油藏继续实施边缘注水开发，工作任务包括已论证经济可行的措施、加密钻井和完井等，以延缓递减）进行了生产动态预测。其最佳方案（基础水驱方案）的生产历史与产量预测剖面参见图 4.9。如图所示，经济极限产量 2,700BOPD 对应的估算最终可采量为 686.3MMSTB（45%OIIP）。这代表了正实施水驱开发方案的最可能或最佳估值，并得到 16 年良好生产动态信息的印证。也进一步印证了 8 年前物质平衡法所确定的采收率 45%。

根据敏感分析研究，基于报告的项目原油原始原地量低估值和高估值以及有代表性的相同采收率，可得到项目的估算最终可采量和储量，相应结果汇总于表 4.8。

假定一个情景方案：所有油井在第 21 年之前安装人工举升装置电潜泵（ESP），并利用上述同一个黑油模型对其进行生产动态模拟研究。根据保守估算，经济极限产量为 3,000BOPD，在边缘水驱 + 电潜泵举升联合开发方式下，预测油藏的估算最终可采量为 793MMSTB（或约

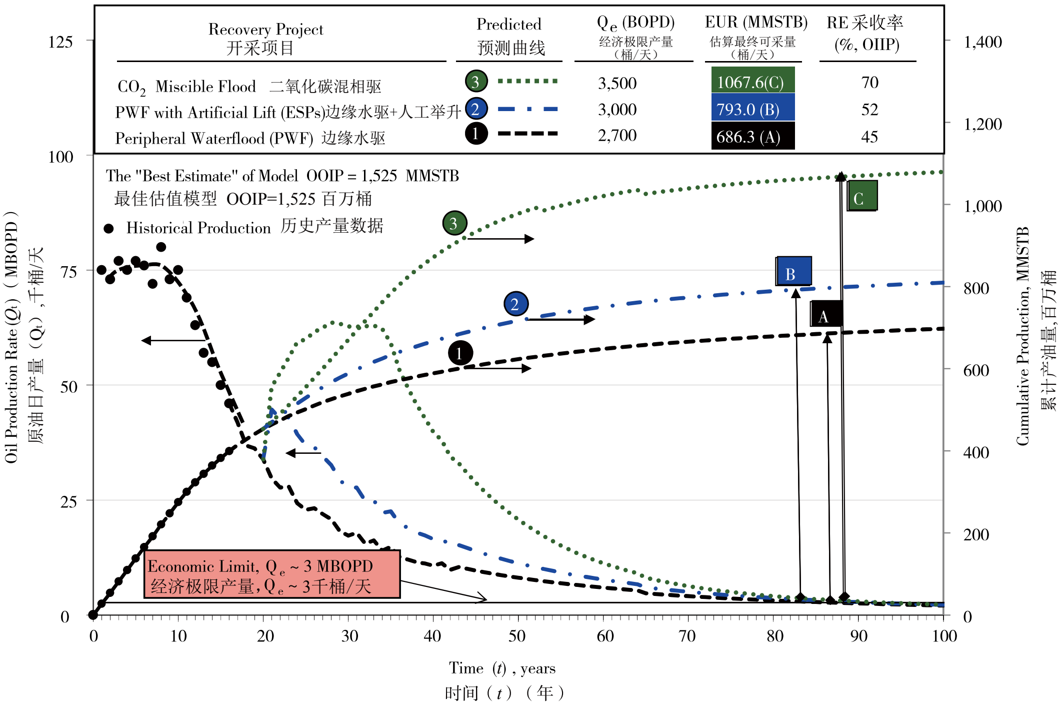


Figure 4.9　Dynamic and Direct Assessment of Reserves Using Reservoir Simulation.

图 4.9　油藏模拟法直接和动态评估储量

project's production profile and resulting estimates are also presented in Figure 4.9 to illustrate its performance relative to the ongoing peripheral waterflood project without the ESPs. This 7% OIIP incremental "what-if" predicted performance had confirmed the results of an earlier study and was supported by several nearby analog artificial lift projects showing incremental economic recoveries as high as 9% OIIP.

The company committed to the ESP implementation. The additional recovery was judged to have reasonable certainty and placed in the Proved category with Undeveloped status at the time, expecting it to be transferred to Proved Developed in 4 years time (or in Year 21), when the project was expected to be completed and put on-stream.

Although some may consider the artificial lift as a separate project, it was in fact a combined project that just enhances the ongoing waterflood by only installing ESPs in some producers. In actual practice, artificial lift is generally implemented in stages (especially with ESPs) to minimize operating expenses because oil producers reach their critical water-cut levels at different times making a fieldwide simultaneous installation as a separate project not as attractive.

Irrespective of how one treats the artificial lift projects, their impact was incorporated with the ongoing peripheral waterflood project by adding this constant 7% OIIP increase in recovery efficiency to the recovery efficiency of each low, best, and high scenario estimated and/or assigned in Table 4.8. The project increased the respective recovery

52%OIIP）。项目的预测产量剖面和评估结果已展示在图 4.9 中，可以与边缘水驱（无电潜泵）基础情景方案的生产动态剖面进行对比。经模拟预测，新增原始原地量采收率 7% 的结论也验证了早期研究的结果，邻区人工举升类比项目显示可增加经济可采量高达原始原地量的 9%。

公司已承诺实施电潜泵项目，相应可采量增量的合理确定性已得到论证，此时可核定其为证实储量级别的未开发状态，并期望该部分储量能在 4 年内（或第 21 年）升级为证实已开发储量，此时项目完全建成与投产。

尽管人工举升可以作为一个单独项目来考虑，但现实中，它与水驱项目是紧密结合的，通常只在部分油井安装电潜泵以提升注水开发的效果。在实际操作中，由于各油井达到极限含水率的时间各不相同，因而可以分阶段实施人工举升（尤其是电潜泵）以降低操作成本；在全油田范围同时安装人工举升设施作为一个单独项目是没有吸引力的。

无论如何运作人工举升项目，其成效已综合体现在边缘注水开发的采收率增量 7%（OIIP）中，即表 4.8 中所估算和 / 或核定的低估值、最佳估值

efficiencies to 47%, 52%, and 57% of the OIIPs. As a result, the respective EURs and reserves categories for the “combined project” were recalculated and the results are now summarized in Table 4.8a.

和高估值情景采收率将分别提升为 47%，52% 和 57%。边缘水驱 + 人工举升联合项目的各级估算最终可采量和储量参见表 4.8a。

Table 4.8 Assessment using Reservoir Simulation Studies (Early-Decline Stage): Estimates of Project PIIPs, EURs, and Reserves under Peripheral Waterflood Only

表 4.8 油藏数模研究评估储量（递减早期）：边缘注水开发项目原油原始原地量、估算最终可采量和储量

Measured and Estimated Parameters 计量和估算参数		Units 单位	Bases and Estimates by Reserves Category 基础数据和各级储量		
			Low Estimate 低估值	Best Estimate 最佳估值	High Estimate 高估值
Cumulative Production 累计产量	Oil 原油	MMSTB	399	399	399
	Raw Gas 原料气	% (OIIP)	27.8	26.2	23.0
		Bscf	227.4	227.4	227.4
Oil Initially-In-Place (OIIP) 原油原始原地量		MMSTB	1434	1525	1739
Recovery Factor [1] 采收率		% (OIIP)	40	45	50
Recoverable Oil（EUR）[2] 原油估算最终可采量	Original 原始	MMSTB	573.4	686.3	869.3
	Remaining[4] 剩余	MMSTB	174.4	287.3	470.3
Economic Oil Rate Limit 原油经济极限量		STB/D	2700	3000	3500
Initial Solution Gas-Oil Ratio（R_{si}） 原始溶解气油比		scf/STB	570	570	570
Gross-Heating Value of Raw Solution Gas 溶解气总热值		Btu/scf	1350	1350	1350
Gas Initially-In-Place（GIIP） 溶解气原始原地量		Bscf	817.1	869.3	990.9
Recoverable Raw Gas（EUR）[1] 原料气估算最终可采量	Original 原始	Bscf	326.8	391.2	495.5
		MMBOE[3]	76.1	91.1	115.3
	Remaining[4] 剩余	Bscf	99.4	163.8	268.0
		MMBOE[3]	23.1	38.1	62.4

[1] Waterflood RFs calculated or implied for the Best Estimate and assigned for the Low and High Estimates.
估算最佳估情景的水驱采收率，然后应用于低估值和高估值情景。

[2] The Best Estimates obtained from the projected production profiles of a project-specfic Reservoir Simulation Study.
采用项目油藏数值模拟研究的产量剖面估算最佳估值。

[3] Calculated using an average conversion factor of 5.8 MMBtu per BOE.
使用平均转换系数 5.8MMBtu/BOE 进行计算。

[4] Estimated Oil and Raw Gas Reserves categories of 1P, 2P and 3P, respectively.
原油和原料气的 1P、2P 和 3P 储量估值。

Table 4.8 a　Assessment Using Reservoir Simulation Studies (Early-Decline Stage): Estimates of Project PIIPs, EURs, and Reserves under Peripheral Waterflood with ESPs

表 4.8 a　油藏数模研究评估储量（递减早期）：边缘注水 + 电潜泵开发项目的原始原地量、估算最终可采量和储量

Measured and Estimated Parameters 计量和估算参数		Units 单位	Bases and Estimates by Reserves Category 基础数据和各级储量		
			Low Estimate 低估值	Best Estimate 最佳估值	High Estimate 高估值
Cumulative Production 累计产量	Oil 原油	MMSTB	399	399	399
	Raw Gas 原料气	%(OIIP)	27.8	26.2	23.0
		Bscf	227.4	227.4	227.4
Oil Initially-In-Place（OIIP） 原油原始原地量		MMSTB	1434	1525	1739
Recovery Factor [1] 采收率		%(OIIP)	47	52	57
Recoverable Oil（EUR）[2] 原油估算最终可采量	Original 原始	MMSTB	673.7	793.1	990.9
	Remaining 剩余 [4]	MMSTB	274.7	394.1	591.9
Economic Oil Rate Limit 原油经济极限产量		STB/D	2700	3000	3500
Initial Solution Gas-Oil Ratio（R_{si}） 原始溶解气油比		scf/STB	570	570	570
Gross-Heating Value of Raw Solution Gas 溶解气总热值		Btu/scf	1350	1350	1350
Gas Initially-In-Place（GIIP） 溶解气原始原地量		Bscf	817.1	869.3	990.9
Recoverable Raw Gas（EUR）[1] 原料气估算最终可采量	Original 原始	Bscf	384.0	452.0	564.8
		MMBOE[3]	89.4	105.2	131.5
	Remaining 剩余 [4]	Bscf	156.6	224.6	337.4
		MMBOE[3]	36.5	52.3	78.5

[1] Waterflood RFs calculated or implied for the Best Estimate and assigned for the Low and High Estimates.
估算最佳估情景的水驱采收率，然后应用于低估值和高估值情景。

[2] The Best Estimate is obtained from the projected production profile of a project-specific Resrvoir Simulation Study.
采用项目油藏数值模拟研究的产量剖面估算最佳估值。

[3] Calculated using an average conversion factor of 5.8 MMBtu per BOE.
使用平均转换系数 5.8MMBtu/BOE 进行计算。

[4] Estimated Oil and Raw Gas Reserves categories of IP, 2P and 3P respectively.
原油和原料气的 1P、2P 和 3P 储量估值。

Furthermore, based on the same geological model representing the best case scenario, and relevant CO_2 and hydrocarbon compositional data (including miscibility test results), an integrated compositional model was developed to study the performance of CO_2 miscible displacement process and several alternatives using different water-alternating-gas (WAG) scenarios. Assumed to be on stream by Year 21 (similar

此外，利用最佳估值情景的地质模型以及配套 CO_2 与烃组分数据（包括混相测试结果）还构建了一个一体化组分模型，以研究 CO_2 混相驱结合不同水气交替注入方案（WAG）的生产动态。假设第 21 年开始实施（类似前面人工举升假定情

to the "what-if" artificial lift study), several production performance predictions were carried out to a 3,500 BOPD economic limit, yielding a cumulative oil recovery of about 1,068 MMSTB (or 70% OIIP) for the case with an optimum CO_2 injection at the crest. The results for this best-case scenario are also presented in Figure 4.9 to illustrate its performance relative to the ongoing base peripheral waterflood and the second peripheral waterflood with artificial lift projects. This predicted incremental recovery of 18% OIIP for a CO_2 EOR project was supported by two CO_2 pilots already implemented in analog oil projects nearby and yielding a reported maximum incremental recovery efficiencies of 22% OIIP, which established the upper limit.

Although the project economics were positive, it was not reasonably certain that the project would be implemented in Year 21 as initially assumed. The infrastructure for sequestration and delivery of CO_2 to the project site were assessed to take longer and delayed because of the expected budgetary constraints at the time. Consequently, the estimated recoverable quantities of oil and raw natural gas were classified as Contingent Resources. Therefore, incremental recoverable quantities attributable to CO_2 miscible project had to be separated from the second project and reported incrementally (using a low and a high recovery efficiency of 15% and 22% OIIP, respectively, to bracket uncertainty) as shown in Table 4.8b. There was a note stating that "these estimates should be reviewed periodically to confirm whether these unfulfilled contingencies still exist and if fulfilled, they can be classified as Reserves."

4.2.3.3 Production Performance Trend (PPT) Analyses

PPT analyses have proved to be very useful and commonly used methods to directly estimate the EURs for oil and gas wells, reservoirs and specific development (or recovery) projects. Although PPT analyses are traditionally known as decline curve analyses (DCAs), other forms of PPTs exist and can also be used to estimate petroleum (oil and gas) reserves. Historical production performance trends observed in mature wells, reservoirs, or projects may generally be extrapolated to the cumulative production at the economic limit, and provide a reasonable assessment of the EUR. Moreover, the predicted production rate profiles obtained using analytical or reservoir simulation studies could establish performance trends that are not long enough to include the project's economic life. In these cases, the DCA can also be used to best-fit these trends and extrapolate them all the way to project economic limit and determine the EURs.

To better comprehend the limitations of PPT analysis, Harrell et al. (2004) pointed out the following conditions under which production decline trends would provide acceptable projections of production profiles and the resulting reserves estimates for the asset under study:

(1) Production conditions, methods, and the overall production strategy are not changed significantly over the projected remaining

景研究）开展顶部 CO_2 驱生产动态预测，设定经济极限产量为 3,500BOPD，优化方案估算累计产油量为 1,068MMSTB（或 70%OIIP）。前面的图 4.9 也展示了该最佳估值情景方案的预测结果，可与正实施的边缘水驱基础方案以及第二个边缘水驱结合人工举升方案的预测结果进行对比。CO_2 提高采收率项目预计可提升采收率 18%（OIIP）；邻区已实施的两个 CO_2 先导试验类比项目报告的最高采收率增量为 22%，可作为评估上限。

尽管项目经济评价结果为经济可行，但第 21 年能否实施，尚不具备合理确定性。鉴于当时资金预算有限，CO_2 存放和现场输送的基础设施建设所需时间长，项目延迟。相应地，原油和原料气的可采量估值划归为条件资源量。因此，CO_2 混相驱贡献的可采量增量须从第二个方案的预测结果中分离出来，以增量方式单独报告（采收率低值和高值分别取 15% 和 22%，以反映不确定性），参见表 4.8b。需要提示，"这些预测结果应定期核验，以确认是否仍存在不满足条件的或有因素；若没有，则可升级为储量。"

4.2.3.3 生产动态趋势（PPT）分析法

实践证明，生产动态趋势分析法可直接估算单井、油藏和特定开发项目的最终可采量，是非常有用的一种常规方法。尽管生产动态趋势分析法在传统意义上被视为是我们熟悉的递减曲线分析法（DCA），但也存在其他形式的生产动态趋势分析方法，也常用于石油（油和气）储量评估。通常，外推成熟单井、油藏或项目的历史生产动态趋势可得到经济极限对应的累计产量，即合理的估算最终可采量。此外，采用其他分析法或油藏数值模拟研究法预测的产量剖面可以涵盖项目的整个经济生命周期；此时，可采用递减曲线分析拟合这些预测曲线，并外推至经济极限以确定估算最终可采量。

为了更好领会生产动态趋势分析方法的局限性，Harrell 等人 (2004) 指出，使用产量递减法合理预测产量剖面和估算储量，应注意以下条件：

（1）项目剩余生产期的总体开发策略、开

Table 4.8 b　Assessment of Contingent Resources Using Reservoir Simulation Studies (Early Decline Stage): EURs under a Planned CO_2 Miscible Project

表 4.8 b　油藏数值模拟研究评估条件资源量（递减早期）：CO_2 混相驱规划项目最终可采量

Measured and Estimated Parameters 计量和估算参数	Units 单位	Bases and Estimates by Contingent Resources Category 基础数据和各级条件资源量		
		Low Estimate 低估值	Best Estimate 最佳估值	High Estimate 高估值
Oil Initially-In-place（OIIP） 原油原始原地量	MMSTB	1434	1525	1739
Initial Solution Gas-Oil Ratio（R_{si}） 原始溶解气油比	scf/STB	570	570	570
Gross-Heating Value of Raw Solution Gas 溶解气总热值	Btu/scf	1350	1350	1350
Incremental Recovery Factor [1] 采收率	%（OIIP）	15	18	22
Recoverable Oil （EUR）[3] 原油估算最终可采量	MMSTB	215.0	274.5	382.5
Recoverable Raw Gas （EUR）[3] 原料气估算最终可采量	Bscf	122.6	156.5	218.0
	MMBOE[2]	28.5	36.4	50.7

[1] Under a CO_2 Miscible Flood based on the results of two implemented analog CO_2 Pilot Projects.
CO_2 混相驱，类比两个已实施 CO_2 先导性试验项目结果。

[2] Calculated using an average conversion factor of 5.8 MMBtu per BOE.
使用平均转换系数 5.8MMBtu/BOE 进行计算。

[3] Estimated Oil and Gas Contingent Resources categories of 1C, 2C and 3C, respectively.
原油和天然气的 1C、2C 和 3C 条件资源量估值。

producing life.

(2) The reservoir has been fully developed, and therefore, the well count is relatively stable.

(3) Wellbore interventions and other remedial work can be classified solely as maintenance.

Production performance trends are not only reservoir specific but also depend on the specific reservoir management and production practices used. Any significant change in these practices could easily lead to erroneous results. Therefore, the reliability of production profiles projected using DCA depends not only on the quality and quantity of the past production data, but also on the evaluator’s professional experience gained through working on many hands-on assessments and reconfirmations of results over time with actual performance, including the use of appropriate analog reservoirs.

4.2.3.3.1 Technical Principles.

Decline analysis is based on the solution of the following differential generalized hyperbolic equation defining the nominal decline rate (D) as the fraction of “change in production rate with time (t)” (also known as loss ratio) as

$$D_t = - (dQ/dt)/Q_t = KQ^b \qquad (4.8)$$

发方式和生产条件不会发生大的变化。

（2）油藏已全面投入开发，生产井数相对稳定。

（3）井筒作业和其他修井措施只是维护正常生产。

生产动态趋势分析结果不仅依赖于特定的油气藏，也依赖于特定的油气藏管理以及生产过程。生产过程中的任何重大变化，都易导致错误结果。因此，产量递减分析预测产量剖面的可靠性不仅依赖于历史生产数据的数量与质量，也取决于评估师亲自参与大量评估工作所积累的专业经验，还需要不断利用实际生产数据和适合的类比油气藏进行重复校验。

4.2.3.3.1 技术原理

递减分析法是基于以下广义双曲微分方程，该方程定义名义递减率（D）是产量随时间（t）变化量的分数比例（也叫损失率）。

$$D_t = - (dQ/dt)/Q_t = KQ^b \qquad (4.8)$$

where

D_t = nominal (or continuous) decline rate (slope of the line) at any time (t) and is a fraction of production rate (Q_t) with a unit of reciprocal time (1/t) in per month, per year, etc, which must be consistent with the units of production rate,

Q_t= production rate (STB/D, STB/month or STB/yr),

b = decline exponent, and

K= integration constant

Decline trends analysis of production rate vs. time advanced by Arps (1945) is a hyperbolic equation similar to Eq. 4.8, and therefore, it has a semitheoretical basis. The PPTs and their extrapolations to the economic limit are governed by the mathematical equations (as solutions to hyperbolic differential Eq. 4.8) summarized in Table 4.9 below.

式中：

D_t—任意时间（t）下的名义（或连续）递减率（直线斜率），是产量（Q_t）随单位时间（每月、每年等，须与产量单位一致）倒数的分数；

Q_t—产量（STB/D，STB/month 或 STB/yr）；

b —递减指数；和

K—积分常数。

Arps (1945) 率先提出产量随时间递减的趋势分析方程为双曲方程（与方程 4.8 相似），具有半理论基础。生产动态趋势分析及其外推至经济极限的过程，可通过表 4.9 中的数学方程约束（如同求解双曲微分方程式 4.8）。

Table 4.9 Traditional Decline Analysis: Governing Equations and Characteristic Linear Plots

表 4.9 常规递减分析：约束方程和特征线性图版

Items 项目	Hyperbolic Model 双曲模型	Exponential Model 指数模型	Harmonic Model 调和模型
Generalized Governing Hyperbolic Decline Equation 广义双曲递减方程	$D = -\frac{dQ/dt}{Q} = KQ^b$		
Nominal Decline Rate (D) 名义递减率（D）	$(D_t/D_i)=(Q_t/Q_i)^b$	$D_t=D_i$=constant（常数）	$(D_t/D_i)=(Q_t/Q_i)$
Decline Exponent (b) 递减指数（b）	“ b ” varies except for 0 & 1 b 为变量，不等于 0 或 1	b=0	b=1
Rate-Time Relationships 产量 - 时间关系	$Q_t=Q_i[1+bD_it]^{(-1/b)}$ $\log Q_t=\log Q_i-(1/b)\log(1+bD_it)$	$Q_t=Q_ie^{-Dt}$ $\log Q_t=\log Q_i-(D/2.3)t$	$Q_t=Q_i(1+D_it)^{-1}$ $\log Q_t=\log Q_i-\log(1+D_it)$
Type of Linear Plots 线性图版类型	$\log Q_t$ vs. $\log(1+C_t)$where $C=bD_i$ $\log Q_t—\log(1+C_t)$ 其中 $C=bD_i$	$\log Q_t$ vs. t $\log Q_t—t$	$1/Q_t$ vs. t or $\log Q_t$ vs. $\log(1+D_it)$ $1/Q_t—t$ 或 $\log Q_t—\log(1+D_it)$
Rate-Cumulative Relationships 产量 - 累产关系	$N_{pt}=\frac{Q_i^b}{(1-b)D_i}[Q_i^{(1-b)}-Q_t^{(1-b)}]$	$N_{pt}=(Q_i-Q_t)/D$ $Q_t=Q_i-DN_{pt}$	$N_{pt}=\frac{Q_i}{D_i}\ln(Q_i/Q)$ $\log Q_t=\log Q_i-D_i/(2.3Q_i)N_{pt}$
Type of Linear Plots 线性图版类型	Not available 无	Q_t vs. N_{pt} $Q_t—N_{pt}$ 图版	$\log Q_t$ vs. N_{pt} $\log Q_t—N_{pt}$ 图版

i= stands for initial time or point at which the decline trend has onset or started.

递减趋势开始的初始时间点。

D_t=nominal decline rate (as fraction of Q_t) with a unit of inverse time (1/t), equals to D_i when $Q_t= Q_i$.

名义递减率，是 Q_t 和单位时间倒数 (1/t) 的分数；当 $Q_t=Q_i$ 时，$D_t=D_i$。

Q_t=oil or gas production rate at any time “ t ” in STB/D or MMscf/D, etc.*

任意时间点（t）的油或气产量（STB/D 或 MMscf/D）。

t=time and the subscript for oil rate & cumulative production variables.*

时间和产量与累产变量的下标。

N_{pt}=cumulative oil or gas production or recovery at any time "t" in consistent unis.*

任意时间点（t）的油或气累计产量或采出量，单位一致。

* Rate(Q) & time (t) must be in consistent units in above formulae(i.e. if. “ Q ” is in STB/D. “ t ” is in days, etc.)

上述公式中的产量 (Q) 和时间 (t) 的单位必须一致（如果 Q 为桶 / 天，t 的单位则为天）。

Well-known and widely used DCAs provide a visual illustration of historical production performance of a well, a group of wells, or a reservoir and of whether the established trend can be extrapolated to the economic limit to estimate petroleum reserves. Review, derivation, and understanding of these governing equations and the characteristic linear plots (summarized in Table 4.9) representing each decline model are very important for correct use and application of the traditional DCA. Note that the exponential and harmonic models are just specific cases of the hyperbolic model with constant decline exponent (b) of 0 and 1, respectively.

The hyperbolic decline model is not only the most common decline trend observed in the actual performance of oil and gas wells and reservoirs, but also represents the most general and challenging decline trend with two unknown parameters of initial nominal annual decline rate (D_i) and decline exponent (b). Moreover, the hyperbolic decline exponent (b) is not fixed but varies, and may have any value except b = 0 and b = 1, which represent the special cases defined by exponential and harmonic models, respectively, among wells and reservoirs producing under different reservoir depletion methods. It has been widely reported that the value of (b) varies with reservoir drive mechanism. Although the development of unconventional reservoirs in North America has resulted in observed “b” values significantly exceeding one, the following values generally applicable to conventional reservoirs reported by Fekete Associates (2008) may be used:

Value of Decline Exponent (b)	Governing Reservoir Drive Mechanism
0	Single-phase liquid (oil above bubblepoint)
0	Single-phase gas at high pressure
0.1 ~ 0.4	Solution gas drive
0.4 ~ 0.5	Single-phase gas
0.5	Effective edgewater drive
0.5 ~ 1.0	Comingled layered reservoirs

Initial nominal decline rate (D_i) is the nominal (or continuous) decline rate corresponding to initial production rate at which decline begins. The ratio of nominal decline rate at any time (t) (or D_t) to initial decline rate (D_i) when production decline first begins is proportional to a power (b) (except 0 and 1) of the respective production rates and defined by

$$D_t /D_i = (Q_t /Q_i)^b \qquad (4.9)$$

Rate of decline depends on several factors, such as the reservoir depletion rate, maturity, the average reservoir pressure, the reservoir rock and fluid properties (magnitude and distribution), and the reservoir management and production practices. The D_i is further related to the

众所周知，广泛应用的递减分析法可形象绘制井、井组或油藏的历史生产动态，并根据其趋势外推至经济极限以估算石油储量。分析检查、推导和理解表 4.9 所列递减公式及其典型线性特征图版，对于正确使用与推广常规递减分析十分重要。需注意，指数模型和调和模型是双曲模型在递减指数 b 分别为 0 和 1 时的特殊情形。

双曲递减模型不仅是油井、气井和油气藏生产动态最常见的递减趋势规律，也通过两个未知参数初始名义年递减率（D_i）和递减指数（b）体现了最普通和最具挑战的递减趋势——即 b=0 和 b=1 分别代表指数递减和调和递减这两种特殊情形。此外，双曲递减指数（b）并非固定不变，可以是 0 和 1 之外的任意值，已体现不同井和油藏在不同开采方式下所呈现出的生产规律。据广泛报道，b 值是随油气藏的驱动机理变化。尽管在北美非常规油气的开发中，人们发现 b 值明显大于 1，但根据 Fekete Associates (2008) 的研究报告，常规油气藏普遍采用以下数值：

递减指数（b）	油气藏主控驱替机理
0	单相液流 （油相压力超过泡点压力）
0	高压单相气流
0.1 ~ 0.4	溶解气驱
0.4 ~ 0.5	单相气流
0.5	有效边水驱
0.5 ~ 1.0	多层合采油气藏（混合驱动）

初始名义递减率（D_i）是递减开始时初始产量对应的名义（或连续）递减率。任意时间（t）名义递减率（D_t）与初始递减率（D_i）的比值和相应产量比的 b 次幂方成比例，定义如下：

$$D_t /D_i = (Q_t /Q_i)^b \qquad (4.9)$$

递减率的大小依赖于多方面的因素，如油气藏的采油速度、开发程度或成熟度、平均油气藏压力、岩石与流体性质（规模和分布）和油气藏管理，以及实际开采过程。初始名义递减率 D_i 与

initial effective (or stepwise) decline rate (d_i), which is a step function rather than a continuous function between two consecutive rates, by the following relationship:

$$d_i = 1-(1+bD_i)^{-(1/b)} \qquad (4.10)$$

For example, if D_i =0.25/yr and b =0.5, then

$d_i = 1-[1+0.5 \text{ x } 0.25]^{-(1/0.5)} = 0.21$/yr.

The governing rate-time relationship of a general hyperbolic decline model (see Table 4.9) is given by

$$Q_t = Q_i\,(1+b\,D_i\,t)^{-1/b} \qquad (4.11a)$$

Eq. 4.11a may also be re-written as:

$$\log Q_t = \log Q_i - (1/b)\log(1+b\,D_i\,t) = \log Q_i - (1/b)\log(1+C_t) \qquad (4.11b)$$

where C = b D_i, which is an arbitrarily defined unknown constant (refer also to Table 4.9).

For a correct value of C, Eq. 4.11b suggests that a log-log plot of Q_t vs. $(1+C_t)$ should yield a straight line with a slope, m (= -1/b) and intercept of Q_i at time zero or when initial decline starts.

Given the initial production rate at the onset of decline (Q_i) and other oil production data observed over the decline period, the traditional and modern DCAs have been largely an exercise in curve fitting to establish characteristic straight lines and/or type curves and conducting nonlinear regression analysis to simultaneously estimate the correct values of these two unknown parameters D_i and b. Hyperbolic decline is known to occur as gravity drainage becomes the dominating reservoir drive mechanism during later stages of a well life. However, it is possible for this trend to become exponential again at a later stage when the solution GOR is very low and stabilized. With estimated correct values of these two unknowns, the EUR defined by the cumulative production at economic limit, N_{pe}, of the petroleum asset under evaluation can now be directly calculated using the following relationship:

$$\mathrm{EUR}=N_{pe}=N_{pi}+N_{pde}=N_{pi}+\frac{Q_i^b}{(1-b)D_i}\left[Q_i^{(1-b)}-Q_e^{(1-b)}\right] \qquad (4.12)$$

where Q_i and Q_e represent the production rate at initial time (i) or time zero (t=0) or at the onset of decline and at economic limit (e), respectively; and N_{pi}, N_{pde} and N_{pe} represent the cumulative production all the way to the initial (i) production rate (Q_i) or to time zero (t=0) before decline begins, during the entire decline period (d_e) analyzed all the way to economic limit, and overall project to economic limit (e) or the EUR, respectively.

4.2.3.3.2 Types of PPT Analysis

Various well-established methods using PPT analyses may be classified and described under three broad categories: (1) traditional DCAs (TDA), (2) modern DCAs (MDA), and (3) other PPT analyses.

(1) Traditional Decline Analysis (TDA)

初始有效（或逐级）递减率（d_i）相关联，后者是两个连续产量的阶梯函数而不是连续函数，关系式如下：

$$d_i=1-(1+bD_i)^{-(1/b)} \qquad (4.10)$$

例如，如果 D_i=0.25/yr 和 b=0.5，则

$d_i=1-(1+0.5\times0.25)^{-(1/0.5)} = 0.21$/yr。

广义双曲递减模型适用于产量 - 时间关系式的表达式如下（参见表 4.9）：

$$Q_t = Q_i\,(1+b\,D_i\,t)^{-1/b} \qquad (4.11a)$$

式（4.11a）也可以表达为：

$$\begin{aligned}\log Q_t &= \log Q_i - (1/b)\log(1+b\,D_i\,t)\\ &= \log Q_i - (1/b)\log(1+C_t) \qquad (4.11b)\end{aligned}$$

式中：C=bD_i，是任意未知常数（参见表 4.9）。

为了获得正确的 C 值，可根据式（4.11b）绘制 Q_t 和（1+C_t）的双对数图版，图版中直线的斜率为 m (= -1/b)，截距为 Q_i（t=0，初始递减开始时），然后求解。

若已知递减刚开始的初始产量 Q_i 和递减期的其他产量数据，则可以采用常规和现代递减分析拟合产量曲线并构建特征直线和/或典型曲线，通过非线性回归分析计算两个未知参数 D_i 和 b 的正确取值。我们知道，双曲递减适用于井的生产后期，该阶段的主要驱替机制为重力驱。当然，当溶解气油比（GOR）在后期非常低且稳定时，也可能再次出现指数递减。基于两个未知参数的合理估值，则可应用式 4.12 直接估算该石油资产经济极限所对应的累产量（N_{pe}），即估算最终可采量（EUR）：

$$\mathrm{EUR}=N_{pe}=N_{pi}+N_{pde}=N_{pi}+\frac{Q_i^b}{(1-b)D_i}\left[Q_i^{(1-b)}-Q_e^{(1-b)}\right] \qquad (4.12)$$

式中：Q_i 和 Q_e 分别代表初始时刻（i）或零时刻（t=0）或递减刚开始时的产量，以及经济极限 (e) 对应的产量；N_{pi}、N_{pde} 和 N_{pe} 分别是初始递减时（t=0）、整个递减期（d_e）以及整个项目至经济极限（e）时对应的累计产量。

4.2.3.3.2 主要 PPT 分析法

各种成熟应用的生产动态趋势分析法可归纳为三大类：常规递减分析（TDA）、现代递减分析（MDA）和其他 PPT 分析法。

A trial-and-error procedure is used to calculate sets of values for $(1+C_t)$ for several assumed values of C and generating the resulting "log Q_t vs. log $(1+C_t)$" plots until a straight line is obtained. As shown in Eq. 4.11b, for a correct value of C (an arbitrary constant defined by the multiplication of these two unknown decline parameters b and D_i), the slope ($m = -1/b$) of such a log-log plot should yield the value of decline exponent ($b = -1/m$) and the initial decline rate is estimated using $D_i = C/b$. However, the practical use of this method is limited. It is extremely difficult to quantitatively evaluate the correct value of the decline exponent (b) because it is very insensitive to this type of analysis attempting to estimate two unknowns (C and b) simultaneously and usually yielding erroneous results. It is quite possible to have the same "b" but different D_i's matching the same decline trend that extrapolates to different estimates of reserves. Hence, this procedure is not recommended.

It would be highly desirable to estimate the nominal decline (D_i) first and then perform a simple trial-and-error procedure iterating on this single insensitive decline exponent (b) to evaluate and establish the best-matched decline trend that corresponds to the best value of (b). In this regard, a method similar to that recommended by Exxon Production Research Company (EPRCO 1982) proved to be very useful in actual practice. It uses the following a 7-step procedure described and applied to the analyses of this example oil project below.

(2) Application of TDA to Example Oil Project

The project produced under peripheral water injection over the past 26 years with a cumulative production of 518.9 MMSTB. Production decline started at the beginning of Year 11. During the latest 10-year period (Years 17 through 26), an additional production of 120 MMSTB was realized by drilling an additional 12 new oil producers and 3 water injectors, bringing the total to 82 oil producers and 25 water injectors. Note that caution is warranted anytime DCA is used at a level of aggregation beyond the well or completion. Changing well count with time and operational adjustments can alter the shape of the aggregated curve in an unpredictable manner. Please refer to section 6.2.1 for further discussion.

Historical decline observed over the past 16 years, with quarterly average production rates reported during the last 5 years to better illustrate possible variations, were used to draw and establish three slightly different plausible decline trends and to estimate the associated annual nominal decline rates (D_i's) that reflect the uncertainty in the observed production data and interpolations. With a total of 82 wells already producing (and only 10 infill wells remaining), the well count is judged to be reasonably stable enough not to significantly impact these decline rates. The resulting D_i's and the observed decline data were

（1）常规递减分析法（TDA）

根据式 4.11b，采用试凑法计算若干假定 C 值对应的（$1+C_t$）值，然后绘制 logQ_t—log（$1+C_t$）图版，直至得到一条直线。由等式 4.11b 可知，C 值是由两个未知递减参数 b 和 D_i 的乘积所确定的任意常数。根据双对数曲线的直线斜率 m（$=-1/b$），则可以计算出递减指数 b（$= -1/m$）和初始递减率 D_i（$=C/b$）。但实际工作中，该方法的应用是有限的。由于该分析方法对同时估算两个未知参数（C 和 b）并不敏感，常得出错误结果，使得准确地定量评估递减指数 b 十分困难。事实上，很可能相同的“b”不同的“D_i”同样可以拟合出相同递减趋势，但外推却得到不同的储量评估结果。因此，不推荐使用该方法。

理想的做法是先估算名义递减率（D_i），然后针对不敏感的递减指数（b）进行简单试凑法迭代，构建最佳递减趋势拟合曲线，从而得到最佳 b 值。Exxon 生产研究公司（EPRCO，1982）推荐了一种类似的技术方法，并在实践中被证实非常有用。可采用 7 个步骤来阐述该方法在原油项目中的应用。

（2）原油项目应用案例

本案例项目采用边缘注水开发 26 年，累计产油 518.9MMSTB。产量递减起始于第 11 年初，过去的 10 年期间（第 17 至 26 年），通过新钻 12 口油井和 3 口注水井（总油井数和注水井分别达到 82 口和 25 口），增产 120MMSTB。请留意，在单井或生产层段之上的层级进行递减分析结果汇并时，要特别小心。随时间变化的井数和生产作业的调整会不可预知地改变汇并曲线的形状。本指南第 6.2.1 节将进一步讨论这一问题。

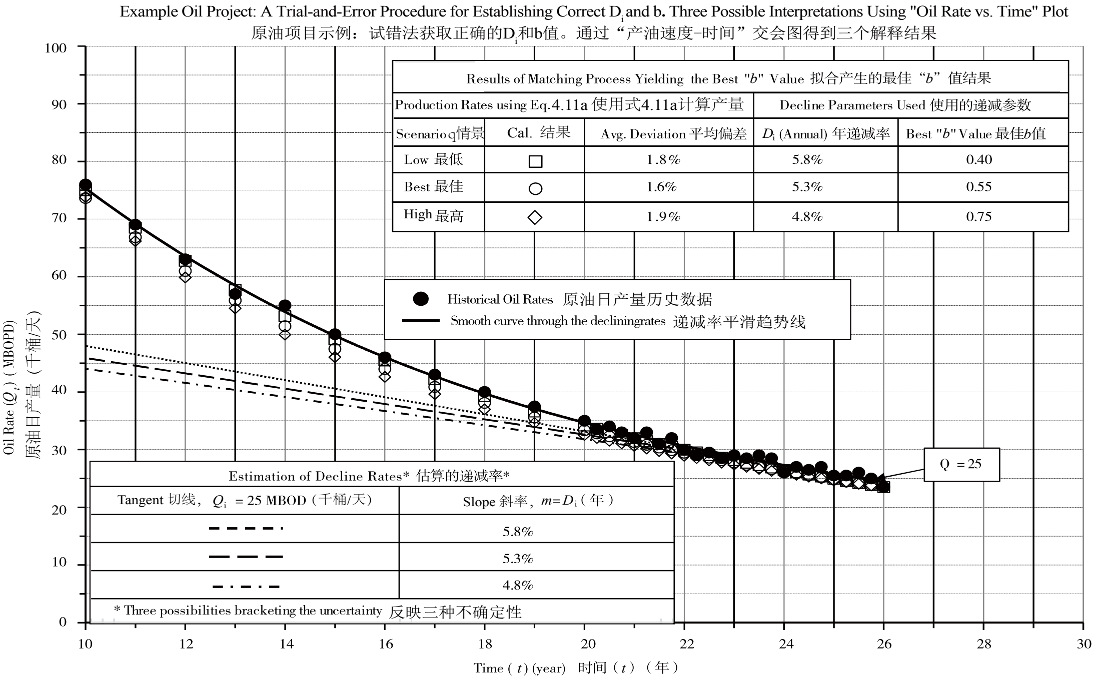
油藏产量递减已持续 16 年，使用历史产量数据（近 5 年数据为季度平均值，以便更好地反映产量变化）可绘制 3 条略有差异的递减趋势线，以计算相应的年度名义递减率（D_i），并反映生产数据和插值的不确定性。由于共有 82 口油井在产（只剩 10 口加密井待钻），可合理判定生产井数稳定，不会明显影响递减率。根据计算得到

used to estimate the related hyperbolic decline exponents (b's) from the respective best-fit trends obtained. These three plausible decline trends or interpretations are judged to quantify the degree of uncertainty in the estimates of respective decline parameters and the extrapolations of these established trends to estimate the reserves (or cumulative production) for low, best, and high scenarios at their respective project economic limits.

The following EPRCO procedure is used to establish the plausible annual decline rates (D_i's) and associated decline exponents (b's) that yield the best fit for three possible hyperbolic decline trends established for the example oil project:

Step 1. Prepare a "Q_t vs. time (t)" (instead of "log Q_t vs. t") plot and draw the best smooth curve through data (quarterly average production rate data are used for the last 5 years to help better show the variations), but giving the greatest weight to and matching the latest data as closely as possible as illustrated in Figure 4.10a. Note that the EPRCO recommended semi-log plot of "log Q_t vs. time (t)" plot almost eliminates the variations in the observed production data and hence does not allow for more than one interpretation and thus it was not used.

Step 2. Draw a series of three plausible straight lines as tangents to the curve at a point near the latest values of production rate at a time (t = 26 years) and production rate (Q_t = 25 MBOPD) to estimate the



Results of Matching Process Yielding the Best "b" Value 拟合产生的最佳"b"值结果				
Production Rates using Eq.4.11a 使用式4.11a计算产量			Decline Parameters Used 使用的递减参数	
Scenario q情景	Cal. 结果	Avg. Deviation 平均偏差	D_i (Annual) 年递减率	Best "b" Value 最佳b值
Low 最低	□	1.8%	5.8%	0.40
Best 最佳	○	1.6%	5.3%	0.55
High 最高	◇	1.9%	4.8%	0.75

Estimation of Decline Rates* 估算的递减率*	
Tangent 切线，Q_i = 25 MBOD（千桶/天）	Slope 斜率，$m=D_i$（年）
– – – – ·	5.8%
— — —	5.3%
–·–·–	4.8%
* Three possibilities bracketing the uncertainty 反映三种不确定性	

Figure 4.10 a　Estimation of Hyperbolic Decline Parameters using Rate vs. Time Plots.

图 4.10 a　利用产量 - 时间关系图版估算双曲线递减参数

的 D_i 和产量递减数据，可利用图版上相应的最佳趋势拟合线则估算出双曲递减指数 b。经分析判断，这 3 条递减趋势线可用于定量评价相应递减参数估值和外推结果——项目经济极限所对应低估值、最佳估值和高估值情景储量（或累计产量）的不确定性。

应用 EPRCO 方法可得到本案例原油项目的三条双曲递减趋势最佳拟合线，并估算相应的名义年度递减率（D_i）及递减指数（b）。步骤如下：

步骤 1；绘制 Q_t—t 图版（不是 logQ_t—t 图版），过实际历史产量数据点（最近 5 年使用季度平均产量数据，以反映变化）绘制最佳平滑线，近期数据的权重加大并尽可能拟合，如图 4.10a 所示。请留意，EPRCO 认为，" logQ_t—t " 半对数图版基本掩盖了产量数据的变化，无法得到多解结果，因此不推荐使用。

步骤 2：选取最近的产量数据点（t=26 年，Q_t=25MBOPD），对曲线作 3 条切线，可得到相应斜率（m）和名义递减率（D_t）。图 4.10a 为该过程的示意图，并标识了计算的双曲递减参数。

respective slopes (m) and hence the nominal decline rates (D_t). Figure 4.10a illustrates how this process works and summarizes the resulting hyperbolic decline parameters.

Step 3. Assume several plausible values of (b) and use any value of D_i (5.3% per year for the best scenario for instance) and Eq. 4.11a to calculate the production rates for various negative values of time (t). Time is negative because decline rate is determined at the most recent time (t =25.75 years) when Q = 25 MBOPD and times between this rate and earlier Q's all the way to Q_i of 75 MBOPD (initial rate at which production decline began) must have negative values to satisfy Eq. 4.11a.

Step 4. Plot both the calculated values of Q's for various plausible values of b obtained in Step 3 and the actual production rate data to establish the best b value for the best-fit curve that has the least average deviation. Calculated data with an b value of 0.55 (shown with hollow circles in Figure 4.10 a) yielded the best-fit to actual data (shown in black dots) with a minimum average deviation of about 1.6%.

Step 5. Repeat Steps 3 and 4 with the remaining annual decline rates of 5.8% and 4.8%, to determine the best "b" values of 0.40 and 0.75 for the low and high scenarios, yielding best-fits with minimum average deviations of about 1.8% and 1.9%, respectively. Figure 4.10a presents the results obtained using the above five-step process.

Step 6. Use the correct decline exponent (b) of 0.55 and the nominal annual decline rate 5.3% at 25 MBOPD and Eq. 4.9 to calculate the initial nominal annual decline rate (D_i) of 9.7% at Q_i of 75 MBOPD (initial rate at which production decline began) for the best-case scenario. Similarly, values of D_i of 9.0% and 11.1% are calculated for the low and high case scenarios, respectively.

Step 7. Finally, for the best scenario for example project operating under peripheral down-dip water injection scheme, use D_i = 9.7% and b = 0.55 and Eq. 4.11a to calculate the oil production rate profile and the cumulative production from Q_i of 75 MBOPD (end of Year 10 when decline first begins) to economic limit determined to be about 3.2 MBOPD and determine the portion of cumulative production over the whole decline period (N_{pde}). Then use Eq. 4.12 to calculate the total EUR (or N_{pe}) of 747.3 MMSTB and the 2P Reserves of 228.4 MMSTB (the EUR adjusted for the cumulative production of 518.9 MMSTB), which illustrated and reported in Figure 4.10b. Note that for the best-case scenario, the same results can be obtained by using D_i of 5.3% and b of 0.55 to forecast oil rates and cumulative production from Q_i of 25 MBOPD (end of Year 26) to the same economic limit and adding to it the cumulative production realized during the first 26 years, etc.

Figure 4.10 b is a resulting characteristic linear plot of "log Q_t vs. log (1+ b D_i t)" for the best-estimate scenario only. High-quality matches obtained from using the EPRCO procedure is clearly demonstrated by

步骤 3：假设几个合理 b 值，使用任意 D_i 值（例如最佳估值情景取年度递减率 5.3%）和方程 4.11a，计算不同时间（t）负值对应的产量。时间取负值，是因为产生递减率的最近时间点（t=25.75 年）的产量为 25MBOPD，为了满足方程 4.11a，该产量与前期 Q 直至初始产量（Q_i 为 75MBOPD）之间的时间必须为负值。

步骤 4：利用第 3 步基于不同 b 值计算的产量 Q 和实际产量数据绘制图版，选取平均偏差最小的最佳拟合线计算最佳 b 值。如图 4.10a 中空圆点所示，b 值为 0.55 时，计算数据可得到实际数据（实心黑点）的最佳拟合线，其最小平均偏差约为 1.6%。

步骤 5：重复第 3、4 步，使用年递减率 5.8% 和 4.8%，分别计算低估值和高估值情景的最佳 b 值，分别为 0.40 和 0.75，最佳拟合线的最小平均偏差分别约为 1.8% 和 1.9%。图 4.10a 展示了上述五个步骤的结果。

步骤 6：使用正确递减指数（b=0.55）和产量为 25MBOPD 时的名义年递减率（5.3%），根据式 4.9 可计算出最佳情景的初始名义年递减率（D_i）为 9.7%（初始递减产量 Q_i=75MBOPD）。同理，可计算 D_i 的低估值和高估值，分别为 9.0% 和 11.1%。

步骤 7：最后，对于本案例实施下倾边缘注水的最佳情景，使用 D_i=9.7%、b=0.55 以及方程 4.11a，可计算得到原油产量剖面及其产量从 75MBOPD（第 10 年末递减开始时）递减到经济极限产量 3.2MBOPD 期间的累产量，即整个递减期的累产量。然后，使用方程 4.12 可计算最终可采量 EUR（或 N_{pe}）为 747.3MMSTB，2P 储量为 228.4MMSTB（最终可采量估值 EUR 减去前 10 年累计产量 518.9MMSTB），如图 4.10b 所示。需注意，对于最佳情景，采用 D_i=5.3% 和 b=0.55 预测产量（Q_i）从 25MBOPD（第 26 年末）递减至相同经济极限产量的累产量再加上前 26 年的累计产量也可得到相同的结果。

图 4.10 b 仅为最佳估值情景的 $\log Q_t$—log

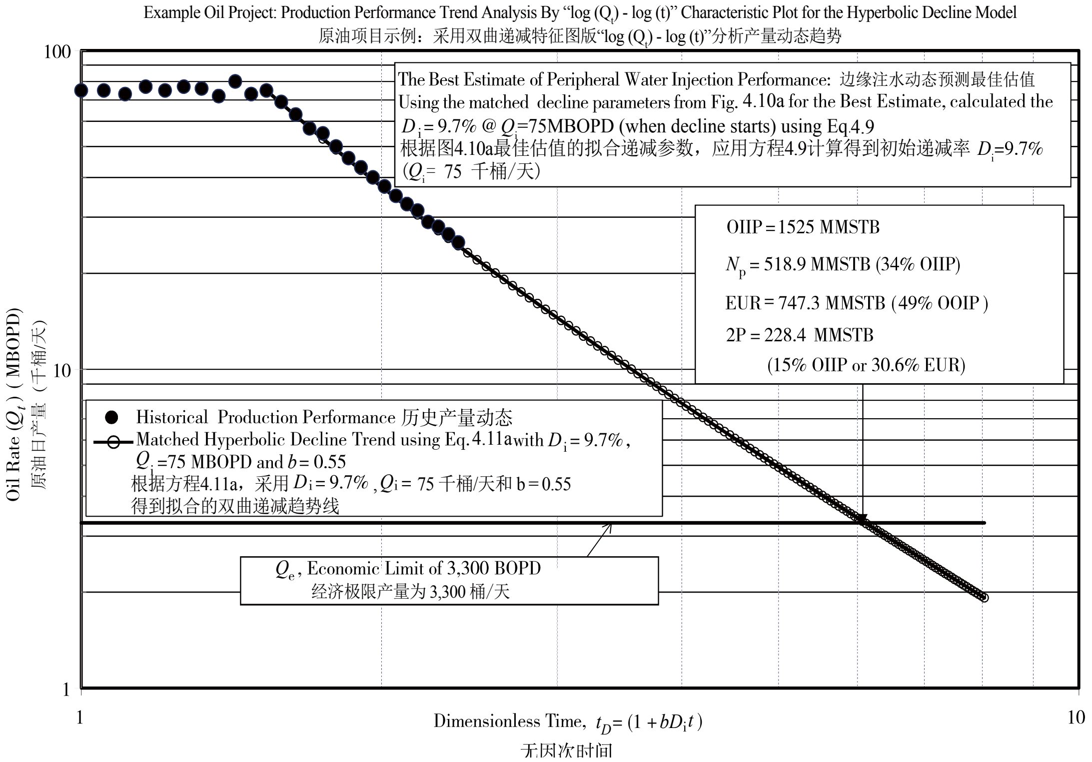


Figure 4.10 b Dynamic and Direct Assessment of Reserves by TDA.

图 4.10 b 常规动态法递减分析评估储量

the actual data (represented by black dots) relative to the calculated data (represented by hollow diamonds, circles, and squares) in Figure 4.10a and the resulting similar high-quality decline trend match obtained in the characteristic linear plot of Figure 4.10b for the best scenario only (for simplicity in the presentation). It confirms a higher-quality match obtained using a more reliable and repeatable EPRCO procedure of estimating these unknown decline parameters sequentially. The traditional trial-and-error method attempts to estimate the complex arbitrary constant C (= b×D_i) and b simultaneously, usually yielding erroneous results because the evaluation of "b" is known to be very insensitive to this procedure [Fekete Associates (2008)].

Table 4.10 documents the resulting reserves categories of 1P, 2P, and 3P estimated based on the plausible scenarios of low, best, and high production performance analyzed and exhibited above, which was supported by the example project under an effective peripheral water injection operation (without artificial lift using ESPs) observed over the past 26 years.

Based on the similar reasons and rationale developed and discussed earlier under Reservoir Simulation Methods, the second combined peripheral waterflood with artificial lift project was expected to have additional oil recovery of 5% OIIP over peripheral waterflood, bringing the project recovery to 54% OIIP for the best scenario. Similarly, these

（1+bD_it）双对数特征线型图版。鉴于 EPRCO 方法所获得的高质量拟合结果已在图 4.10a 中得到实际生产数据的印证（实心黑点为实际数据，空心的菱形、圆圈和正方形为计算数据），图 4.10b 仅为最佳估值情景基于特征线型图版所得到拟合的高质量递减趋势线及拟合结果。这验证了 EPRCO 方法可重复、更可靠，通过有步骤地确定未知递减参数，可获得最佳拟合结果。常规试凑法同时估算复杂的任意常数 C（=b×D_i）和递减指数 b 值，通常会导致错误结果，因为 b 值对该方法不敏感（Fekete Associates，2008）。

基于案例油藏过去 26 年的有效边缘注水开发（无电潜泵人工举升），表 4.10 列出了 3 种生产动态情景（低、最佳和高）对应的 1P、2P 和 3P 储量估算结果。

根据前面油藏模拟方法一节所讨论和得出的类似依据与原因，第二种组合开发方式（边缘水驱结合人工举升）最佳情景可比边缘水驱（基础方案）提高采收率 5% 至 54%（OIIP）。与前面

additional reserves are placed in Proved with Proved Undeveloped status for now, subject to transfer to Proved Developed in 2 years (or in Year 28) when the project is expected to be completed and put on-stream.

情形类似，目前新增的储量划为证实储量，状态为未开发，可在 2 年后（或第 28 年）待项目全面建成和投入运营再升级为证实已开发。

Table 4.10　Assessment using Decline Curve Analysis（Production Decline Period）: Estimates of Project EURs and Reserves under Peripheral Waterflood Only
表 4.10　递减曲线分析评估储量（产量递减期）：边缘注水项目估算最终可采量和储量

Measured and Estimated Parameters 计量与估算参数		Units 单位	Bases and Estimates by Reserves Category 基础数据和各级储量估值		
			Low Estimate 低估值	Best Estimate 最佳估值	High Estimate 高估值
Cumulative Production 累计产量	Oil 原油	MMSTB	518.9	518.9	518.9
		%（OIIP）	34.0	34.0	34.0
	Raw Gas 原料气	Bscf	295.8	295.8	295.8
Oil Initially-In-Place（OIIP） 原油原始原地量		MMSTB	1525	1525	1525
Recovery Factors Calculated [1] 测算采收率		%（OIIP）	46.0	49.0	54.0
Recoverable Oil（EUR） 原油估算最终可采量	Original 原始	MMSTB	701.5	747.3	823.5
	Remaining [3] 剩余	MMSTB	182.6	228.4	304.6
Initial Solution Gas-Oil Ratio（R_{si}） 原始溶解气油比		scf/STB	570	570	570
Gross-heating Value of Raw Solution Gas 溶解气总热值		Btu/scf	1350	1350	1350
Gas Initially-In-Place（GIIP） 溶解气原始原地量		Bscf	869.3	869.3	869.3
Recoverable Raw Gas（EUR） 原料气估算最终可采量	Original 原始	Bscf	399.9	426.0	469.4
		MMBOE[2]	93.1	99.1	109.3
	Remaining [3] 剩余	Bscf	104.1	130.2	173.6
		MMBOE[2]	24.2	30.3	40.4

[1] As a ratio of "direct estimates of project EURs under peripheral water injection" and "the project OIIPs, if available".
边缘注水项目的最终可采量直接评估结果与项目原始原地量（若有的话）的比值。

[2] Calculated using an average conversion factor of 5.8 MMBtu per BOE.
使用平均转换系数 5.8MMBtu/BOE 进行计算。

[3] Estimated Oil and Raw Gas Reserves categories of 1P, 2P and 3P, respectively.
原油和原料气的 1P、2P 和 3P 储量估值。

Table 4.10 a summarizes the resulting EURs and reserves categories for the peripheral waterflood with artificial lift project as they were recalculated using the increased recovery efficiencies of 51%, 54%,

表 4.10 a 列出了项目采用边缘水驱结合人工举升情景的最终可采量与储量估算结果——根据提高后的采收率（51%，54% 和 59%）重新计算

and 59% of the OIIPs. The estimates were considered to have a slightly reduced degree of uncertainty relative to those obtained under the peripheral waterflood project only (refer to Table 4.10).

It may be important to point out the following qualifications about the oil example project producing under peripheral water injection:

① As summarized in Table 4.10, the low, best, and high project EURs and Reserves are estimated directly. Although it was not necessary to know the latest estimates of respective OIIPs, it would have been definitely desirable. They were not available at the time. For a relative illustrative purpose, the best estimate of 1,525 MMSTB was used to show the recoverable estimates in terms of percent OIIP as well, and to report in respective figures and tables.

② Since last assessment using reservoir simulation models, the project had produced another 120 MMSTB, bringing the total to 518.9 MMSTB (34% of OIIP) in 26 years, drilled and analyzed 15 additional new wells, and obtained numerous well tests thereby reducing uncertainty in the new estimates. The EURs represented relative waterflood recovery efficiencies of 46%, 49%, and 54% of this single OIIP estimate, respectively and correspond to project economic lives (at around 3 MBOD) estimated to be 78, 96 and 127 years, respectively. Long economic and/or operation project lives such as these should not be assumed without proper consideration and documentation. In this example the estimates were considered valid because:

a. The best or 2P estimate of 228.4 MMSTB (or remaining reserves) represents only 15% OIIP or about 30% of the 747.3 MMSTB EUR (see Table 4.10).

b. In actual practice, for projects with long-life reserves exceeding 100 years, depending on the sustainable future growth in worldwide demand for oil, the project's economic life will most likely vary between 50 and 70 years as a natural consequence of the higher depletion rates, which are not only required to meet the expected target production rates, but also result from implementation of the approaching planned artificial lift using ESPs and EOR projects. They are needed to both accelerate production (e.g., higher depletion rates) and increase ultimate recovery.

The incremental 7% OIIP oil recovery by artificial lift using ESPs (discussed earlier under Reservoir Simulation Methods) was revised downward to 5% OIIP to further ensure reasonable confidence and to bring the overall project recovery to 54% OIIP for the "best scenario." Similarly, these additional reserves are placed in Proved Undeveloped status for now, subject to Proved Developed status in 2 years (or in Year 28), when the project is expected to be completed and put on-stream.

Table 4.10a summarizes the resulting EUR's and reserves categories for the peripheral waterflood with artificial lift project recalculated using the increased recovery efficiencies of the peripheral waterflood by a constant 5% OIIP to 51%, 54%, and 59% of the OIIPs.

得到。相对于仅实施边缘水驱的项目而言，该结果的不确定性程度略有降低（参见表 4.10）。

针对本案例项目（边缘注水开发）的评估工作，需强调以下质量保障事项：

① 表 4.10 中，项目估算最终可采量和储量的低估值、最佳估值和高估值是通过直接估算得到的。尽管不需知道相应的最新原始原地量评估结果，但如果有的话是最理想的。当时可能没有该数据，为了对比说明，使用最佳估值 1525MMSTB 以及 OIIP 百分数的形式来体现最终可采量估值，并在相应图表中进行报告。

②自上一阶段油藏数值模拟评估之后，该项目又生产原油 120MMSTB，使前 26 年生产期的原油累计产量达到 518.9MMSTB（采出程度 34%OIIP）。该阶段新完钻和测试了 15 口井，获得大量资料，进一步降低了评估的不确定性。最终可采量的估算是基于相同 OIIP 和水驱采收率 46%、49% 和 54%——在经济极限为 3MBOPD 时所对应的项目经济生命期分别为 78 年、96 年和 127 年。如此长的项目经济生命期或作业期，若没有合理原因和文书依据是不予考虑的。本案例的评估结果是合理可靠的，原因如下：

(a) 最佳估值或 2P 估值为 228.4MMSTB（或剩余经济可采量），为原油原始原地量 15% 或估算最终可采量 747.3MMSTB 的 30%（参见表 4.10）。

(b) 实践中，对于储量寿命超过 100 年的项目，根据未来世界对石油需求的可持续增长情况，项目的经济生命期很可能因为开采速度加大而在 50~70 年之间变化。这不仅要求提高目标产量，也需要实施计划的电潜泵人工举升和提高采收率项目，以加速油藏开采和提高最终可采量。

为进一步保障合理确定性，将前期油藏模拟研究评估的电潜泵人工举升采收率增量由 7% 下调至 5%，项目最佳估值情景的采收率相应地调整为 54%。同样，目前将这一部分储量增量归置为证实未开发状态，待 2 年后（第 28 年）项目全面建成运营时再转为证实已开发。

表 4.10a 汇总了边缘水驱结合人工举升项目的最终可采量和各级储量结果。该结果是在边缘水驱基础上分别考虑 5% 采收率增量（分别至 51%、54% 和 59%OIIP）进行重新计算而得到的。

Table 4.10 a　Assessment using Decline Curve Analysis（Production Decline Period）：
Estimates of Project EURs and Reserves under Peripheral Waterflood with ESPs
表 4.10 a　递减曲线分析评估（产量递减期）：油藏边缘水驱 + 电潜泵开发项目估算最终可采量和储量

Measured and Estimated Parameters 计量和估算参数		Units 单位	Bases and Estimates by Reserves Category 基础数据和各级储量估值		
			Low Estimate 低估值	Best Estimate 最佳估值	High Estimate 高估值
Cumulative Production 累计产量	Oil 原油	MMSTB	518.9	518.9	518.9
		%（OIIP）	34.0	34.0	34.0
	Raw Gas 原料气	Bscf	295.8	295.8	295.8
Oil Initially-In-Place（OIIP） 原油原始原地量		MMSTB	1525	1525	1525
Recovery Factors Calculated [1] 估算采收率		%（OIIP）	51.0	54.0	59.0
Recoverable Oil（EUR） 原油估算最终可采量	Original 原始	MMSTB	777.8	823.6	899.8
	Remaining [3] 剩余	MMSTB	258.9	304.7	380.9
Initial Solution Gas-Oil Ratio（R_{si}） 原始溶解气油比		scf/STB	570	570	570
Gross-heating Value of Raw Solution Gas 溶解气总热值		Btu/scf	1350	1350	1350
Gas Initially-In-Place（GIIP） 溶解气原始原地量		Bscf	869.3	869.3	869.3
Recoverable Raw Gas（EUR） 原料气估算最终可采量	Original 原始	Bscf	443.3	469.4	512.9
		MMBOE [2]	103.2	109.3	119.4
	Remaining [3] 剩余	Bscf	147.5	173.7	217.1
		MMBOE [2]	34.3	40.4	50.5

[1] Under peripheral water injection (see Table 4.10), supplemented with field-wide installed artificial lift using ESPs.
边缘注水（参见表 4.10），辅以全油田电潜泵人工举升开发。

[2] Calculated using an average conversion factor of 5.8 MMBtu per BOE.
使用平均转换系数 5.8MMBtu/BOE 进行计算。

[3] Estimated Oil and Raw Gas Reserves categories of 1P、 2P and 3P, respectively.
原油和原料气的 1P、2P 和 3P 储量估值。

Similarly, supported further by the full performance of a second analog CO_2 miscible pilot project nearby with a realized incremental recovery efficiency of about 20% OIIP, it was judged prudent to revise the incremental recovery efficiencies (assigned earlier under Reservoir Simulation Methods) downward by 2% to 13%, 16%, and 20% OIIP, respectively, bracketing the uncertainty for the planned CO_2 miscible project (scheduled to be on-stream by Year 32). The respective Contingent Resources categories of 1C, 2C, and 3C are summarized in Table 4.10b.

相似地，进一步根据邻区第二个 CO_2 混相驱先导试验类比项目的完整动态与成效（采收率增量约 20%OIIP），谨慎地将前期油藏数模评估的采收率增量分别下调 2% 至 13%、16% 和 20%，以控减 CO_2 混相驱项目（计划第 32 年实施）的不确定性。相应的 1C、2C 和 3C 条件资源量估值结果汇于表 4.10b。

Table 4.10 b Assessment of Contingent Resources (Production Decline Period): EURs under a Planned CO_2 Miscible Project
表 4.10 b 条件资源量评估（产量递减期）：CO_2 混相驱规划项目估算最终可采量

Measured and Estimated Parameters 计量和估算参数	Units 单位	Bases and Estimates by Contingent Resources Category 基础数据和条件资源量估值		
		Low Estimate 低估值	Best Estimate 最佳估值	High Estimate 高估值
Oil Initially-In-place (OIIP) 原油原始原地量	MMSTB	1525	1525	1525
Initial Solution Gas-Oil Ratio (R_{si}) 原始溶解气油比	scf/STB	570	570	570
Gross-Heating Value of Raw Solution Gas 溶解气总热值	Btu/scf	1350	1350	1350
Incremental Recovery Factor [1] 采收率增量	%（OIIP）	13	16	20
Recoverable Oil（EUR）[3] 原油估算最终可采量	MMSTB	198.3	244.0	305.0
Recoverable Raw Gas （EUR）[3] 原料气估算最终可采量	Bscf	113.0	139.1	173.9
	MMBOE[2]	26.3	32.4	40.5

[1] Under a CO_2 Miscible Flood based on the results of two implemented analog CO_2 Pilot projects.
CO_2 混相驱，类比两个已实施的 CO_2 先导性试验项目。

[2] Calculated using an average conversion factor of 5.8 MMBtu per BOE.
使用平均转换系数 5.8MMBtu/BOE 进行计算。

[3] Estimated Oil and Gas Contingent Resources categories of 1C, 2C and 3C, respectively.
原油和天然气 1C、2C 和 3C 条件资源量估值。

(3) Modern Decline Analysis (MDA)

Similar to TDA, the objective of MDA is also to determine the best-fit values of constants n and D_i to the observed production rate trend for a well, a number of wells or the entire reservoir. While not illustrated in this particular example oil recovery project, advances in computing have facilitated the application of MDA using type-curve analysis and nonlinear regression techniques. Among many available in the literature, these following two methods are judged to be significantly different and may be used to analyze PPTs using MDA:

① Fetkovich Type-Curve Analysis (Fetkovich 1980 and Fetkovich et al. 1987).

② Hsieh et al. Dual Exponent Power Function Model (Hsieh et al. 2001). PS-CIM (2004) provides a procedure for using spreadsheet software analysis with automatic curve-fitting options to use and apply the Hsieh et al. (2001) method.

Examples for and discussion of these and other methods of both TDA and MDA can also be found in various published articles by Long and Davis (1988), Mannon and Porter (1989), and COGEH Volume 2 (2005).

(4) Other Production Performance Trend Analyses.

There are other well-established production performance analyses that may be used to predict recoverable volumes based on trends

(3) 现代递减分析法（MDA）

和常规递减分析类似，现代递减分析也是基于井、井组或油气藏的产量变化趋势分析，来确定递减参数 n 及 D_i 的最佳拟合值。虽然该方法没有在本指南的原油案例项目中进行阐述，但典型曲线分析和非线性回归技术计算能力方面的优势有力促进了现代递减分析方法的应用。根据现有文献，可知以下两种现代递减分析法可能会用于生产动态趋势分析，但它们有显著的不同之处：

① Fetkovich 典型曲线分析（Fetkovich，1980 和 Fetkovich 等，1987）。

② Hsieh 等的双指数幂函数模型（Hsieh 等，2001）。PS-CIM（2004）提供了具有自动拟合曲线功能的电子表格软件，以方便 Hsieh 方法的应用。

有关常规递减分析法和现代递减分析方法的案例和相关讨论在 Long 和 Davis（1988），Mannon 和 Porter （1989），以及 COGEH 卷 2（2005）等文献中都能找到。

(4) 其他生产动态趋势分析方法

还有其他一些成熟的生产动态分析方法，可以

exhibited for a well and/or a reservoir even before the production rate begins to decline. These reservoir drive specific analyses are briefly discussed by Cronquist (2001). Salient points of these methods may be summarized as follows:

① Cumulative Gas Production vs. Cumulative Oil Production Trends: For oil reservoirs with solution-gas drive, a semi-log plot of log G_p vs. Np_t may develop a trend that could be extrapolated to estimate oil recovery with the maximum G_p being equal to original solution gas in-place (GIIP = R_{si} ×OIIP).

② Water Cut or Water/Oil Ratio (WOR) vs. Cumulative Production Trends: These performance trends have been found particularly useful in analyzing an oil reservoir with waterdrive or producing with downdip water injection and pattern waterflood. The established trend is extrapolated to economic water cut (f_w) or WOR to estimate ultimate recovery under the prevailing production method over which the trend has been established. It may be useful to note the following reported observations:

a. A semi-log plot of “log f_w (or f_o) vs. N_{pt}” trend may turn down at small values f_o but earlier for light oils and later for viscous oils (Brons 1963).

b. A semi-log plot of (WOR+1) and total fluids withdrawal (F_p) vs. time (t) may help define oil rate trend (Purvis 1985). It is reported that a semi-log plot of “(WOR+1) vs. N_{pt}” tends to be linear at WOR’s less than 1 and therefore may help define performance trends at low values of WOR or water cuts.

c. Ershaghi and Omoregie (1978) and Ershaghi and Abdassah (1984) recommended that a plot of $[1/f_w-\ln(1/f_w-1)]$ vs. N_{pt} should be linear. However, they noted that due to the inflection point of the f_w vs. S_w curves, the method will work only at higher water-cuts when $f_w > 50\%$.

It logically follows that one should use Purvis-type performance trend analysis for reservoirs with low water-cuts, and the Ershaghi et al.-type for those with high water-cuts exceeding 50%. Finally, it must be emphasized that although the significant portion of semi-log plot of (k_{rw}/k_{ro}) vs. S_w is linear, the floodout performance of wells and reservoirs are also governed by the rock heterogeneity and the combined impact of gravity, viscous and capillary forces.

Actual PPT analyses require a thorough understanding of their semitheoretical technical bases and the well-established and widely used methods and procedures. However, the correct application of these procedures is not straightforward. One could easily and incorrectly obtain an excellent match, but end up with inaccurate reserves. COGEH Volume 2 (2005) provides the following advice on this very point: “The choice of the best-estimate case reserves, which represents the 2P reserves estimate, must consider the quality of the fit, the uniqueness of the fit, the range of expected exponents, and the reasonableness of the reserves or life. Caution must be used however in relying on computer generated best-

在一口井和 / 或一个油藏的生产动态趋势（甚至递减前）分析基础上预测可采量。Cronquist（2001）简要探讨了这些与油藏驱动机理密切相关的分析方法，要点如下：

①累计产气量— 累计产油量关系趋势分析：对于溶解气驱油藏，可构建累计产气量— 累计产油量的半对数关系图版，然后外推趋势线至最大累计产气量Gp等于初始溶解气原始原地量(GIIP=R_{si}×OIIP)处，确定相应的原油最终可采量估值。

②含水率或水油比（WOR）— 累计产油量关系趋势分析：该方法特别适用于天然水驱、下倾边缘注水和面积注水开发的油藏。根据构建的趋势线外推至经济极限含水率（f_w）或水油比（WOR），则可得到该主控开采方式下的最终可采量估值。应用该方法时，需注意以下方面：

a. “ logf_w（或 f_o）— N_{pt} ” 半对数图版的趋势线会在 f_o 值较低时向下偏移；但对轻质油而言，该现象出现在早期；稠油条件下，出现在后期（Brons，1963）。

b. “[水油比（WOR）+1] - 总液量（F_p）半对数曲线有助于确定原油产量的变化趋势（Purvis，1985）。有关文献报导，（WOR+1）— N_{pt} 半对数图版趋势线在 WOR 小于 1 时表现为线性特征，因而有助于确定低WOR或含水率期的产量动态趋势。

c. Ershaghi 与 Omoregie （1978），Ershaghi 与 Abdassah （1984）推荐的 [1/f_w-ln（1/f_w-1）]— N_{pt} 关系曲线为线性，但由于含水率与含水饱和度关系曲线上存在拐点，该方法在高含水（f_w 大于 50%）时才能应用。

正常情况下，低含水油藏可应用 Purvis 典型曲线分析动态趋势；含水率超过 50% 的高含水油藏应采用 Ershaghi 等人的典型曲线。最后，需强调，尽管大部分（K_{rw}/K_{ro}）— S_w 半对数图是线性的，但井与油藏的水淹动态规律还受控于岩石非均质性，以及流体重度、黏度和毛管压力的综合影响。

生产动态趋势分析方法的实际应用需要全面了解其半理论技术基础，以及其已成熟和广泛应用的方法与步骤。当然，这些方法的正确应用并非轻而易举。有时可能很容易就得到很好的拟合，但方式方法并不正确，得到的储量结果也是不正确的。对于上述问题，COGEH 卷 2 (2005) 建议如下：“ 在决策最佳估值情景储量（对应 2P 储量）时，必须考虑拟合的质量和唯一性、递减指数的范围、储量及

fits, because there is always reservoir uncertainty and late time behavior, which may change decline rates and exponents in the future.”

Production performance trends are not only reservoir specific but also depend on the specific reservoir management and production practices. Any significant change in these practices could easily shift and change the previously established decline trends and invalidate their extrapolations. Therefore, proper application of these procedures, to a large extent, depends on the experience and skill levels of the professional evaluators and their ability to judge the reasonableness of results obtained by comparing them to known analogs and/or other performance-based methods.

4.3 Summary of Results

Consistent with PRMS guidelines on petroleum resources and reserves definitions, classification and categorization, different deterministic assessment methods and procedures have been used to estimate oil and raw gas resources and reserves for an example oil project. The project retraces its E&P life cycle, starting from the exploration (pre- and post-discovery stages) and appraisal phase and going through all three stages (including initial development) of its production phase (refer to Figures 4.1 and 4.1a). It covers 5-year appraisal and initial development period after the initial discovery followed by an actual production history of 26 years.

Results of project’s OIIPs and EURs of oil resources and reserves estimated using Volumetric and Analogous Methods during its Exploration and Appraisal Phase and Initial Development Period are summarized in Figure 4.11.

其生命期的合理性。虽然拟合过程主要由计算机完成，但需特别小心，因为油藏总存在不确定性，运营的变化可能会改变未来的递减率与递减指数。”

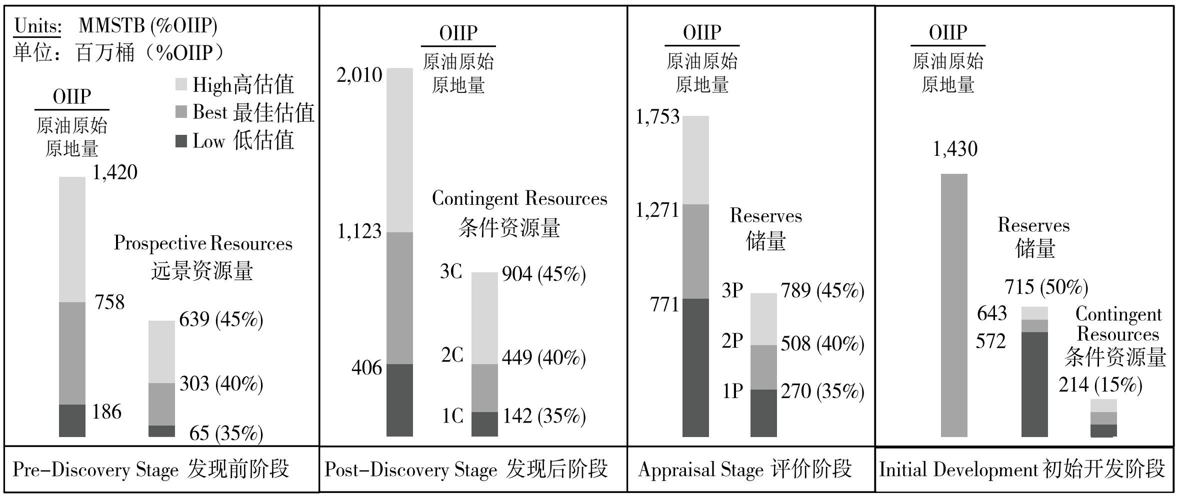
生产动态的趋势不仅依赖于油气藏的特性，还依据于油气藏管理和生产开发的实践过程。实践中任何大的变化都可能轻易改变已形成的递减趋势，使得外推结果无效。因此，这些方法的合理应用，很大程度上依赖于专业评估师的经验与技能，及其对各种方法（类比和 / 或其他动态方法）评估结果合理性的判断能力。

4.3 结果小结

遵循 PRMS 关于石油资源量和储量的定义、分类和分级，原油案例项目应用了不同确定性评估方法和程序来评估原油和原料气的资源量和储量。本案例追溯项目的勘探与生产生命期，从勘探（发现前和发现后）和评价期开始，然后经历生产期的三个阶段（包括开发初期，参见图 4.1 和图 4.1a），包括初始发现之后的 5 年评价与开发初期，以及随后 26 年的实际生产历史。

如图 4.11 展示了在勘探、评价和开发初期阶段，采用容积法和类比法评估的项目原油原始原地量（OIIP）与估算最终可采量（EUR）。

Estimates of OIIP , EURs and Reserves using Volumetric and Analogous Methods
容积法和类比法估算的原油原始原地量、最终可采量与储量结果



Source: Table4.1 Table4.2 Table4.3 Table4.4
来源： 表 4.1 表 4.2 表 4.3 表 4.4

Figure 4.11 Project Resources and Reserves Assessment during Exploration and Appraisal Phase：Estimates of OIIP, EURs and Reserves using Volumentric and Analogous Methods

图 4.11 勘探与评价阶段资源量和储量评估：容积法和类比法评估原油原始原地量、估算最终可采量与储量

Table 4.11　Reserves Assessment using Performance-Based Methods: Estimates of Project OIIPs, EURs and Reserves during Production Phase

表 4.11　动态法储量评估（生产期）：项目原油原始原地量、估算最终可采量与储量

Assessment Method、Depletion Stage & Parameters 评估方法、开采阶段和参数	Units 单位	Estimates under Waterflood Performance only 注水开发动态评估			Estimates under Waterflood and Artificial Lift Perfomance 注水 + 人工举升动态评估		
		Low Estimate 低估值	Best Estimate 最佳估值	High Estimate 高估值	Low Estimate 低估值	Best Estimate 最佳估值	High Estimate 高估值
Assessment Method：Material Balance（MB） Analyses（Source:Table 4.6） 评估方法：物资平衡法分析（来源：表 4.6）							
Depletion Stage：Early Production Stage with 8 years of actual production performance 开采阶段：稳产早期—— 8 年实际生产数据							
Cumulative Production 累计产量	MMSTB	220.8	220.8	220.8			
An Indication of Project Maturity 项目成熟度指标	%（OIIP）	17.0	13.8	11.0			
Oil Initially-In-place（OIIP） 原油原始原地量	MMSTB	1300	1600	2000			
Recovery Factor 采收率	%（OIIP）	40	45	50			
Recoverable Oil（EUR） 原油估算最终可采量	MMSTB	520	720	1000			
Oil Reserves 原油储量	MMSTB	299	499	779			
Assessment Method：Reservoir Simulation Model （RSM） Studies （Source: Tables 4.8 and 4.8a） 评估方法：油藏数值模拟（RSM）研究（来源：表 4.8 和表 4.8 a）							
Depletion Stage：Early Decline Stage with 16 years of actual production perfomance 开采阶段：递减早期—— 16 年实际生产数据							
Cumulative Production 累计产量	MMSTB	399.0	399.0	399.0	399.0	399.0	399.0
An Indication of Project Maturity 项目成熟度指标	%（OIIP）	27.8	26.2	23.0	27.8	26.2	23.0
Oil Initially-In-place（OIIP） 原油原始原地量	MMSTB	1434	1525	1739	1434	1525	1739
Recoverable Oil（EUR） 原油估算最终可采量	MMSTB	573	686	869	674	793	991

Assessment Method、Depletion Stage & Parameters 评估方法、开采阶段和参数	Units 单位	Estimates under Waterflood Performance only 注水开发动态评估			Estimates under Waterflood and Artificial Lift Perfomance 注水 + 人工举升动态评估		
		Low Estimate 低估值	Best Estimate 最佳估值	High Estimate 高估值	Low Estimate 低估值	Best Estimate 最佳估值	High Estimate 高估值
Implied Recovery Factor 采收率	%（OIIP）	40	45	50	47	52	57
Oil Reserves 原油储量	MMSTB	174	287	470	275	394	592
Assessment Method：Production Performance Trend（PPT）Analysis. （Source:Tables 4.10 and 4.10 a） 评估方法：生产动态趋势（PPT）分析（来源：表 4.10 和表 4.10 a）							
Depletion Stage：Late Decline Stage with 26 years of actual production performance 开采阶段：递减后期—— 26 年实际生产动态							
Cumulative Production 累计产量	MMSTB	518.9	518.9	518.9	518.9	518.9	518.9
An Indication of Project Maturity 项目成熟度指标	%（OIIP）	34.0	34.0	34.0	34.0	34.0	34.0
Oil Initially-In-place（OIIP）原油原始原地量	MMSTB	1,525	1,525	1,525	1,525	1,525	1,525
Recoverable Oil（EUR）原油估算最终可采量	MMSTB	702	747	824	778	824	900
Implied Recovery Factor 采收率	%（OIIP）	46	49	54	51	54	59
Oil Reserves 原油储量	MMSTB	183	228	305	259	305	381

Similarly, the results of estimated project OIIPs, EURs, and Reserves using performance-based methods at three different periods during its production phase are presented in Table 4.11. Finally, based on these project OIIPs and the results of nearby analog pilot projects and supported by a reservoir simulation study carried out for the example oil project, the estimated respective Contingent Resources under a planned CO_2 Miscible Project are summarized in Table 4.12. A close examination of Figure 4.11, Tables 4.11 and 4.12 should provide a reasonable picture of how estimates of project in-place and recoverable quantities (reserves and/or resources) could change over its E&P life cycle.

类似地，表 4.11 列出了在项目生产期三个不同阶段基于动态方法评估的原油原始原地量（OIIP）、估算最终可采量（EUR）和储量。最后，根据上述评估获得的 OIIP，邻区类比项目先导试验结果，以及该案例项目的油藏数模研究成果，对一个 CO_2 混相驱规划项目所确定的条件资源量进行了评估，结果汇于表 4.12。对比分析图 4.11、表 4.11 和表 4.12，则可以了解项目的原地量和可采量（储量和 / 或资源量）在其勘探与生产生命期的变化过程。

Table 4.12 Assessment of Contingent Resources Estimates of Project OIIPs and EURs during Production Phase

表 4.12　条件资源量评估（生产期）：项目原油原始原地量和估算最终可采量

Assessment Method 评估方法	Depletion Stage 开采阶段	Parameters 参数	Units 单位	Bases and Estimates by Contingent Resources Category（under a Planned CO_2 Miscible Project） 基础数据和各级条件资源量估值（CO_2 混相驱规划项目）		
				Low Estimate 低估值	Best Estimate 最佳估值	High Estimate 高估值
Material Balance and Analogous Methods（Source:Table 4.6） 物质平衡分析和类比法 （来源：表 4.6）	Early Production Stage: 8 years of production performance under Peripheral Waterflood and results of one analog CO_2 Pilot 稳产早期： 8 年实际水驱动态数据和 1 个 CO_2 混相驱先导性试验类比项目	Cumulative Production 累计产量	MMSTB	220.8	220.8	220.8
		An Indication of Project Maturity 项目成熟度指标	%（OIIP）	17.0	13.8	11.0
		Oil Initially-In-Place（OIIP） 原油原始原地量	MMSTB	1300	1600	2000
		Incremental Recovery Factor 提高采收率	%（OIIP）	5	10	15
		Recoverable Oil（EUR） 原油估算最终可采量	MMSTB	65	160	300
Reservoir Simulation Model Studies and Analogous Methods（Source:Table 4.8 b） 油藏数值模拟研究和类比法 （来源：表 4.8 b）	Early Decline Stage: 16 years of production performance under Peripheral Waterflood and the results of two analog CO_2 Pilots（only one fully realized） 递减早期： 16 年实际水驱动态数据和 2 个 CO_2 混相驱先导试验类比项目（仅 1 个已完全实施）	Cumulative Production 累计产量	MMSTB	399.0	399.0	399.0
		An Indication of Project Maturity 项目成熟度指标	%（OIIP）	27.8	26.2	23.0
		Oil Initially-In-Place（OIIP） 原油原始原地量	MMSTB	1434	1525	1739
		Incremental Recovery Factor 提高采收率	%（OIIP）	15	18	22
		Recoverable Oil（EUR） 原油估算最终可采量	MMSTB	215	275	382
Single OIIP Estimate and Analogous Methods（Source:Table 4.10 b） 相同原始原地量和类比法 （来源：表 4.10 b）	Late Decline Period 26 years of production performance under Peripheral Waterflood and fully realized results of two analog CO_2 Pilots 递减后期： 26 年实际水驱动态数据和 2 个完全实施的 CO_2 混相驱先导试验类比项目	Cumulative Production 累计产量	MMSTB	518.9	518.9	518.9
		An Indication of Project Maturity 项目成熟度指标	%（OIIP）	34.0	34.0	34.0
		Oil Initially-In-Place（OIIP） 原油原始原地量	MMSTB	1525	1525	1525
		Incremental Recovery Factor 提高采收率	%（OIIP）	13	16	20
		Recoverable Oil（EUR） 原油估算最终可采量	MMSTB	198	244	305

As a concluding remark, it may be beneficial to reiterate the commonly practiced development and production strategy for projects with long-life reserves similar to our example oil project. Because of the availability of many development opportunities in excess of their development needs, oil reservoirs have been developed at relatively low annual depletion rates from 2 to 5% of EUR initially by many Middle East producers. That is why the full reservoir development (drilling of all well-spacing units) typically requires 20 to 30 years to complete, and extends the economic lives beyond 100 years. Having the leverage to practice a low reservoir depletion strategy and continuous drilling to maintain the initially established plateau production rate as long as possible provides significant benefits including the opportunity to take better advantage of new technological advancements to maximize the ultimate recovery and keep the unit development and production costs at significantly lower levels than those prevalent elsewhere.

Key takeaways from this chapter are as follows:

(1) Petroleum resources assessment is and must be a continuous ongoing technical process supported by good practices and collaborative efforts across many disciplines.

(2) Petroleum resources assessment should use the methods most suitable for analyzing the data available, including static geoscientific and engineering as well as dynamic actual production performance, and be carried out by a collaborative multidisciplinary team of expert evaluators consisting of geoscientists and engineers.

(3) Assessment of subsurface petroleum resources is complex and subject to many uncertainties in static and dynamic reservoir parameters coupled with regulatory, operational and economic uncertainties. Although exceptions will continue to exist, the quantity of reliable data and degree of certainty in the estimates of PIIP and EUR are expected to increase over time.

(4) Irrespective of project maturity and the amount and quality of performance data available, the degree of certainty in resource estimates largely depends on the ability of experienced reserves evaluation professionals not only to know the most appropriate methods to use, but also to exercise prudent judgment, ensuring the reasonableness and validity of these estimates by always comparing them with those estimated using different methods and/or with the known analog reservoirs.

(5) Use of the full PRMS classification and categorization matrix provides a standardized framework for characterizing the estimates of marketable hydrocarbon volumes according to their associated risks and uncertainties.

作为结束语，为有利于实践，这里要重申储量生命期长的项目（类似本指南原油项目案例）的通用开发与生产策略。由于油藏的开发潜力远超过需求，中东许多油气生产商都是选择较低的初始开采速度（估算最终可采量的 2% 至 5%）进行油藏开发。这使得油藏的整体开发建设（完钻所有井）通常需要 20 ～ 30 年才能完成，经济生命期可长达 100 年以上。实施油藏低速开发策略和持续钻井的好处是可以尽可能长时间地维持油藏初始高峰产量，给生产商带来巨大收益，包括有更多机会利用新技术的进步来最大化最终可采量，使开发与生产的单位成本远低于普遍水平。

本章的重要结论如下：

（1）石油资源评估是且必须是一项持续开展的技术工作，需要丰富的实践经验和多学科的协作。

（2）石油资源评估应根据已有数据（包括地质、工程静态数据，也包括实际生产动态数据）情况选用最适合的评估方法，并由地质师和工程师组成的多学科专业评估师团队开展评估工作。

（3）评估地下石油资源是一项复杂工作，很容易受油藏动态、静态数据的不确定性，以及规章制度、作业与经济不确定性等多方面因素的影响。除非特殊情况，随着时间的推移和可靠数据数量的增加，原始原地量和最终可采量估值的可靠性程度也会增加。

（4）无论项目成熟度和可用动态数据的数量与质量如何，资源评估的确定性主要依赖于专业评估师的技能与经验，不仅要会使用最适合的评估方法，也要会谨慎判断，对比不同评估方法和 / 或类比油藏的结果，确保评估结果的合理性与有效性。

（5）应用完整的 PRMS 分类分级格架，可为可销售油气量评估风险与不确定性的表征提供标准框架。

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第 5 章
CHAPTER 5

概率法储量估算
Probabilistic Reserves Estimation

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5.1 Introduction

Understanding and managing the range of uncertainty in reserves and resources estimation are important aspects of the business of exploration and production of oil and gas. Oil and gas professionals want to capture this uncertainty in order to

(1) Make development plans that can cover the range of possible outcomes

(2) Provide a range of production forecasts to evaluate the expected outcome of their ventures

(3) Measure exploration, appraisal, and commercial risks

(4) Ensure that they can handle an unfavorable outcome (i.e., that they have an economic project, even if the low case materializes)

(5) Understand and communicate the confidence level of their reserves estimate

Approaches to handle uncertainty in resource estimates can be seen on a scale from completely deterministic to fully probabilistic as follows:

(1) The Deterministic Method—A single value is used for each parameter, resulting in a single value for the resource or reserves estimate. The estimated volumes can be categorized as Proved, Probable, or Possible in the incremental approach, or 1P, 2P, or 3P in the cumulative approach described in the PRMS, depending on the level of uncertainty. Each of these categories can be related to specific areas or volumes in the reservoir.

(2) The Scenario Method (sometimes called Realizations Method)—This is essentially an extension of the Deterministic Method. In this case, a range of possible deterministic outcomes or scenarios is described. Usually, this collection of scenarios is then translated into a pseudoprobability curve. The scenario method combines elements of the deterministic approach and of the full probabilistic method.

(3) The Probabilistic Method—The statistical uncertainty of individual reservoir parameters is used to calculate the statistical uncertainty of the in-place and recoverable resource volumes. Often a stochastic (e.g., Monte Carlo) method is applied to generate probability functions by randomly sampling input distributions. Such functions lend themselves readily to various quantitative risk analysis and decision-making methods. Probability levels of the total recoverable volume can then be related to 1P, 2P, and 3P reserve categories, or the corresponding resources categories, using the Petroleum Resources Management System (SPE-PRMS, 2007) guidelines. In many cases, there is no one-to-one relation between one of these outcomes and a physical volume or area in the reservoir.

5.1 引言

认识和管理储量与资源量评估的不确定性范围是油气勘探和生产业务的重要内容。油气行业的专家们希望把握其不确定性，以便开展以下工作：

（1）编制开发方案，涵盖可能的开发方案结果；

（2）预测产量范围，以评估投资的预期结果；

（3）衡量勘探、评价和商业风险；

（4）确保能应对处理不利结果的出现（即便出现低估值情景，项目也是经济的）；

（5）了解和互通储量估值的置信度。

可以采用多种方法处理资源评估中不确定性，从完全确定法到完全概率法，如下所示：

（1）确定法：每个参数选用一个单一数值，也得到一个单一的资源量或储量估算结果。在PRMS中，根据不确定性程度，估算的体积量可按增量法分级为证实、概算或可能储量，或采用累积法分级为1P、2P或3P。每个级别都对应于油气藏中的具体区域或体积。

（2）情景法（有时也称实现法）：其实质是确定法的延伸。采用该方法可得到一系列确定法可能结果或情景。通常，这些情景的组合可转换为一条视概率曲线。情景法结合了确定法和完全概率法的要素。

（3）概率法：利用一个油气藏参数的不确定性统计分布曲线来计算原始原地量和可采资源量的不确定性范围。通常可采用随机模拟方法（如蒙特卡洛法）从输入分布曲线中随机采样，生成概率函数。这些函数可很容易地用于各种量化风险分析与决策方法。按照《石油资源管理系统》（SPE-PRMS，2007），总可采量的概率分布可与1P、2P和3P储量级别或相应资源量级别相关联。多数情况下，这些结果与具体油气藏的体积或面积之间没有一一对应的关系。

本章重点介绍了上述三种方法中的后面两种方法。与第一种确定法相比，后两者均具有概

This chapter focuses on the last two of these three approaches, which both have a probabilistic nature, as opposed to the first approach, which is deterministic. Increasingly, industry and regulatory bodies are accepting the use of these methods; see for example, the modernized US Securities and Exchange Commission rules (US SEC 2008).

The value of the probabilistic and scenario methods in the business process is that

(1) Both describe the full range of uncertainty and reveal upsides and downsides

(2) They easily allow calculation of the value of information of various activities

(3) Both allow calculation of effects of interdependent uncertainties

(4) They provide a good interface with decision support and financial modeling methods

(5) Both methods can easily be applied across the boundary between exploration and production activities

We will briefly describe the deterministic method, then we will discuss the scenario approach, and finally we will address issues in the application of probabilistic methods.

5.2 Deterministic Method

The deterministic method uses a single value for each parameter, based on a well-defined description of the reservoir, resulting in a single value for the resource or reserves estimate. Typically, three deterministic cases are developed to represent either low estimate (1P or 1C), best estimate (2P or 2C), or high estimate (3P or 3C), or Proved, Probable, and Possible estimates. Each of these categories can be related to specific areas or volumes in the reservoir and a specific development plan.

Advantages of the deterministic method are

(1) The method describes a specific physical case; physically inconsistent combinations of parameter values can be spotted and removed.

(2) The method is direct, easy to explain, and manpower efficient.

(3) The estimate is reproducible.

(4) Because of the last two advantages, investors and shareholders like this method, and it is widely used to report Proved Reserves for regulatory purposes.

A feature and potential weakness of the deterministic method is that it handles each reserves category in isolation and does not quantify the likelihood of the mid, high, and low case.

率法特色。行业和监管机构已逐步接受了这些方法，如美国证券交易委员会的最新披露规定（US SEC，2008）。

概率法和情景法在业务中的价值在于：

（1）均可表征完整的不确定性范围，及其浮动情况；

（2）易于计算各种作业活动的信息价值；

（3）均可计算内在关联的不确定性因素影响；

（4）可为决策支持和财务指标模拟提供良好的衔接；

（5）两种方法均可方便地交互应用于勘探和生产领域。

本章将先简述确定法，然后讨论情景法，最后探讨概率法在应用中应注意的问题。

5.2 确定法

在油气藏精细描述的基础上，确定法的每一个参数均选用一个单一数值，所获得到的资源量或储量估算结果也是一个单一数值。通常，采用三个确定性情景来代表低估值（1P 或 1C）、最佳估值（2P 或 2C）和高估值（3P 或 3C），或者证实、概算和可能储量。每一个级别都与油气藏的具体区域或体积，以及具体的开发方案相对应。

确定法的优点包括：

（1）该方法表述的是一个具体的实际情形；现实中不相匹配的参数组合可以挑出来并予以剔除。

（2）方法简单明了，容易解释，节省人力。

（3）评估过程可重复再现。

（4）由于上述后两个优点，该方法受到投资者和股东青睐，广泛用于向管理机构上报证实储量。

确定法的一个特点和潜在缺陷是每个级别储量均单独评估，未量化中、高和低情景的可能性。

5.3 Scenario Method

The scenario method describes a range of possible outcomes for the reservoir, which are consistent with the observed data. A single, physically consistent outcome within this range with its estimated in-place volume is called a subsurface realization. For the purpose of obtaining a recovery factor, we can then define a development scenario for each subsurface realization and subsequently book recoverable volumes in the appropriate PRMS categories. The collection of scenarios can also be translated into a pseudoprobability curve by assigning associated chances of occurrence. This method combines elements of the deterministic approach and of the full probabilistic method.

Multiple realizations of the subsurface should be

(1) Based on ranked uncertainties. For this purpose we first have to specify and rank the main uncertainties.

(2) Internally consistent (i.e., a realization should consist of parameter values or sets of conditions that can physically exist together).

(3) Associated with a probability of occurrence (but not necessarily equally probable).

(4) Related to a technically sound development option.

When using PRMS, the Proved Reserves are a high-confidence commercial case within the set of scenarios (i.e., a realization that results in a reserves number at the low end of the range).

The scenario method can also be used with each branch representing an individual simulation run (history-matched, if production history exists). By assigning probabilities to these branches, it is possible to define appropriate low (1P or 1C), best (2P or 2C), and high (3P or 3C) estimates from the set of simulation runs. Because this is not strictly a probabilistic method, it is not necessary to select outcomes at precisely the probability equivalents of these categories.

Various methods are available to represent and visualize a set of realizations. The two most important ones are the probability-tree method and the use of scenario matrices.

5.3.1 Probability-Tree Representation of the Scenario Method

When using probability trees to represent scenarios, each branch in the tree represents a set of discrete estimates and associated probability of occurrence, as shown in the relatively simple example in Figure 5.1.

Each end branch in this tree is the result of a possible route along the branching points in the tree and hence represents a specific subsurface realization, for which an in-place volume (Gas Initially-In-Place (GIIP) in this case) can be calculated. The example shows

5.3 情景法

与实际观测数据一致，情景法描述了油气藏一系列可能结果的范围。该结果范围中的一个与实际一致的单一原始原地量估值称为一个地下实现。为了得到采收率，可为每一个地下实现确定一个开发情景，然后为可采量核定适合的 PRMS 级别。为情景组合配置发生几率后，则可以转换成一条视概率曲线。该方法结合了确定法和完全概率法的要素。

地下多重实现应：

（1）基于不确定性排序。为此，必须首先确定主要不确定性，然后排序。

（2）具有内在一致性（也就是说，一个实现应该由一组在现实中同时存在的参数值或条件构成）。

（3）与发生几率关联（但可能性不必等同）。

（4）与一个技术可行开发方案相对应。

当采用 PRMS 时，证实储量是情景组合中具有高置信度的一个商业情景（也就是储量估值处在分布范围低端的那一个实现）。

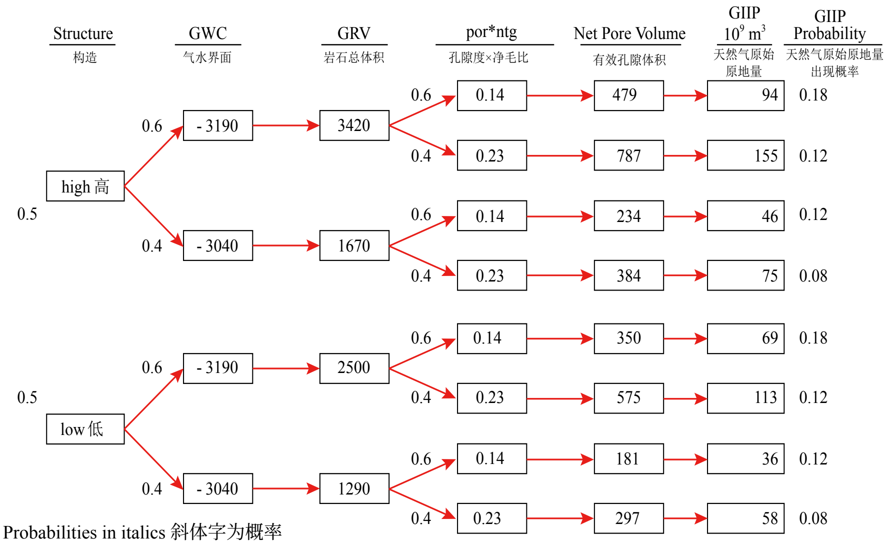
情景法的每一个分支也可用来表示一个模拟运算（基于历史拟合，若有生产历史数据）。为分支赋以概率，就可通过模拟计算确定合理的低估值（1P 或 1C）、最佳值（2P 或 2C）和高估值（3P 或 3C）。由于这并非严格意义上的概率法，不必选择准确的概率值对应的结果作为这些级别的估值。

可通过多种方法来表述和直观展示一组实现。最重要的两种方法是概率树和情景法矩阵。

5.3.1 情景法概率树

当采用概率树表征情景，树的每一个分支代表一组离散的估算值和相应的发生概率，如图 5.1 所示的简单案例。

概率树每一个分支的终点值表示经分支各点之后的一个可能结果，代表一个特定地层条件下的实现，我们可以计算其原始原地量［本案例为天然气原始原地量（GIIP）］。案例中的分支相



Probabilities in italics 斜体字为概率

Figure 5.1　Probability-Tree Example (GRV=gross rock volume; GWC=gas/water contact).

图 5.1　概率树案例（GRV= 岩石总体积；GWC= 气水界面）

that the branches are associated with different probabilities, and thus a combined probability can be calculated for each endpoint. By combining the endpoint GIIP values and their cumulative probabilities, this tree also can be used to generate a cumulative probability curve, which is provided in Figure 5.2, for the example in Figure 5.1. In this curve, the 90, 50, and 10% probability values can be easily identified. In this example, a GIIP estimate of about 40 x 10^9 m^3 has a probability of 90% to be exceeded.

Obviously such a tree can straightforwardly handle dependencies between probabilities on the branching points.

均分配了不同概率值，这样在每个端点就可计算出其组合概率。结合各端点处的 GIIP 值及其累积概率，则可构建相应的累积概率曲线（图 5.1 所示概率树的累积概率曲线参见图 5.2）。从该曲线可很容易地确定 90、50 和 10% 对应的概率值。本案例中，GIIP 估值 40×10^9m^3 所对应的累积概率超过 90%。

很显然，这种概率树能够直截了当地表征各分支点概率值之间的相关性。

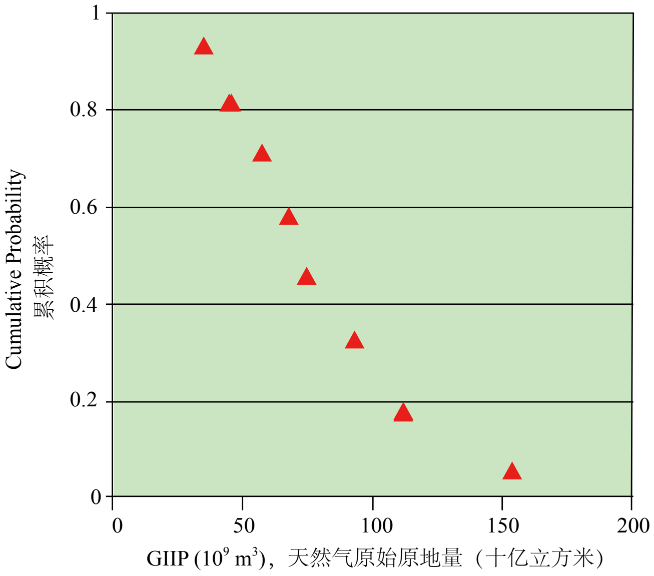


Figure 5.2　Cumulative Probability Density Function (PDF) Constructed from Probability Tree.

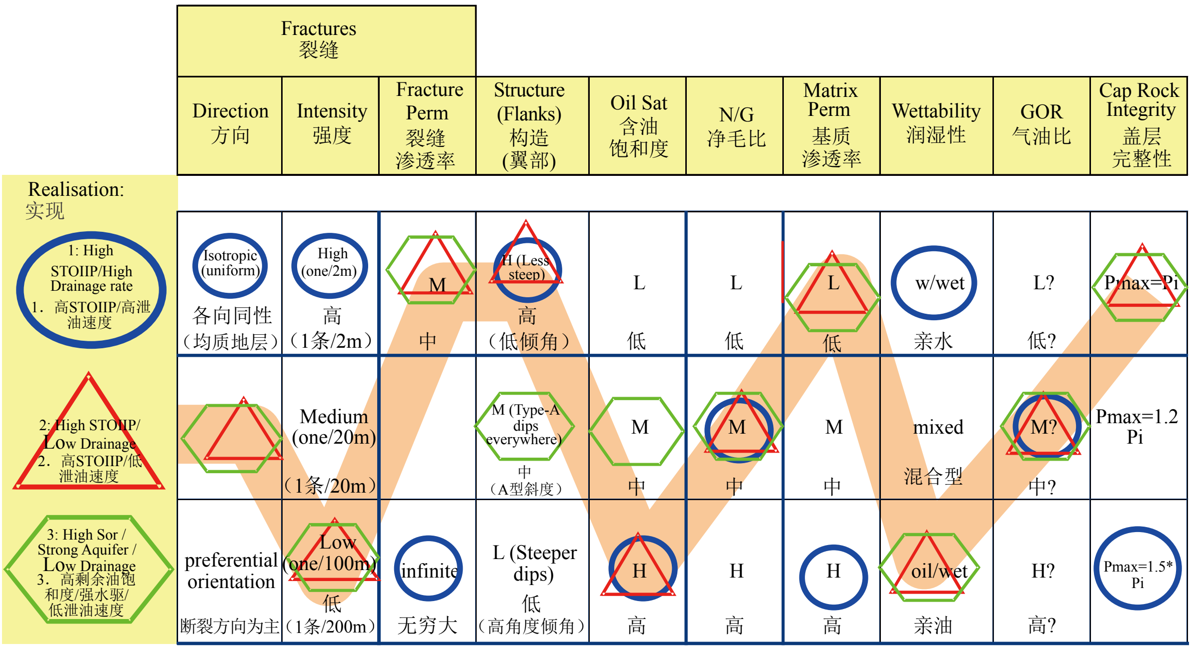
图 5.2　由概率树构建累积概率密度函数（PDF）

5.3.2 Matrix Representation of the Scenario Method

The realization matrices method to represent subsurface realizations and development concepts is more qualitative but often richer in content than the probability-tree method described above. The example in Figure 5.3, modified from a recent project, shows various reservoir aspects that are represented by columns. Each cell in the columns describes a possible outcome. A realization is the consistent combination of a set of possible outcomes. The example also shows that realizations can be described according to a specific theme (e.g., in this case a “High-STOIIP/Low-Drainage” case is represented by triangles in the diagram, while the hexagons represent a scenario characterized by high residual saturation, strong aquifer, and low drainage).

5.3.2 情景法矩阵

实现矩阵法可更定性地表征地层条件下的多个实现和开发理念的方法，比上一节所述的概率树法更富内涵。图 5.3 中的案例是基于近期的一个项目改编的，矩阵的每一列代表油气藏的不同属性。每一列每个方格表示一个可能结果。于是，一个实现则是一组可能结果的匹配组合。从案例可看出，根据特定内容可描述不同实现（例如“ 高 STOIIP/ 低开采速度 ”情景在图中用三角形表示，而六角形代表的情景特征为高残余油饱和度、水体活跃和泄油面积小）。



	Fractures 裂缝									
Realisation: 实现	Direction 方向	Intensity 强度	Fracture Perm 裂缝渗透率	Structure (Flanks) 构造(翼部)	Oil Sat 含油饱和度	N/G 净毛比	Matrix Perm 基质渗透率	Wettability 润湿性	GOR 气油比	Cap Rock Integrity 盖层完整性
1: High STOIIP/High Drainage rate 1．高STOIIP/高泄油速度	Isotropic (uniform) 各向同性（均质地层）	High (one/2m) 高（1条/2m）	M 中	H (Less steep) 高（低倾角）	L 低	L 低	L 低	w/wet 亲水	L? 低?	Pmax=Pi
2: High STOIIP/Low Drainage 2．高STOIIP/低泄油速度		Medium (one/20m) （1条/20m）		M (Type-A dips everywhere) 中（A型斜度）	M 中	M 中	M 中	mixed 混合型	M? 中?	Pmax=1.2 Pi
3: High Sor / Strong Aquifer / Low Drainage 3．高剩余油饱和度/强水驱/低泄油速度	preferential orientation 断裂方向为主	Low (one/100m) 低（1条/200m）	infinite 无穷大	L (Steeper dips) 低（高角度倾角）	H 高	H 高	H 高	oil/wet 亲油	H? 高?	Pmax=1.5* Pi

Figure 5.3 Example of scenario method.

图 5.3 情景法案例

The scenario matrix is useful for generating scenarios that cover a wide range of possible outcomes and hence can play an important role in project-framing exercises. This representation does not allow as much quantitative treatment of probabilities as the scenario tree method. For an example see O’Dell and Lamers (2005).

5.3.3 Strengths and Weaknesses.

The scenario method combines the strengths of probabilistic (stochastic sampling) and deterministic approaches. Its strong points are

(1) It allows generation of subsurface realizations made up of consistent sets of parameters.

(2) It is a useful approach to identify development concepts.

情景法矩阵对于生成多种不同可能结果非常实用，因而可在项目框架设计中起到重要作用，但这种表征方式不能像情景树法那样量化处理大量的概率数据。相关案例可参见 O'Dell 和 Lamers 的文献（2005）。

5.3.3 情景法的优缺点

情景法结合了概率法（随机取样）和确定法的长处。其优点在于：

（1）可生成由关联参数构成的多个地下实现。

（2）是确定开发理念的有效途径。

(3) Development concepts can be tested against all possible reservoir outcomes.

(4) It can be helpful in defining targets for appraisal (through value-of-information analysis).

(5) It provides an auditable method to identify the selected reserves or resources category outcomes.

A weakness of the scenario method is the limited number of scenarios that can usually be handled, with the risk of undersampling the range of possibilities. Assigning a probability to each scenario relies heavily on geological and petroleum engineering judgment. Both of these shortcomings are sometimes tackled by using experimental design methods, as described by Al Salhi et al. (2005).

5.4 Probabilistic Method

In the probabilistic method, we use the full range of values that could reasonably occur for each unknown parameter (from the geosciences and engineering data) to generate a full range of possible outcomes for the resource volume. To do this, we identify the parameters that make up the reserves estimate and then determine a so-called probability density function (PDF). The PDF describes the uncertainty around each individual parameter based on geoscience and engineering data. Using a stochastic sampling procedure, we then randomly draw a value for each parameter to calculate a recoverable or in-place [e.g., stock-tank oil initially-in-place (STOIIP)] resource estimate. By repeating this process a sufficient number of times, a PDF for the STOIIP or recoverable volumes can be created. This Monte Carlo procedure is schematically shown in Figure 5.4.

（3）测试各种开发理念可能带来的各种油气藏开发结果。

（4）有利于确定勘探评价目标（通过信息价值分析方法）。

（5）为储量或资源量评估结果的确定提供核查方法。

情景法的一个缺点是通常可用情景的数量有限，其概率分布有采样点过疏的风险。此外，给每一个情景赋以概率在很大程度上依赖于地质和石油工程分析与判断。这两个短板有时可通过实验设计法解决，参见 Al Salhi 等（2005）的论述。

5.4 概率法

概率法，是用每个未知参数值（根据地质和油气藏工程资料）的可能合理完整分布，生成一个资源体积的可能结果的完整分布。为了开展这项工作，先判定储量评估所需的参数，然后确定其概率密度函数（PDF）。基于地质与工程数据分析，PDF 可描述每个参数的不确定性。然后，应用随机取样程序，为每一个参数抽取一个数值，用来计算可采量或原地量［也就是储罐油原始原地量（STOIIP）］。重复这一过程足够多次之后，就可生成 STOIIP 或可采量的一个 PDF。图 5.4 为该蒙特卡洛法计算过程的概略示意图。

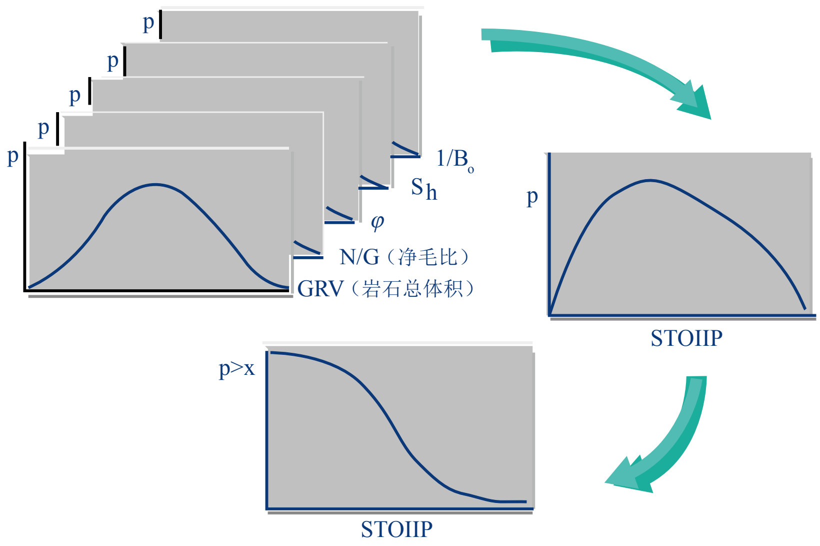


Figure 5.4　Monte Carlo approach to volumetric
图 5.4 蒙特卡洛容积法计算过程示意图

Dependencies between parameters often exist and must be represented in the probabilistic estimation of recoverable volumes. Commonly encountered positive correlations are between net-to-gross gas saturation and porosity in clastic reservoirs. An obvious negative correlation exists between the oil and gas volumes in a gas-capped oil reservoir. It should be noted that the resultant PDF for the recoverable resources is often asymmetrical.

It is important to remove physically impossible realizations from the model because they will inappropriately skew the range of outcomes. A good practice is to select a realization that represents a “typical” 1P or 2P case and to supplement each probabilistic assessment with discrete realizations for the low, mid, and high cases. This ensures that one is clear about the development scenario that the probabilistic estimate represents and should guard against allowing unrealistic cases into the assessment. It should be noted that probabilistic estimates for an accumulation will differ depending on the development scenario selected.

For fields where production data exists, the workflow includes the additional step of history matching. A result of this workflow is a group of equally probable history-matched models created by a combination of parameters, using for instance genetic algorithms and evolutionary strategy to match the production history.

5.4.1 Volumetric Parameters and Their Uncertainty Distribution

Uncertainty in volumetric estimates of petroleum reserves and resources is associated with every parameter in the equations.

5.4.1.1 Gross Rock Volume (GRV)

Usually, the most important contribution to overall uncertainty is in the GRV of the reservoir—just how big is it? This uncertainty may be related to

(1) Lack of definition of reservoir limits from seismic data
(2) Time-to-depth conversion in seismic observations
(3) Dips of the top of the formation
(4) Existence and position of faults
(5) Whether the faults are sealing to hydrocarbon migration and production

The GRV depends critically on the height of the hydrocarbon column because the volume of a reservoir anticline increases roughly proportionally with the cube of the column. Typical reporting requirements (US SEC 2008) for Proved Reserves recognize this sensitivity by limiting the rock volume to that above the lowest known hydrocarbons (LKH) unless otherwise indicated by definitive geosciences, engineering, or performance data.

5.4.1.2 Rock Properties: Net-to-Gross and Porosity

The uncertainty associated with the properties of the reservoir rock originates from the variability in the rock. It is determined through

通常，参数之间存在相关性，必须在可采量的概率法评估中有所体现。对于碎屑岩气藏而言，通常含气饱和度与孔隙度正相关。气顶油藏的原油与天然气体积明显呈负相关。应注意，可采资源的 PDF 时常是非对称的。

有一点很重要，即剔除模型中物理上不可能的实现——它们会使结果分布出现不合理偏移。好的做法是选择“ 典型的 ”1P、2P 或 3P 情景，然后分别用离散的低、中和高实现进行概率法评估。这样可确保评估师对概率法评估的开发方案有清晰认识，并防止评价中出现不切实际的情形。应注意，一个油气聚集体的概率法评估可能会出现不同结果，这依赖于所选择的开发方案。

对于有生产数据的油气田，评估程序还多一步历史拟合。该步骤可采用遗传算法和进化策略等方法拟合油气田的生产历史，得到一组拟合参数组合所构建的历史拟合模型。

5.4.1 容积法参数及其不确定性分布

容积法评估石油储量与资源量的不确定性与其公式的每个参数相关。

5.4.1.1 岩石总体积（GRV）

一般情况下，总体上看，评估的不确定性主要是来源于油气藏岩石总体积——有多大呢？其不确定性大小可能与以下因素有关：

（1）地震资料缺少对油气藏边界的定义。
（2）地震数据的时 - 深转换。
（3）地层顶面的倾角。
（4）断层的存在及其位置。
(5) 断层对油气运移与生产是否有封堵作用。

岩石总体积关键取决于烃柱高度，因为背斜油气藏的体积大致是烃柱高度的三次方。证实储量特定披露要求（US SEC，2008）认识到了这一敏感性，进而将有效岩石体积限定在已知烃底（LKH）以上，除非有明确的地质、工程和动态数据显示其深度位置。

5.4.1.2 岩石物性——净毛比和孔隙度

储层岩石物性的不确定性来源于岩石的多样性。可通过岩石物性评价、岩心测试分析、地震

petrophysical evaluation, core measurements, seismic response, and their interpretation. While petrophysical logs and measurements in the laboratory may be quite accurate, the samples collected may be representative only for limited portions of the formations under analysis. A core 4 in. wide is not necessarily a representative sample of a buried and altered river delta, superimposed plains of meandering river channels, a suite of beach deposits, turbid marine landslides, or other geological formations. Only in rare instances can precise measurements of porosity, net-to-gross ratio, fluid saturation, and factors affecting fluid flow be applied directly and with confidence. For the most part, they help to condition one or several alternative (uncertain) interpretations.

5.4.1.3 Fluid Properties

For fluid properties, a few well-chosen samples may provide a representative selection of the fluids. The processes of convection and diffusion over geologic times have generally ensured a measure of chemical equilibrium and homogeneity within the reservoir, although sometimes gradients in fluid composition are observed.

Sampling and analysis may be a significant source of uncertainty. Reservoirs with initial gradients in fluid composition or where phase changes have occurred will be affected by production. Here, samples may be unrepresentative of the initial fluids and they may be misinterpreted easily. Hence, fluid definition under such conditions is less certain than in virgin reservoirs. Additionally, sampling may be affected by acquisition methodology, such as recombination procedures in surface sampling, and fluid properties may also be impacted by other factors, such as storage, which can alter original reservoir conditions.

5.4.1.4 Recovery Factor (RF)

Recovery is based on the execution of a project and affected by the shape and the internal geology of the reservoir, its properties and fluid contents, and the development strategy. If a reservoir can be described in sufficient detail, then numerical models can be made of the effects of well and drainage-point density and location, fluid displacement, pressure depletion, and their associated production and injection profiles. Realistic alternatives, conditioned by available information and consistent with the definitions, may be modeled to assess the uncertainties. If a reservoir is poorly defined, material balance calculations or analog methods may be used to arrive at an estimate of the range of RFs. Uncertainty ranges in the RF can often be based on a sensitivity analysis.

5.4.1.5 Selecting Distribution Functions for Individual Parameters

In probabilistic resource calculations, it is the task of the estimator to specify a PDF that fits the information available. Modern tools (such as spreadsheet-based or other commercially available statistical

响应及相关解释来确定。虽然岩石物性测井和实验室分析的数据可能相当精确，但分析的岩样可能仅代表地层的有限部分。一个 4 英寸的岩心并不一定能表征一个经埋藏、改造后河流三角洲、曲流河道叠加平原、整套滩海沉积、海底浊积泥石流或其他地质结构。只有在个别情况会直接应用这些精确测量的孔隙度、净毛比、流体饱和度和影响流体流动的参数，绝大部分情形，它们仅是用于辅助约束一个或多个可供选择（不确定）的解释结果。

5.4.1.3 流体性质

对于流体性质，精心挑选的样品可以成为流体的代表性样品。在地质年代中经过对流和扩散，基本上可确保油气藏内部的化学平衡与均质性，尽管有时也能见到流体组分的梯度变化。

采样与分析过程可能是不确定性的重要来源。生产过程会影响油气藏的流体组分初始梯度变化或在油气藏内出现流体相变；这种情形下采集的样品可能无法代表原始流体，且很容易得出错误解释。因此，该条件下对流体性质判定的确定性低于原始油气藏状态。另外，采样质量可能会受采集方法影响（例如地面配样过程），流体性质也可能受其他改变油气藏原始状态的因素影响，如存储方式。

5.4.1.4 采收率

油气藏的开采是基于项目的执行，受油气藏形态与内在地质特征、物性和流体，以及开发策略的影响。如果有足够资料描述油气藏，则可以利用井数据和泄油点密度与位置、流体驱替过程、压力衰竭变化情况以及注产剖面等资料建立数值模型。一些经现有信息约束、符合各种条件定义的替代现实模型可用于评价不确定性。如果对油气藏的认识尚没有把握，那么就可采用物质平衡计算或类比法来估算采收率的范围。采收率不确定性范围的确定通常基于敏感性分析。

5.4.1.5 选择参数的分布函数

在概率法资源计算中，为数据参数匹配适合的概率密度函数（PDF）是评估师的职责。许多现代工具（如电子表格软件或其他商业性统计软件）

software) allow for a wide choice of PDFs (normal, log-normal, triangular, Poisson, etc.).

The following offers some practical guidance on the selection of the parameter distributions:

(1) Make a conscious decision on range and shape of the input distributions for the volumetric calculation on the basis of direct reservoir and geoscience information or appropriate analogs.

(2) The distributions must be applied only in the range for which they usefully reflect the underlying uncertainty. Avoid distributions that extend into infinity. Ensure that distributions do not become negative or exceed unity for parameters expressed as fractions or ratios, such as porosity, net-to-gross, saturation, or recovery efficiency.

(3) The most generic PDFs to describe the uncertainty of the mean are normal and log-normal distributions. Their disadvantage is the infinite tail, which can lead to unrealistic scenarios. One solution is to apply truncation at meaningful values; however, if truncation significantly impacts the overall shape of the PDF, then it is probably more appropriate to use another PDF as the starting point.

(4) Recall that the range of values required is that which represents the evaluator's uncertainty in the value of the mean, rather than the distribution of the data itself.

(5) Do not confuse the three measures of centrality (expectation or mean, mode, and median) when defining the distribution.

(6) Be aware of what the low and high value estimates represent: extremes (such as minima and maxima (P100/P0) or some other probability value (such as P95/P05, P90/P10, etc.).

(7) The PDF of a sum of log-normal distributions tends toward a normal distribution. As a result, a product of independent factors, whose logarithms are of the same magnitude, tends toward a log-normal distribution. Examples of entities that are strongly affected by products are the reserves of an accumulation and the permeability of a porous system.

(8) The PDF of the sum of a large number of independent quantities of the same magnitude tends toward a normal distribution. Examples are the reserves of a large number of equally sized fields in a portfolio and the porosity of a rock body.

(9) If the independent quantities are not of the same magnitude, the sum and its PDF will be dominated by the largest ones.

Many practitioners approximate PDFs with triangular distributions, particularly when data are limited and the range is narrow. In cases where a probability distribution cannot be determined easily, a uniform distribution is sometimes used. Such distributions may be considered coarse approximations of reality. However, uncertainty ranges of the

可供选择各种概率密度函数（正态分布、对数正态分布、三角分布、泊松分布等）。

下面对参数分布的选择提供一些实用性指引：

（1）基于油气藏和地质的直接数据或适合的类比油气藏信息，有意识选择容积法输入参数的分布范围与概型。

（2）该分布须仅用于有效反映不确定性范围，避免无限扩展。对于用小数或比率表示的参数，例如孔隙度、净毛比、饱和度或采收率等，要确保其数值的分布范围不为负或大于 1。

（3）描述均值不确定性的最通用概率密度函数（PDF）是呈正态分布和对数正态分布。其缺陷是尾部无限长，可能导致不切实际的情景组合。解决方案是在有意义数值处作截断处理；当然，如果截断值明显影响 PDF 的整体形态，那更恰当的做法是另行选择 PDF。

（4）重申，所需的参数分布是针对评估师对均值的不确定表征，而非数据分布本身。

（5）选择概率分布函数时，不要混淆三个中值（期望值或均值、众数和中值）的度量。

（6）要清楚认识低估值和高估值的涵义，以及极值［如最小值和最大值（P100/P0）］或其他一些概率值（如 P95/P05，P90/P10 等）。

（7）一组对数正态分布之和的 PDF 趋于呈正态分布。因此，对数级数相同的独立分布的乘积，其结果趋向于呈对数正态分布。企业的案例显示，受此影响大的分布是油气聚集体的储量和多孔介质渗透率。

（8）众多级数相同独立分布之和的 PDF 趋向于呈正态分布。例如一个资产组合中大量规模相当油田的储量，以及岩石的孔隙度。

（9）若独立分布的级数不同，其求和函数及其 PDF 形态将取决于数值大的分布。

许多实践者采用三角分布作为近似 PDF，特别是在资料有限且分布范围窄的情形。当概率分布不易确定时，有时可采用均一值分布。这种分布可视为是对现实情形的粗略近似。当然，评估

resulting volumes are more influenced by mean values and standard deviations than they are by the shape of the distributions of the individual parameters that make up the estimate.

The most common error when working with poorly defined quantities is to underestimate the possible uncertainty range of each parameter. Particular attention should therefore be paid to this, regardless of the distributions chosen. As a general principle, the less the information, the wider the range. It should be emphasized that distributions to be used in a probabilistic analysis routine, even if measured data are available, should properly describe the uncertainty of the specific input parameters being represented. For example, the porosity distribution from core or logs is conceptually different from the distribution of the average porosity in the reservoir. Therefore, the use of existing data distributions as observed in the existing wells is not valid. Figure 5.5 illustrates an example. In this example some of the core plugs have 0% porosity. Obviously 0% porosity cannot be used as the low value in the distribution of average fieldwide porosity if it is known that average porosity is always above zero. A further discussion of the differences between distributions of the raw data and of the reservoir average is provided in Cronquist (2001).

The known distribution of available data should be considered only as the starting point to define the PDF for reservoir parameters.

结果（体积）的不确定性范围往往更多地是受均值和标准偏差的影响，而不是评估单一参数的分布概型。

当数据质量差时，最常见的错误是低估其不确定性。因此，无论选择哪一种分布函数，都需十分小心。总的原则是：资料信息越少，分布范围越宽。应强调，在日常概率分析使用分布函数时，即使有测量数据，也应对其代表的输入参数进行适当的不确定性描述。例如，岩心分析或测井解释得到的孔隙度分布与储层的平均孔隙度分布在概念上是不同的。因此，采用现有井数据的分布是无效的。图 5.5 是一个案例。该案例显示一些岩样的孔隙度为 0。显然，若已知平均孔隙度总是大于 0，那么孔隙度 0 值就不能用作油田平均孔隙度分布的低值。更多有关原始数据分布与油气藏均值分布之间差异的讨论，参见 Cronquist（2001）的文献。

现有数据的已知分布应只是油气藏参数概率密度函数（PDF）确定的工作起点。如果油气藏的

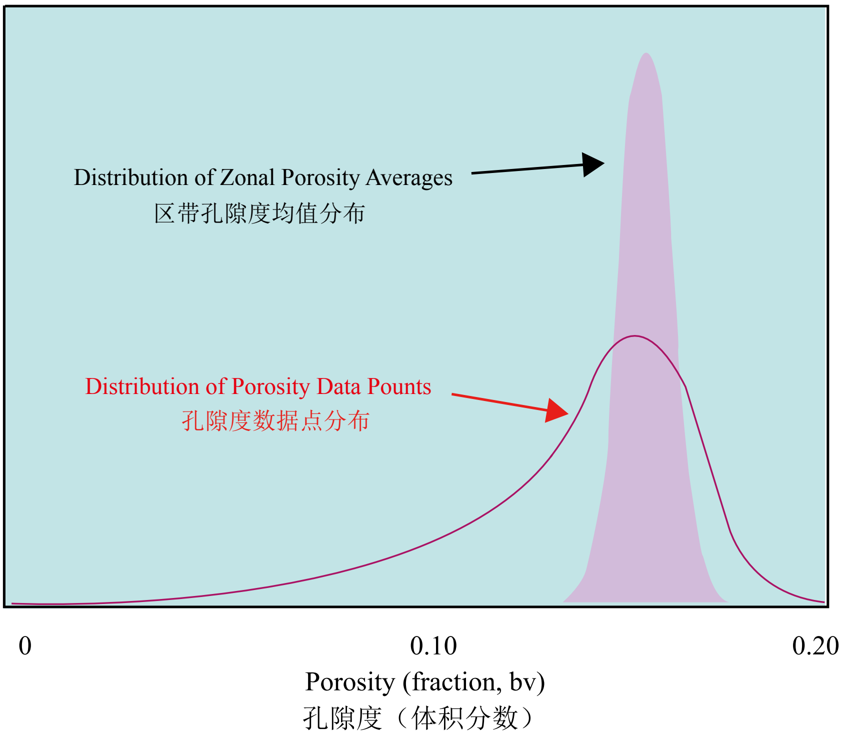


Figure 5.5—Frequency distributions of porosity.
图 5.5　孔隙度频率分布

If cutoffs are applied to the reservoir parameters (e.g., if net sand has a 5% porosity cutoff), then these should be reflected in the reservoir parameter PDF.

If abundant data are available (e.g., computer analyses of the porosity logs), and the geologic processes of sedimentation, deformation, and diagenesis are such that the variability along the hole is representative of the variability in the reservoir, then the actual distribution of these data, after cutoffs, can be used as a starting point. If only scarce data are at hand, then the range should be defined and turned into a distribution. Always keep in mind that the distribution function should describe the distribution of the reservoir-averaged parameter value. Table 5.1 provides typical ranges of uncertainty in the most common reservoir parameters.

参数采用截止值（例如，有效砂岩孔隙度截止值为 5%），然后应在油气藏参数的 PDF 上有所体现。

若有充足的数据资料（例如，孔隙度测井的计算机分析），且沿井筒变化的地层沉积、构造变形和成岩等地质作用特征能代表储层的变化，那么考虑了截止值之后的实际数据分布，可以作为确定油气藏参数分布函数的起始点。若手头仅仅有稀少数据，则应识别其不确定性范围，并转化为分布函数。须始终牢记，分布函数应该描述的储层平均参数的分布。表 5.1 给出了最常见储层参数的典型不确定性分布范围。

Table 5.1 Some Reservoir Parameters and Typical Ranges of Uncertainty

表 5.1 储层参数及其典型不确定性范围

Parameters 参数	Range 范围	Source 数据来源
GRV 岩石总体积	+/– 30%	3D Seismic, 2D Seismic 3D 地震 , 2D 地震
Net-to-Gross 净毛比	+/– 20%	Well Logs 测井
Porosity from Logs 测井孔隙度	+/– 15%	Logs 测井
Porosity from Cores 岩心孔隙度	+/– 10%	Cores 岩心
Hydrocarbon Saturation 烃饱和度	+/– 20%	Well Logs 测井
Dip 地层倾角	+/– 10%	Dipmeter 倾角测井
	+/– 30%	Seismic 地震
Formation Volume Factor (B_o or B_g) 地层体积系数 (B_o 或 B_g)	+/– 5%	PVT Test PVT 测试分析

Note: Ranges are a percentage of the actual measurement, not e.g., porosity percentage points.

注：上述范围值为实际测量值的比例百分数，例如，对孔隙度而言，不是指孔隙度百分数本身。

Warning: The values in this table are typical ranges provided to use for comparison with your actual parameter ranges. Do not use as default uncertainty ranges.

警示：该表中数值为典型范围值，仅作为实际参数范围值的对比与参照，不要用作不确定性的默认范围。

5.4.2 Performance Methods

5.4.2.1 Parameters and Their Uncertainty Distribution

When sufficient production performance information is available, reserves can be assessed by using performance-based methods, such as decline curve analysis (DCA). In classical DCA, the uncertainty in the estimated ultimate recovery is mainly caused by the selected decline model (exponential, hyperbolic, or harmonic) and the selected matching or regression period.

A possible approach to arrive at a probabilistic estimate using performance-based methods is by using the hyperbolic decline equation:

$$q=\frac{q_i}{(1+bd_it)^{\frac{1}{b}}} \tag{5.1}$$

and matching on the hyperbolic decline constant b, as well as the initial nominal decline rate d_i. Since exponential decline (b=0) and harmonic decline (b=1) are limiting cases of the hyperbolic decline, this eliminates the problem of selecting a decline model. By varying b, d_i, and the matching period within reasonable limits, a distribution for the resulting ultimate recovery can be obtained, from which Proved, Probable, and Possible Reserves can be derived. Other approaches have been explored (Cheng et al. 2005).

5.4.2.2 Combining Risk and Uncertainty

PDFs resulting from the methods described previously can be combined with risk factors, which will result in typical shapes for different situations on both sides of the exploration/production boundary. Figure 5.6 shows cumulative risked PDFs for resources in five different situations. First of all, there are four curves that intersect the y-axis at a value below one. For these cases, there is a finite probability that the STOIIP is 0 (i.e., these curves describe prospects for which it is not certain that they contain oil). The intersection point with the y-axis is the probability of success (PoS), as used in exploration situations. The curve that intersects the y-axis at Probability 1, describes a discovered oil accumulation, with a range of uncertainty and PoS=1. In more detail, the figure shows the following:

(1) Relatively poor prospect; volume is small and PoS is also limited.

(2) Speculative prospect; small probability of a large volume.

(3) Either/or prospect; in case of success there is a relatively well-defined volume.

(4) Small confident prospect; PoS is relatively large, mean volume in the success case is in the order of 30 million bbl.

(5) Discovery; in this example case the P10, or the upside, is almost twice the P50, the P90 value is some 60% of the P50.

5.4.2 动态法

5.4.2.1 参数及其不确定性分布

当生产动态资料充足时，可采用动态法评估储量，如递减曲线分析法（DCA）。经典递减曲线分析中，估算最终可采量的不确定性主要来源于所选择的递减模型（指数、双曲或调和），以及选定的拟合阶段或回归区间。

开展动态法概率评估的一个可行方法是使用双曲递减方程：

$$q=\frac{q_i}{(1+bd_it)^{\frac{1}{b}}} \tag{5.1}$$

并拟合双曲递减常数 b，以及初始名义递减率 d_i。由于指数递减（b=0）和调和递减（b=1）是双曲递减的极端情形，这就规避了递减模型选择的问题。通过改变 b，d_i，以及选择合理拟合区间，就可得到最终可采量估值的分布，从中得到证实储量、概算储量和可能储量估值。其他方法，参见 Cheng 等（2005）的文献。

5.4.2.2 风险与不确定性的组合

用上述方法得到的 PDF，还可以与风险系数进行组合，从而构建跨勘探 / 生产阶段不同情形的典型曲线形态。图 5.6 展示了 5 种不同情形下资源的风险后累计 PDF 分布。首先，有 4 条曲线与 y 轴的交点数值小于 1。这意味着这些情形有可能存在 STOIIP=0（即也就是说，这些曲线所表征的勘探有利目标，并不确定是否含油）。y 轴交点的对应数值即勘探成功几率（PoS）。与 y 轴交点概率值为 1 的曲线，表征的是一个已发现原油聚集体，其发现几率等于 1 且存在不确定性。图中还展现更多细节：

(1) 前景不好勘探目标：体积小，PoS 也有限。

(2) 推测勘探目标：发现大量油气的概率小。

(3) 或有勘探目标：若成功发现，油气数量相对明确。

(4) 具有一定置信度的勘探小目标：PoS 较大，平均发现体积规模约为 30×10^6 桶。

(5) 发现：本案例为 P10（或更高位置）对应的估值，P50 对应估值几乎是其两倍，而 P90 对应估值约为 P50 的 60%。

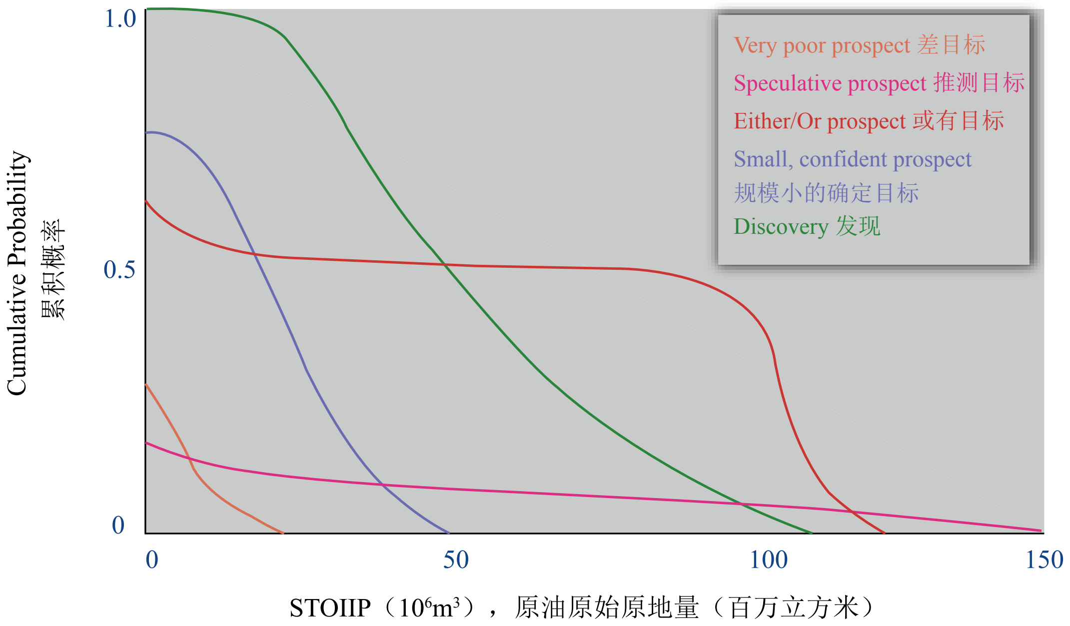


Figure 5.6 PDFs.
图 5.6 累积概率密度曲线

5.4.3 Strengths and Weaknesses

Strengths of the probabilistic method include

(1) The uncertainty range of the result can be derived from basic parameter uncertainty ranges

(2) Easily lends itself to numerical treatment

(3) Can be applied throughout the business cycle from exploration to production

(4) Naturally links in with value-of-information work

(5) Allows capture of the range of outcomes when insufficient detailed data are available

Weaknesses, on the other hand, are

(1) Can lead to extensive, complicated, and sometimes ineffective calculation work

(2) Categories (e.g., P90, P50, P10) may not correspond to specific physical areas or volumes when simple Monte Carlo methods are used. In cases where geological and simulation models are used to do the analysis, the models and parameters used for the P90, P50, and P10 scenarios can be identified.

(3) The PDF of basic parameters is not always known and technical judgment has to be applied

(4) Dependencies between parameters are even more difficult to assess.

5.4.3 优势与缺陷

概率法的优势包括：

(1) 评估结果不确定性范围可根据基础参数的不确定性范围来获取。

(2) 易于开展数值处理工作。

(3) 可应用于勘探到生产的全业务过程。

(4) 可与信息价值分析工作自然衔接。

(5) 可在详细资料不足时，拾取可能结果的分布。

另一方面，其缺陷在于：

(1) 可能导致大量、复杂，而且有时无效的计算工作量。

(2) 在应用简单蒙特卡洛法时，储量级别（如 P90、P50、P10）可能并不对应具体的实际面积或体积。当应用地质和数值模拟模型进行概率法分析时，才可能识别 P90、P50 和 P10 情景所对应的模型与参数。

(3) 基本参数的 PDF 并非总是已知，必须进行技术判断。

(4) 参数间的相关性甚至更加难以评估。

5.5 Practical Applications

The probabilistic approach to resource estimation can be applied usefully to other economic and engineering tasks, such as resource categorization, experimental design, and value-of-information calculations.

5.5.1 Resource Categorization

Under PRMS, when the range of uncertainty in recoverable volumes is represented by a probability distribution, then low, best, and high estimates are defined as follows:

(1) There should be at least a 90% probability (P90) that the quantities actually recovered will equal or exceed the low estimate [Proved (1P) for Reserves, 1C for Contingent Resources].

(2) There should be at least a 50% probability (P50) that the quantities actually recovered will equal or exceed the best estimate [Proved + Probable (2P) for Reserves, 2C for Contingent Resources].

(3) There should be at least a 10% probability (P10) that the quantities actually recovered will equal or exceed the high estimate [Proved + Probable + Possible (3P) for Reserves, 3C for Contingent Resources].

Although the most probable value of the distribution is the mode, common industry practice (as described in the PRMS) is to use the median (P50) as the best technical estimate for a single entity (reservoir or zone).

5.5.2 Experimental Design

Experimental design is a well-known set of statistical methods that are helpful in generating the scenarios or cases required to efficiently cover all possible outcomes of the reservoir or field development at hand. Steps in the evaluation typically include the following:

(1) Define the set of parameters and their ranges.

(2) Perform a sensitivity analysis and select the parameters that have the most impact on the result.

(3) Calculate the reserves for a limited number of realizations of the model. These realizations are based on combinations of parameters determined by an experimental design procedure.

(4) Use the results of this limited number of model runs to generate a so-called response function, or response surface, using regression techniques.

(5) Use the PDFs of the input parameters to generate the PDF of the response function in a stochastic sampling (e.g., Monte Carlo) process.

Experimental design is particularly useful when the analysis is based on performance data, such as material balance or reservoir

5.5 实践应用

资源评估采用的概率法程序可以有效地应用于其他经济和工程领域的工作，例如资源分级、实验设计以及信息价值计算等。

5.5.1 资源分级

根据 PRMS，当可采量的不确定性范围用概率分布表征时，那么其低估值、最佳估值和高估值结果定义如下：

（1）实际采出量将大于或等于低估值（1P 证实储量、1C 条件资源量）的概率应该至少为 90%（P90）。

（2）实际采出量将大于或等于最佳估值 [证实 + 概算储量（2P)、2C 条件资源量] 的概率应该至少为 50%（P50）。

（3）实际采出量将大于或等于高估值［3P 证实 + 概算 + 可能储量、3C 条件资源量）的概率应该至少为 10%（P10）。

尽管分布函数的最可能数值是众数，但业界通常采用中值（P50）（如 PRMS 所述）作为单一实体（油气藏或储层）的最佳技术估值。

5.5.2 实验设计

实验设计是一套非常有名的统计方法，可以很方便地高效生成覆盖油气藏或油气田开发各种结果可能的情景或方案。其评价步骤通常包括：

（1）确定参数集及其分布。

（2）开展敏感性分析，选择对结果最有影响的参数。

（3）计算有限数量实现模型的储量。采用实验设计方法确定这些实现的参数组合。

（4）利用有限次模型运算的结果，采用回归技术，生成所谓的响应函数或响应曲面。

（5）通过随机抽样（如蒙特卡洛法），将输入参数的 PDF 生成其响应函数的 PDF。

当概率法分析是基于生产动态数据（例如物质平衡或油藏模拟），那实验设计方法就特别有用。该方法的介绍可参考 van Elk 等人 (2000) 文献，

simulation. A description of this method is provided in van Elk et al. (2000), and an illustrative example is described by Al Salhi et al. (2005).

5.5.3 Value of Information

The goal of appraisal is to reduce uncertainty, and it is necessary to address the value of the additional information gained against cost. In the appraisal example represented by Figure 5.7, the curve for the STOIIP estimation has a gentle slope before appraisal, indicating a wide distribution of possible values. After appraisal, the slope is much steeper, indicating that the range of possible answers has been narrowed. Even if the outcome is unfavorable (i.e., the post-appraisal curve is below the economic minimum), the appraisal activity has delivered value by preventing unnecessary investments. A post-appraisal curve that is in the economic realm will allow for a more focused development.

This narrowing of possible answers allows the design of a more cost-effective development, provided that the post-appraisal range of STOIIP exceeds some economic threshold. The increased cost-effectiveness of the development is the value of the information (VoI) gained by the appraisal. As long as the appraisal cost is lower than this VoI, further appraisal is necessary.

有关应用案例的描述可参见 Al Salhi 等人（2005）文献。

5.5.3 信息价值

评价的目的是降低不确定性，因而有必要探讨获取更多信息的价值与成本。图 5.7 所示勘探评价案例，其 STOIIP 结果分布曲线的斜度在评价之前比较平缓，表明可能结果的分布范围比较宽。评价工作完成后，曲线斜度变陡，表明可能结果的分布范围减小。即便结果不利（也就是说，评价后曲线低于最小经济界限），评价工作仍给出了避免不必要投资的有价值结论。若评价后的曲线在经济范围内，则可开展更有针对性的开发活动。

若评价后的 STOIIP 范围超过经济门槛，那么可能结果分布范围的减小，将有利于开展更具成本效益的开发设计。开发增加的效益便是评价工作所获取的信息价值（VoI）。只要评价工作的成本低于该 VoI，就有必要进一步推进。

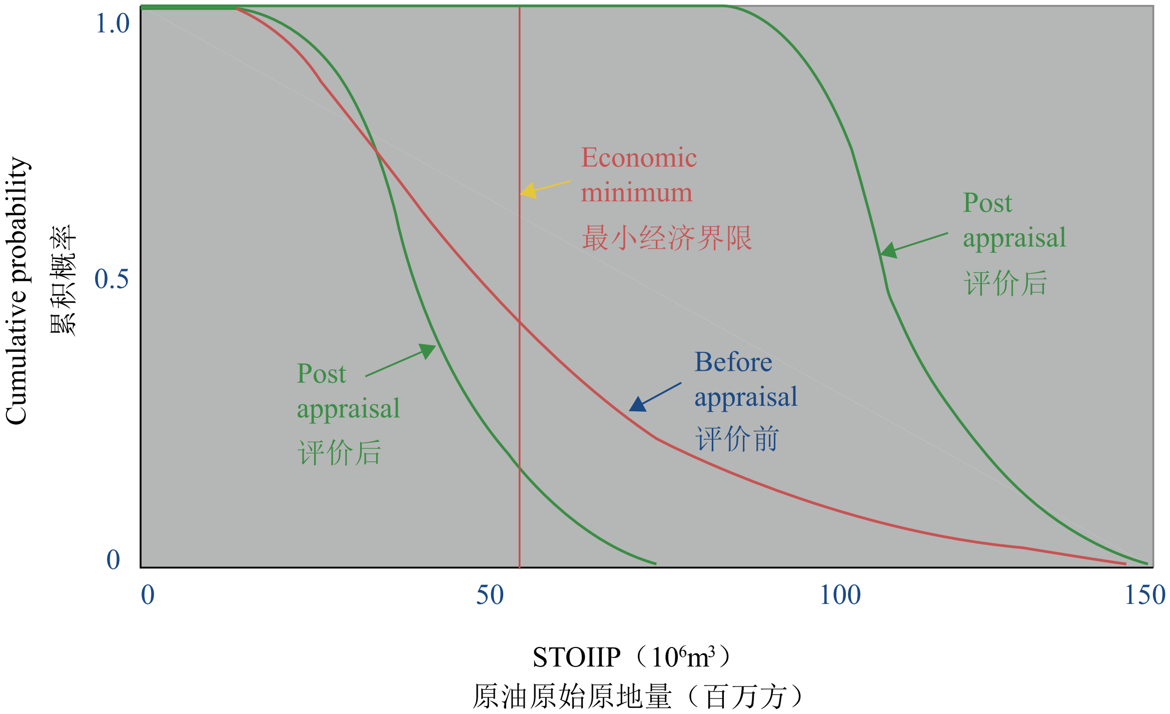


Figure 5.7 Value of Information.
图 5.7 信息价值

Definitions and Rules
定义与规则

Probability 概率	The extent to which an event is likely to occur measured by the ratio of the number of occurrences to the whole number of cases possible. ⑤ 某事件可能发生的几率，是事件出现次数与全部事件总次数的比率。⑤ Note that the probability used in reserves estimation is a subjective probability, quantifying the likelihood of a predicted outcome. 应注意，储量评估使用的概率是一种主观概率，用于量化预测结果的可能性。
Probability Density Function（PDF） 概率密度函数	Probability as a function of one or more variables, such as a hydrocarbon volume. 概率是一个或多个变量的函数，例如烃（油气）体积。
Cumulative PDF(C_{df}); 累积概率密度函数 Survival Function (S_f) 生存函数	To each possible value of a variable, a C_{df}(S_f) assigns a probability that the variable does not exceed (or does exceed) that value. 对于某一个变量所有可能值，其 C_{df}(S_f) 可分配一个不超过（或超过）该数值的概率。 The "SPE/WPC Petroleum Reserves Definitions" use survival function in the statement: "if probabilistic methods are used, there should be at least 90% probability that the quantities actually recovered will equal or exceed the estimate." “SPE/WPC 石油储量的定义”在以下表述中使用了生存函数：“如果使用概率方法，实际开采量将等于或超过评估值的概率至少为 90%。”
Measures of Centrality 中心度测量	The three measures of centrality defined below coincide only when PDFs are symmetrical. This is seldom the case for reserves. In general, and for most practical purposes, they differ. 下面定义的三个中心的度量仅在 PDF 对称时重合一致。储量评估中极少出现这种情形。一般来说，它们是不同的。
Mean, Expectation, or Expected Value 均值、期望，或期望值	The mean is also known as the expectaition or the expected value. It is the average value over the entire probability range, weighted with the probability of occurrence. 均值也称为期望或期望值，它是整个概率范围由发生概率加权的参数平均值。 $\text{Mean}=\sum_{i=1}^{n} x_i\cdot P(x_i)\text{or}\int x\cdot P(x)\cdot d(x)$ Where，x = reserve value and P(x) = probability of x. 其中，x 为 储量估值，P(x) 为 x 出现的概率。 The mean of statistical distributions can be added arithmetically in aggregation. 统计分布的平均值在汇并时可以进行算术加合。
Mode, or Most Probable Value 众数或最可能值	The mode is the most probable value. It is the reserves quantity where the PDF has its maximum value. 众数是指最可能出现的数值。它是 PDF 最大值对应的储量数量。
Median(also known as P50) 中值 (也称为 P50)	The value for which the probability that the outcome will be higher is equal to the probability that it will be lower. 结果比该数值更高的概率等于更低的概率。
	Measures of Dispersion 离散性的度量
Percentiles 百分位数	The quantity for which there is a certain probability. Quoted as a percentage, that the quantities actually recovered will equal or exceed the estimate. 某一概率的数量。以百分比表示，如实际采出量将等于或超过估算值的概率。

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⑤ New Concise Oxford Dictionary.
参见《新牛津简明词典》。

P90	The quantity for which there is a 90% probability that the quantities actually recovered will equal or exceed the estimate. In reserves estimation, this is the number quoted as the proven value. 实际采出量将等于或超过该估算量的概率为 90% 的数量。储量评估中，P90 是证实储量估值。
P50, or Median P50, 或中值	The quantity for which there is a 50% probability that the quantities actually recovered will equal or exceed the estimate. 实际采出量将等于或超过估算量的概率为 50% 的数量
P10	The quantity for which there is a 10% probability that the quantities actually recovered will equal or exceed the estimate. 实际采出量将等于或超过估算量的概率为 10% 的数量
Variance 方差	The variance is calculated by adding the square of the difference between values in the distribution and the mean value and calculating the arithmetic average: 方差的计算方法是将分布数值与均值之差进行平方加合，然后计算其算术平均值。 $$s^2 = \frac{\sum_{i=0}^{n}(x_i - \mu)^2}{n} = \int_a^b (x-\mu)^2 f(x)dx$$ Where x = reserve, μ= mean, and f(x) = PDF. 其中，x 为 储量 , μ= 平均值 , 和 f(x) 为其概率密度函数。 It is convenient to square the differences because this avoids the cancelling of positive and negative values. The same effect may be obtained by taking absolute values of the difference, but the mathematical properties of such a measure are not as elegant as those of the variance. 可很方便地对差值进行平方处理，这可以避免正负值的影响。取差值的绝对值进行计算也可得到同样的效果，但不如方差的数学特性好。
Standard Deviation 标准偏差	Describes the spread of a variable around its mean value. It is defined as the square root of the variance. 描述变量偏离其均值的情况，定义为方差的平方根。

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第 6 章
CHAPTER 6

储量汇并
Aggregation of Reserves

Wim J.A.M. Swinkels　著　衣艳静　译

6.1 Introduction

In reserves and resources estimation, estimates are based on performance evaluations and/or volumetric calculations for individual reservoirs or portions of reservoirs. These estimates are summed to arrive at estimates for fields, properties, and projects. The uncertainty of the individual estimates at each of these aggregation levels may differ widely, depending on geological setting and maturity of the resource. This cumulative summation process is usually referred to as "aggregation" (SPE 2007).

Adding up estimates, or ranges of estimates, with such different levels of uncertainty can be impacted by the purpose for which the estimate is required.

Oil companies, considering long-term performance of their assets, will use the "best estimate" of the volumes for investment purposes; this generally is based on the sum of Proved plus Probable (2P) volumes. They work on the assumption that in the long run, the portfolio of their best estimates will be realized, with the downside in one case compensated for by the upside in another situation. However, it is best practice that reserve estimates always be reported as a range (1P/2P/3P or, in the case of Contingent Resources, 1C/2C/3C). Where assessments are based on deterministic methods, summations are arithmetic and by category. Where probabilistic assessments are available, companies may aggregate probabilistically to the field/property/project level, but subsequent summations are generally arithmetic. For internal portfolio analyses, companies may use fully probabilistic methods, with risking applied where appropriate.

Investors, accountants, and utilities will usually require a high level of certainty and concentrate on the Proved (1P) volumes, or to a lesser extent, the Proved plus Probable (2P) volumes. Gas contracts are typically based on Proved Reserves, which adds a strong business incentive to the accurate determination (and summation) of Proved Reserves. Long-term gas contracting is sometimes based on Proved plus Probable Reserves where there is a large gas resource that is most economically developed over the life of the gas contract.

Accountants may use the ratio of production to Proved Developed Reserves or other reserves categories as the basis for depreciating or depleting the cost of acquiring and developing reserves over time as the reserves are produced. In some areas, the ratio of production to Proved plus Probable Reserves (including any Undeveloped Reserves) is used as the basis for depreciation. Depreciating the cost of investments has an impact on business profits and indicators as return on average capital employed (ROACE). For these calculations, accountants require the reserves to be assessed at the level at which the investments apply.

Thus, reported aggregates of reserves and resources not only encompass variations in associated uncertainties, but also require

6.1 引言

在油气储量和资源量评估中，通常是采用动态法和 / 或容积法对单个油气藏或其中一部分进行评估。将这些评估结果汇并起来就可以得到油田、资产和项目层级的数量。由于地质条件和资源成熟度在不同层级有所不同，不同层级估值的不确定性可能差异很大。累计求和的过程通常称之为“汇并”（SPE，2007）。

不同不确定性层级的评估结果的加合或估值范围，因评估目的不同而有所不同。

油公司在考虑其资产的长期业绩时，为了投资目的，通常采用最佳估值，即证实储量与概算储量之和（2P）。其投资规划的基础为未来长期阶段内，投资组合中的不利因素由有利因素补偿，以实现最佳投资组合。当然，最佳实践做法是储量评估始终报告估值的范围（1P/2P/3P，或者条件资源量 1C/2C/3C）。采用确定法评估时，汇并是按级别算术求和。当评估方法为概率法时，油公司可以通过概率加合得到油田 / 资产 / 项目层级的结果，但随后更高层级的汇总往往为算术求和。对于内部投资组合分析，公司采用完全概率法，并在适合环节考虑风险折算。

投资者、会计师和公共服务机构通常要求高确定性，主要关注证实储量（1P），或再其次，是证实储量 + 概算储量（2P）。天然气销售合同的签订通常是基于证实储量，因而更加注重尽可能准确估算（并加合）证实储量。当天然气资源规模很大，其整个合同期均可以最经济方式进行开采时，也可以基于证实储量 + 概算储量签订长期天然气合同。

会计师可能会使用产量与证实已开发储量（或其他级别储量）的比值，作为项目在开采过程中获取储量和开发储量的成本折旧或折耗依据。在某些地区，是使用产量与 2P（证实储量 + 概算储量，包括未开发储量）的比值作为折旧依据。资本成本的折旧对企业利润和平均占用资本回报率（ROACE）指标有一定影响。在这些计算中，会计师要求储量评估的层级与投资层级相对应。

因此，报告储量与资源量的汇并结果不仅要包括不确定性变化，还要详细分析投资组合的现

a detailed portfolio cash flow analysis to understand the value they represent.

Sec. 6.2 addresses some general technical issues in reserves aggregation. The discussion on the aggregation of reserves also addresses the issue that the uncertainty of the sum of volumes will be less than the sum of the uncertainties of the individual volumes. In other words, the uncertainty decreases with an increasing number of independent units available. The implications of the resulting uncertainty reduction in a diverse portfolio, also called the portfolio effect, will be discussed in Sec. 6.3.

Sec. 6.4 discusses aggregation over reserves categories, and the use of scenario methods for reserves aggregation is shown in Sec. 6.5, followed in Sec. 6.6 by a few notes on normalization and standardization of volumes. Sec. 6.7 summarizes the chapter in a few simple guidelines.

6.2 Aggregating Over Reserves Levels (Wells, Reservoirs, Fields, Companies, Countries)

6.2.1 Reservoir Performance

The best estimate of ultimate recovery (EUR) can be derived through volumetric methods or through extrapolation of well performance in mature fields [e.g., by decline curve analysis (DCA)]. In applying DCA methods, good industry practice is to work from the lowest aggregation level (e.g., wells or completions) upwards, comparing both individual and reservoir or field-level analysis. Performance extrapolation at the reservoir level can lead to a higher EUR than the sum of the extrapolated well decline curves for that reservoir for many reasons. A summation of individual-well-level DCA may not adequately address catastrophic failures, such as wellbore or completion damage. Also, the comparison of individual-well DCAs to a field-level DCA will highlight small, systematic biases that could otherwise be undetectable at the low level of analysis.

One reason for this may be that aggregating from individual-well decline curves does not capture the effect that shutting in a well can sometimes give, an extra economic life to the surviving wells in the reservoir. Another problem, which is specific to gas fields, is that the p/z plot per well often does not properly reflect the overall reservoir pressure decline. In such situations, it is good practice to use an overall reservoir performance extrapolation if possible.

This effect is aggravated if we use a 1P estimate for the well extrapolations. If we sum the individual well results into a reservoir-level estimate, then we assume full dependence (i.e., that all wells will develop their low case simultaneously). There always will be some dependency for wells in the same reservoir because they have the same geological formation, drive mechanism, mode of production,

金流，以了解其价值。

第 6.2 节讨论了储量汇并涉及的常见技术问题。关于储量汇并的讨论也介绍了体积加合的不确定性将小于单个体积评估的不确定性之和。也就是说，独立评估单元数量增加，不确定性减小。多样化投资组合对不确定性减小的影响，即投资组合效应，将在第 6.3 节进行探讨。

第 6.4 节将讨论不同级别储量的汇并；第 6.5 节讲述情景法在储量汇并中的应用；接下来的第 6.6 节，是有关体积数量的规范化和标准化问题；第 6.7 节将汇总几条指导性建议作为本章小结。

6.2 储量汇并层级（井、油气藏、油气田、公司、国家）

6.2.1 油气藏生产动态

估算最终可采量（EUR）的最佳估值可通过容积法计算，或通过成熟油气田的生产动态外推（例如递减曲线分析）获取。在应用递减曲线分析方法时，好的实践做法是从底层（如按井或按完井层段）开始评估，然后逐级向上汇并，并同时开展单井和油气藏（或油气田）层级的评估对比分析。由于多种原因，油气藏层级生产动态外推得到的 EUR 估值会高于该油气藏单井递减曲线的外推结果之和。基于单井层级递减分析，然后汇并的方式也不足以说明有严重问题的情形，例如井筒或完井层段损坏。同样，进行单井层级与油气田层级递减分析的对比有助于发现小的系统性偏差，否则这种偏差在低层级分析中无法检测。

造成这种偏差的原因之一，可能是由于单井递减曲线分析的汇并值无法反映关停一口井有时会使同一油气藏中的其他在产井延长经济寿命。另一个问题是气田特有的，即单井的视地层压力（p/z）常不能正确反映整个气藏的压力递减。在此情况下，若可能，好的做法是使用整个气藏的生产动态进行外推。

若按井外推 1P 估值，该影响会更加明显。如果我们把单井的外推结果相加得到油气藏层级的数据，即相当于假定各井之间完全相关（也就是说所有井同时出现低估值情形）。在同一油气藏内，井和井之间始终存在某种相关性，因为其

etc., but disregarding the fact that the well results have some statistical independence may result in overly conservative estimates at the reservoir level for the sum of high confidence estimates.

Two approaches have been proposed to avoid the effect of arriving at too low aggregates for P1 (or C1) volumes when adding low cases:

(1) Apply decline analysis at the reservoir level.

(2) Statisticaly add Proved estimates from well level to reservoir level.

6.2.1.1 Method 1: Performance Extrapolation and DCA at the Reservoir Level

The first approach, performance extrapolation at the reservoir level is, along with the individual well DCAs, an obvious and necessary supporting part of the performance analysis. In cases where reliable production data at the well level are not available, DCA analysis at a higher level of aggregation (e.g., platform, plant, production station, or reservoir) may be the only basis for the performance extrapolation. Another condition that calls for a higher-level DCA is the occurrence of strong interference effects between neighboring wells.

Performance extrapolation at the reservoir level has a number of pitfalls:

(1) The performance will include the effects of ongoing drilling, development, and maintenance activities.

(2) The aggregate may include wells at different stages of decline, with different GORs, etc.

(3) It has been shown that for multiwell aggregates, the decline will be dominated by the high-rate wells, which may lead to over- or underestimation of the reserves.

Discussion of these issues in DCA are provided by Harrell et al. (2004) and Purves in his chapter (PS-CIM 1994) on DCA methods.

6.2.1.2 Method 2: Statistical Aggregation of Well-Level Proved Estimates

Another approach to compensate for arithmetic addition of high-confidence estimates may be to apply a form of statistical addition. This has other pitfalls:

(1) Well-level Proved estimates are often mutually dependent because of common aquifers, formation heterogeneity, facilities, operation constraints, etc. If independence is assumed, it is up to the reserves evaluator to justify this assumption.

(2) The proposed methods often rely on statistical simplifications (e.g., the assumption of normal distributions for the reserves estimates).

It should be noted that the above problems are avoided when using simulation models to capture reservoir performance. However, often DCA is the method of choice because of its independence from various modeling assumptions.

地层、驱替机理、生产方式等是相同的；但忽略单井估值在统计意义上的独立性，可能导致油气藏层级的高置信度估值过度保守。

为了避免低层级加合造成 P1（或 C1）体积数量汇并值过低，推荐以下两种方法：

（1）在油气藏层级进行递减分析。

（2）采用统计加合方法将单井层级证实储量汇并至油气藏层级。

6.2.1.1 方法 1：油气藏层级动态外推与递减分析

第一种方法，油气藏层级的动态外推，与单井递减分析一样，是生产动态法评估的有效和必要内容。当无法得到单井层级的可靠生产数据时，更高汇并层级（如平台、处理厂、油气计量站或油气藏）的递减分析可能是动态法外推的唯一数据基础。另一种需要在更高层级进行递减分析的情形是存在严重的井间干扰。

油气藏层级的动态法外推存在以下缺陷：

（1）生产动态趋势受钻井、开发和维护作业等生产活动的影响。

（2）生产数据的汇并可能把处于不同递减阶段（气油比不同）的井合并在一起。

（3）有证据表明，在多井汇并时，递减规律主要受高产井控制，这可能导致乐观或保守评估储量值。

有关递减分析中对这些问题的讨论，请参见 Harrell 等人（2004）文献以及 Purves 关于递减分析方法的章节（PS-CIM，1994）。

6.2.1.2 方法 2：单井层级证实储量的统计汇并

统计加合是对高置信度估算值算术求和的补偿方法。该方法的一些缺陷是：

（1）由于共享水体、相似的地层非均质性以及设施与作业条件限制等，单井层级的证实储量估值通常相互依存。若假定其相互独立，则需要储量评估师对这一假设进行论证。

（2）该统计法通常依赖于简化的统计模型（例如，假定储量估值呈正态分布）。

应注意，当采用数值模拟方法分析油气藏生产动态时，可避免出现上述问题。当然，由于无需模拟各种假设条件，递减分析方法是最常用的分析方法。

6.2.2 Correlations Between Estimates

One of the major reasons why summation of reserves, particularly Proved Reserves, sometimes leads to complications is that many parameters in the reserves calculation are dependent upon each other. This leads to further dependencies between individual reserves estimates for reservoir blocks, reservoirs, or subreservoirs, such that low reserves in one reservoir element will naturally be associated with low reserves in another one, or just the opposite. There are numerous reasons for dependency between reservoirs of a geological (fault location, contact height), methodological (similar interpretation methods), or personal (same optimistic geologist for a number of reservoirs) nature, as classified in Table 6.1.

Rigorous methods for evaluating measures of dependency and correlation matrices are discussed in van Elk, Gupta, and Wann (2008).

An example of a positive relation between two estimates can be illustrated with the area-vs.- depth plot of a field shown in Figure 6.1, which consists of two reservoir sands divided by a shale layer. The sands have a common oil/water contact (OWC). Obviously, in this case, the reserves for both sands will change in the same direction if an exploration well finds the OWC somewhat shallower or if a new seismic interpretation lifts the flank of the structure. Adding up the low or Proved values for the two sands is justified to arrive at an estimate for a low reserves case for the field.

A negative correlation occurs when there is uncertainty about the location of a fault between two noncommunicating reservoir blocks. An example is a reservoir with two blocks, A and B, separated by a fault. There is an uncertainty of several hundreds of meters in the fault location. The impact of this uncertainty can be represented by a relation between the fault position and the GRV of the two blocks, Blocks A and B, as Figure 6.2 illustrates.

Calculating the gas initially-in-place (GIIP) is now possible in both blocks; obviously, there is a negative correlation between the volume in one block and the volume in the other. If we now add up the Proved values in each of the two blocks, we are adding two low cases, which in reality will never occur simultaneously. It is clear that, in this case, the Proved value of the two blocks combined will be larger than the arithmetic sum of the two Proved values.

A probabilistic picture of this situation is given in Figure 6.3, which shows the cumulative probability curves of Blocks A and B. The figure also shows the arithmetic sum of the two blocks (curve Block A + Block B) compared with the actual distribution of the

6.2.2 评估结果相关性

储量（特别是证实储量）的求和有时会很复杂，其主要原因之一是储量计算过程中许多参数存在相互依赖性。这使得不同断块、油气藏或者油气层的储量估算值之间也存在相关性，以至于一个储量要素的低估值自然地与另一个要素的低估值相关，或者关联关系相反。表 6.1 分类列出了地质（断层位置、流体界面高度）、分析方法（类似解释方法）或人为主观因素（同一地质家对一些油气藏的乐观解释）等方面使油气藏之间存在相关性的各种原因。

有关相关性度量的严谨评估方法和关联矩阵的探讨，参见 van Elk，Gupta 和 Wann（2008）的文献。

可以用某油田面积 - 深度交会图来阐述两个评估结果呈正相关的情形，如图 6.1 所示。案例油田由两套砂岩储层（中间为页岩隔层）构成。两套储层的油水界面（OWC）相同。显然，在这种情形下，若一口探井查明 OWC 深度变浅，或者新的地震解释结果抬高了构造翼部，则两个砂岩储层的储量变化方向是一致的。两个砂岩储层的储量低估值或证实储量估值相加合是合理的，可以得到油田层级的储量低估值 (或证实储量)。

对于两个互不连通的断块油藏，断层位置的不确定性则对两个断块估值的影响存在负相关性。例如，某油藏由断层分割为断块 A 和 B。断层的具体位置存在几百米的不确定性，其影响可通过断层位置与断块 A 和断块 B 岩石总体积（GRV）的关联关系来体现，如图 6.2 所示。

现在可以计算两个断块天然气原始原地量（GIIP）；显然，一个断块的岩石体积与另一个断块的岩石体积呈负相关关系。如果我们现在把两个断块的证实储量相加，即加合两个低估值——现实中这种情景不可能同时出现。明显，两个断块作为整体进行评估的证实储量估值将大于两个断块证实储量估值的算术和。

图 6.3 是断块 A 和 B 估值的累积概率曲线，展现了上述情形。图中也给出了两个断块估值的算术和（曲线“ 断块 A+ 断块 B ”），可与整个气藏层级的实际分布作对比。两个断块 90%

Table 6.1 Causes of Dependence between Reserves Estimates of Fields or Reservoirs (Modified from Carter and Morales, 1998)
表 6.1 油气田或油气藏储量估值的相关性原因分类（改自 Carter 和 Morales，1998）

Type of Dependence 相关性类型	Example of Situation/Parameter 情形 / 参数举例
None 不相关 No shared risk identifed (fully independent) 无共享风险（非关联）	Local, independent pressure systems 局部、独立的压力系统
Weak 弱相关 A shared risk is not considered to important when compared to other, known, independent risks 与其他已知、独立风险相比，共享风险不重要	Common seismic survey or seismic interpreter; 共用地震采集或地震解释信息； Common source of recovery factor estimates, tools (e.g, reservoir simulator), and ranges; Saturation-calculation method (e.g, Waxman Smits, Archie); Saturation-height function (e.g, using capillary-pressure data from other fields). 共享数据（包括采收率估值、油藏模拟软件等工具）的来源和范围； 饱和度计算方法（如瓦克斯曼一史密斯公式、阿尔奇公式）；饱和度 - 油柱高度函数（如采用其他油田毛管压力资料）。
Medium 中等相关 The shared risks could be real and significant 共享风险可能存在且重大	The success of a low-pressure compression project in one field is a prerequisite of success in another, and hence the recovery factor estimates are potentially linked. 一个油气田的低压增压项目的成功是另一个油气田成功的先决条件，该情形下的采收率估值是潜在相关的。 However, the major components of the uncertainties in reserves of the two fields (structure, etc.) remain independent. 当然，影响两个油气田（构造等）储量不确定性的主要因素依然保持相互独立。
Strong 强相关 The shared risks are known to be real and signifcant 已知共享风险将出现，且重大	The aquifer and pressure systems between two adjacent fields are likely to be common , and actions in one field will affect recovery in the others. 两个相邻油气田很可能有统一的水体和压力系统，一个油气田的动态会影响另一个的开采。
Total 完全相关 The shared risks are absolute 存在绝对共享风险	Two adjacent oil accumulations have commonality assumed in all essential risks (reservoir unit , velocity model, aquifer drive); thus ,their reserves estimates should be added arithmetically. 假如两个相邻石油聚集体共同拥有所有重要风险（储层单元、速度模型、水体驱动类型等），那么其储量估值应该算术加合。
Negative 负相关 The shared risks are absolute and inverse 存在绝对共享风险，且为反向作用	An oil field is developed in a core area only. Additional upside in stock-oil initially-in-place (STOIIP) in flank areas will result in a reduction in the average recovery factor. 一个油田仅在核心部位开发，增加翼部原始原地量（STOIIP）会导致平均采收率的降低。 Uncertainty in fault location works in the opposite direction for gross rock volume (GRV) in two adjacent blocks. 断层位置的不确定性对两个相邻断块的岩石总体积（GRV）起着反向作用。

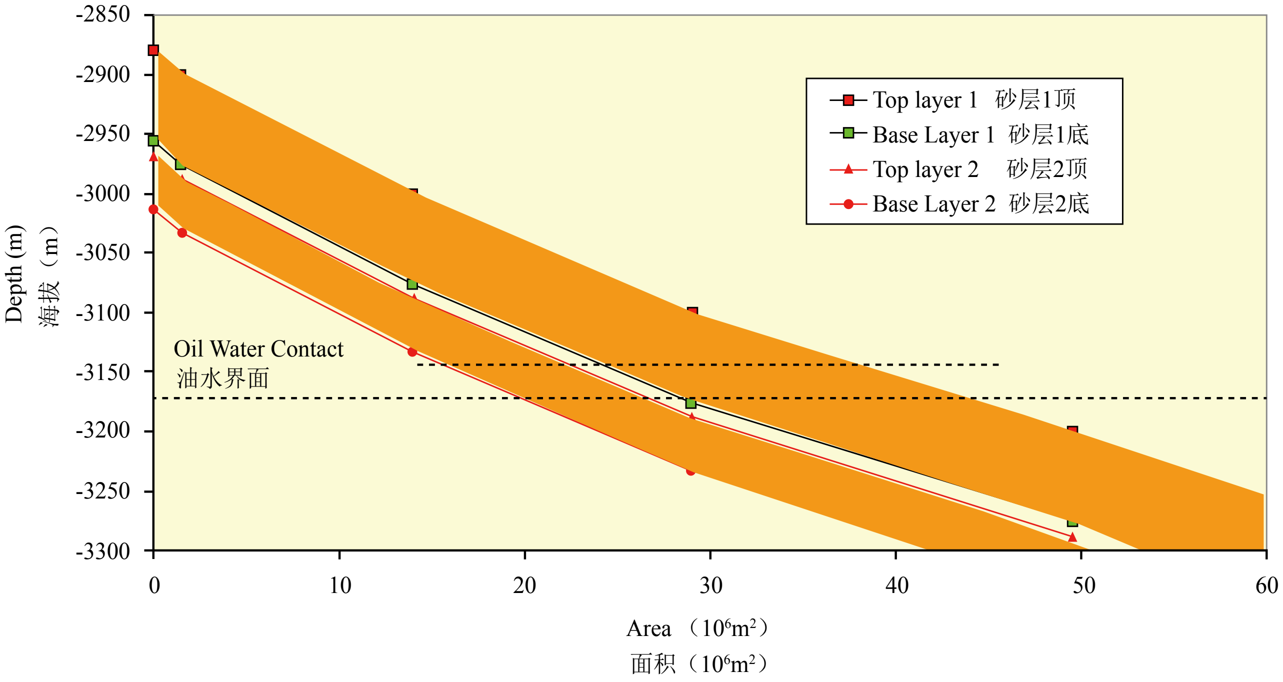

Figure 6.1　West Star field area vs. depth
图 6.1　West Star 油田面积 - 深度交会图

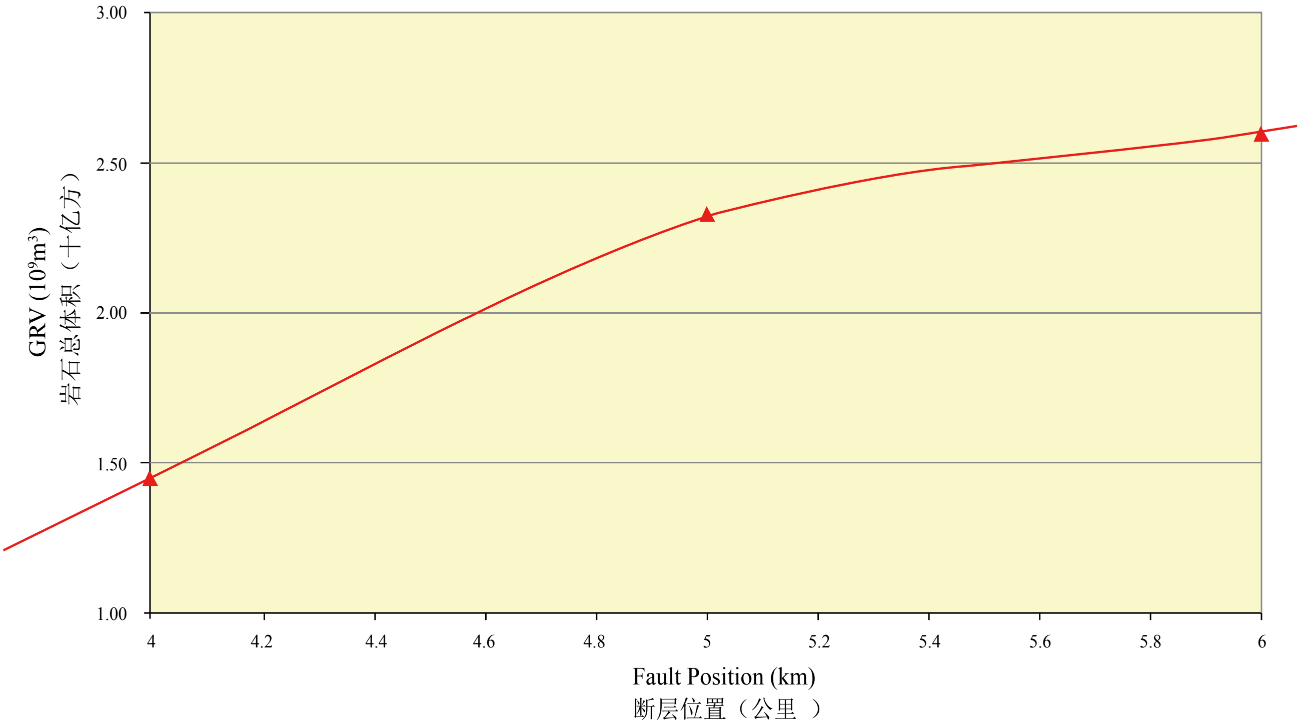

Figure 6.2　GRV of Fault Block A as a Function of Fault Position
图 6.2　断块 A 岩石总体积（GRV）为断层位置的函数

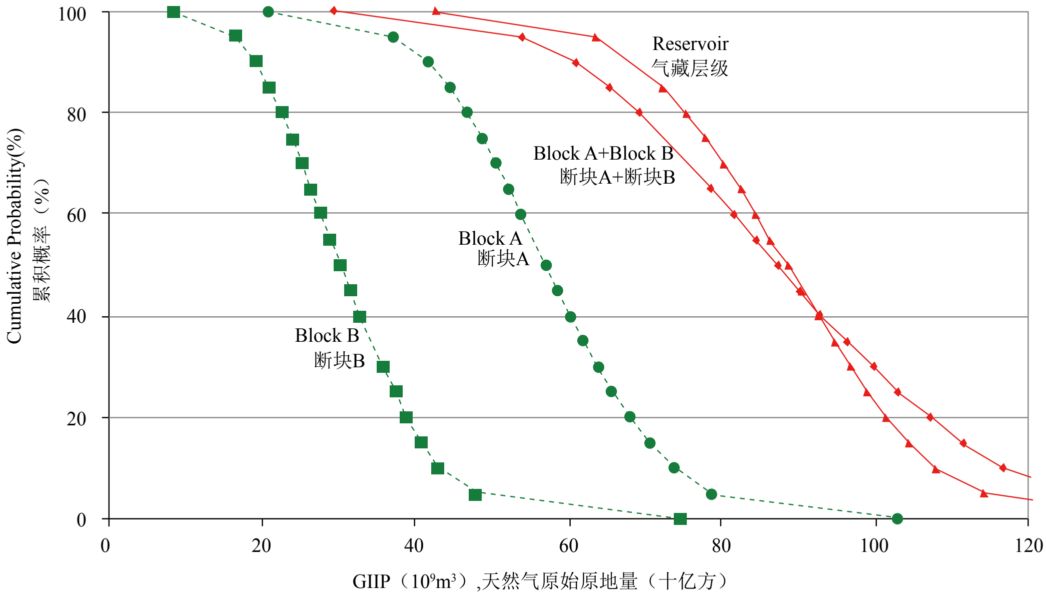

Figure 6.3 Probability Distribution—Reservoir Blocks A and B

图 6.3 断块气藏（A 和 B）评估结果概率分布

full reservoir. The sum of the Proved values of the two blocks at the 90% level is some 7x10^9 m^3 (0.245 Tcf), or 11% less than the Proved value at the 90% level derived for the full reservoir.

Another commonly encountered negative correlation is the situation in an oil reservoir with a gas cap, where solution gas below the gas/oil contact (GOC) is estimated separately. If there is an uncertainty in the GOC depth, then there is a negative correlation between the gas reserves that are carried above and below the GOC. (There is also, of course, a negative correlation between oil reserves and gas-cap reserves. Unless information is available, such as detailed fluid properties, to guide the placement of the GOC, it is usually appropriate to assume that the volume above the highest known oil is occupied by the lower-value product (usually gas)).

Adding up the best estimate, or 2P, values makes good sense to arrive at the combined value of total GIIP, being the sum of free gas and solution gas. Obviously, this is not the case for the Proved Reserves because the low case for free gas will correspond with a high case for solution gas and vice versa. To handle this, a stochastic procedure (using a spreadsheet add-in such as Crystal Ball^{TM} or @ Risk^{TM}, for example) can be used to arrive at the resultant distributions for GIIP and reserves at the field level.

6.2.3 Levels of Aggregation.

As discussed above, summation of Proved Reserves in a statistical way will often result in different volumes than the straightforward “bookkeeping” arithmetic summation. Theoretically, the probabilistic summation can go up to the highest levels of aggregation. Many companies and organizations now appear

概率对应的证实储量估值之和约为 70×10^9m^3（0.245×10^{12}ft^3），相比气藏层级 90% 概率对应的证实储量估值小 11%。

另一种常见负相关的情形是气顶油藏单独估算其油气界面（GOC）以下的溶解气量。若油气界面的深度存在不确定性，那么油气界面上、下两部分的天然气储量则呈负相关关系。显然，原油储量与气顶气储量也为负相关。除非有可靠资料(如详实的流体性质分析)来确定GOC的位置，一般合理的做法是假定最浅已知油顶以上为低价值流体（通常指天然气）。

加合最佳估值（或 2P 估值），则可以试算天然气总原始原地量（GIIP）——自由气与溶解气之和。显然，该方法不适用于证实储量，因为自由气低估值情景是与溶解气高估值情景相关联，反之亦然。为应对这种情况，可采用一种随机模拟程序（电子表格应用程序，如水晶球^{TM}或 @Risk^{TM} 软件）来求取油田层级天然气原始原地量（GIIP）与储量的分布。

6.2.3 汇并的层级

如上所述，与简单“记账式”算术求和相比，统计法加合的证实储量结果往往有所不同。理论上，概率法加合可以逐级应用至汇并的最高层级。在相关性等到适当处理的条件下，许多公司和机

comfortable with the idea of adding probabilistically up to the field level for specific purposes, provided dependencies are handled properly.

The PRMS (SPE 2007) recommends that reserves figures should not incorporate statistical aggregation beyond the field, property, or project level, an approach that has been followed by others in the industry (SEC 2008).

A field containing different reservoir blocks (layers, pools, accumulations) can be fiscally ring fenced and developed as one unit. Fiscal unit-of-production depreciation of the assets is then defined at this level. Above this level of aggregation, statistical summation may lead to fiscal problems. For that reason, there is much less industrywide acceptance for statistical treatment of aggregation above the field level and up to company or regional level. Probabilistic summation at these higher aggregation levels may be of interest only to the small group of professionals involved in portfolio management in the larger companies.

It should be noted that if only deterministic estimates are available, the only option is to use arithmetic summation. The discussion of statistical aggregation only applies if we have a probabilistic analysis (or convert scenarios to quantitative probabilities).

6.3 Adding Proved Reserves

6.3.1 Pitfalls of Arithmetic (Dependent) Addition of Proved Reserves

If we quote Proved Reserves, we commonly refer to volumes that are “estimated with reasonable certainty to be commercially recoverable” in the development of the field. In probabilistic reserves estimation methods, PRMS interprets reasonable certainty as a 90% probability (P90) of meeting or exceeding the quoted value (SPE 2007). The Proved Reserves represent a high-confidence (i.e., relatively conservative) estimate of the recoverable resources; for this reason, it is widely used by investors and bankers. In dealing with only a single asset, this makes sense because it allows for the risk that the development may result in much less than the expected hydrocarbon recovery.

Whenever oil investors or companies add Proved Reserves of several reservoirs arithmetically, they underestimate the aggregated value of their assets. This is because the upsides on most reserves estimates will more than compensate for the downsides on the 10% underperforming assets in the portfolio. This will certainly happen if the estimates of the volumes are independent of each other. For this reason, most companies will rely more on the 2P numbers than on the high-confidence 1P estimates for business planning purposes.

In daily life, we are aware of this when we try to spread our

构为了特定目的，愿意采用概率法加合至油气田层级。

PRMS（SPE，2007）建议，开展储量汇并工作时，统计法的应用不宜超出油气田、资产或项目层级；行业其他机构（SEC，2008）随后采纳了该做法。

当一个油气田包含不同断块（油气层、油气藏、油气聚集体），财税机制为一个篱笆圈，则可作为一个财务单元进行开发。那么该资产的财务产储法折旧也在该层级进行。超出该层级的汇并，统计法加合可能会带来财务问题。鉴于此，行业界很少采纳统计法在高于油气田的层级（公司和地区层级）进行储量汇并。只有大公司涉及资产组合管理的小部分专业人士可能有兴趣采用概率法加合进行这些高层级的储量汇并。

应注意，若仅有确定法评估结果，则储量汇并方法的唯一选择仍为算术求和。有关统计法汇并的讨论只适用于已有概率法分析的情形（或将情景法结果转换为定量化的概率法结果）。

6.3 证实储量加合

6.3.1 证实储量算术求和（关联加合）的缺陷

如果我们提及证实储量，通常是指油气田开发过程中“ 可合理确定、商业开采 ”的油气数量。当采用概率法时，PRMS 解释：合理确定性，是指有 90% 的概率达到或超过所指定数量（SPE，2007）。证实储量体现了资源可采量估值的高置信度（即相对保守），因而被投资方和银行家广泛使用。对于一个单一资产而言，这是有意义的，可让人体会开发风险可能导致结果——油气开采量远低于预期数量。

无论何时，当石油投资方或油公司算术加合多个油气藏的证实储量时，他们会低估整个资产的价值。这是因为在资产组合中，大部分储量估值上调的潜力将大于 10% 概率因表现不佳而储量下调所需的补偿。这种情况会发生在储量评估结果相互独立的情形。因此，大多数油公司在编制业务规划时，更多采用的是最佳估值 2P 数据，而不是高置信度的 1P 估值。

日常经营中，我们意识到应分摊风险，避免

risks and avoid, for example, putting all our investments in one particular asset. For instance, a company committing a number of gas fields to a contract seems unnecessarily conservative in assuming that, ultimately, each field will produce only its initially estimated Proved volume or less. If the reserves estimates are independent, then the upsides in one field may offset a disappointing outcome in others. In other words, the P90 of the total is certainly higher than the (arithmetic) sum of the P90 volumes of the individual fields [see also Schuyler (1998)]. For the same reason, arithmetic addition of the 3P values of individual reservoirs will overestimate the real upside of the combined asset.

If we stick to arithmetic aggregation of Proved Reserves, we run the risk of systematically underestimating the value of our combined assets. Technically, this can be avoided because tools are readily available to account for the favorable condition of having a mix of assets. In addition, it is sometimes possible to convince the investing community (and some governments) to value a combination of assets higher than the sum of the Proved volumes of the individual parts.

Organizations that have a portfolio of very diverse resources will naturally be interested in accounting for the uncertainty reduction that is caused by the diversity of their portfolios. This may be true for larger oil and gas companies as well as for governments. Aggregates derived in this way are outside the scope of the PRMS and other classification systems.

Governments of some countries around the North Sea, such as Norway and the Netherlands, add the national Proved Reserves in a probabilistic way to account for the independent nature of these volumes. For instance, the Dutch Ministry of Economic Affairs has applied the method of probabilistic summation for Proved Reserves since the mid-1980s. In 1996, it stated in its annual report on Dutch exploration and production activities: “The result of applying the method of probabilistic summation is that the total figure obtained for the Proved reserves now indeed represents the Proved proportion of total Dutch reserves in a statistically more valid manner.”

6.3.2 Arithmetic or Dependent Summation

Arithmetic summation is the usual straightforward way of adding volumes and thus of aggregating reserves. Let us look at two gas-bearing reservoir blocks, A and B, with the dimensions in Table 6.2.

With the range and PDF of these parameters, we can construct a probability distribution of the individual blocks as shown in Figure 6.4, with the cumulative probability of exceeding a given volume on the vertical axis.

Note that for the sum of the Proved Reserves in Table 6.2, we have

将所有投资集中在某特定资产。例如，一个公司承诺开发一定数量的气田以履行合同；那么，若假定这些气田最终将只产出最初估算的证实数量甚至更少，这似乎有些不必要地保守。如果储量估值之间是相互独立的，那么一个气田估值的上调就可以补偿另一个气田出现的不利结果。换而言之，总储量的 P90 估值肯定大于各气田 P90 估值的算术求和［另见 Schuyler（1998）］。同理，各气藏 3P 估值的算术加合将高估资产组合的实际潜力。

若我们坚持算术汇并证实储量，会面临系统性低估资产组合价值的风险。从技术上讲，这是可以避免的，因为已有现成工具可考虑混合资产的有利条件。另外，有时可以说服投资机构（和政府机构）接受资产组合的储量估值应大于各单一资产证实数量之和。

资产组合的多样性会降低其不确定性，拥有资源多样性组合的机构，自然会对此感兴趣。大型石油和天然气公司，以及政府可能都很关注这方面具体做法。有关资产组合的汇并方法超出了 PRMS 和其他分类系统的范畴。

在北海周边的一些国家政府（如挪威和荷兰），基于资源禀赋的独立性，采用概率法来加合其国家层级的证实储量。例如，荷兰经济事务部从 20 世纪 80 年代中期起开始采用概率法加合证实储量。该部门在其 1996 年报的“荷兰勘探与生产活动”板块表述到：“应用概率法加合证实储量得到的总数量，目前确实代表了荷兰总储量的证实部分，该数据在统计意义上，更为有效。”

6.3.2 算术求和或关联加合

算术求和是储量汇并的常用方式，即直接加合相应体积的数量。表 6.2 所示为两个断块气藏 A 和 B 的相关数据。

借助这些参数值及其概率密度函数，我们可构建每个断块 GIIP 估值的概率分布曲线，参见图 6.4（纵轴上的累积概率超出了给定数值）。

请注意，表 6.2 中的证实储量之和，是两个

Table 6.2 Example Case: Gas Reservoirs A and B

表 6.2 案例：气藏 A 和 B

Parameters 参数		Block A 断块 A	Block B 断块 B	Total 合计
Total GRV GRV 总量	(10^9m^3)	1.74	1.16	2.9
Porosity 孔隙度		0.22	0.22	0.22
Net to Gross 净毛比		0.85	0.85	0.85
Saturation 饱和度		0.8	0.8	0.8
Gas Expansion 气体膨胀系数		205	205	205
Expectation of GIIP GIIP 期望值	(10^9m^3)	53.4	35.6	89.0
Proved GIIP 证实 GIIP	(10^9m^3)	43.3	28.5	71.8

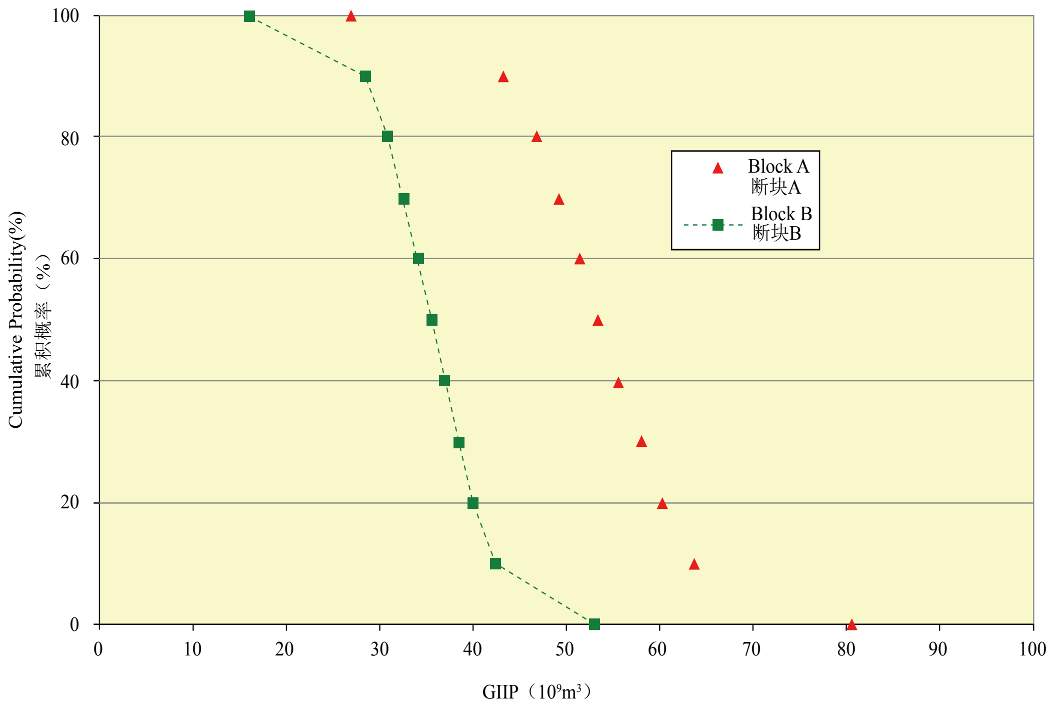

Figure 6.4　Probability Distribution—Reservoir Blocks A and B

图 6.4　断块气藏（A 和 B）估值概率分布

taken the arithmetic sum of two Proved numbers, both of which have a 90% probability of being met or exceeded. In fact, by adding these, we assume complete dependency between the two cases; i.e., we assume that if the low side of one case materializes, the same thing will happen

证实储量（均有 90% 概率达到或超出）的算术求和。事实上，将两者直接加合，即假定其完全相关；也就是说，当一个断块出现低估值情景时，另一个将同时出现低估值。由此，所得到的证实 GIIP with the other case. In this way, we arrive at a potentially pessimistic number for the Proved GIIP, representing the situation that both blocks turn out to be relatively disappointing. However, this could well be the case if both blocks have a common gas/water contact (GWC), or if their volumes are determined by the same seismic phenomena, as shown in one of the examples in the previous section. Even the bias introduced by the same subsurface team, applying the same methods, working on two reservoir blocks may introduce a positive correlation.

6.3.3 Probabilistic or Independent Summation

If the reservoir volumes of the two blocks are deemed to be truly independent of each other, we can still calculate the sum of the mean ⑥ values by straightforward summation. However, if we now derive the Proved value from the distribution of the sum, we may have situations (e.g., in a Monte Carlo simulation of this case) where a low outcome of Block A will be combined with a high outcome of Block B, or the other way around. What happens in practice is that optimistic outcomes in one block compensate for the disappointing outcomes in the other block. This results in a cumulative distribution curve for the combined GIIP that is steeper (i.e., has a smaller spread) than the curve for the arithmetically added volumes, as shown in Figure 6.5. This tendency of the uncertainty range to narrow is a statistical phenomenon that will always be observed if we stochastically add up quantities that have independent statistical distributions.

可能是一个很悲观的数字，表示两个断块的评估结果都令人失望。当然，在两个断块具有同一气水界面（GWC）或其体积的确定是基于相同地震资料时，这种情形是可能出现的，正如前面章节所述的一个案例。即使同一个地质研究团队介绍了断块之间的差异，但采用相同方法、针对两个断块气藏同时工作可能会导致正相关的认识。

6.3.3 概率求和或非关联加合

如果认为两个断块气藏的体积是完全相互独立的，我们仍可以对其评估结果的均值进行直接算数求和⑥。但是，如果我们现在从气藏总体积分布曲线来获取证实储量估值的话，会出现以下情形（如应用蒙特卡洛法模拟）：断块 A 低估值与断块 B 高估值组合，或者反过来。现实情况往往是，一个断块的乐观结果可以补偿另一个断块的悲观结果。这使得资产组合的 GIIP 累积分布曲线比单个资产算术加合的曲线陡（即延伸范围更小），参见图 6.5。不确定性范围缩小趋势属于一种统计现象——在对统计分布相互独立的数值进行随机加合时，总能观察到这一现象。

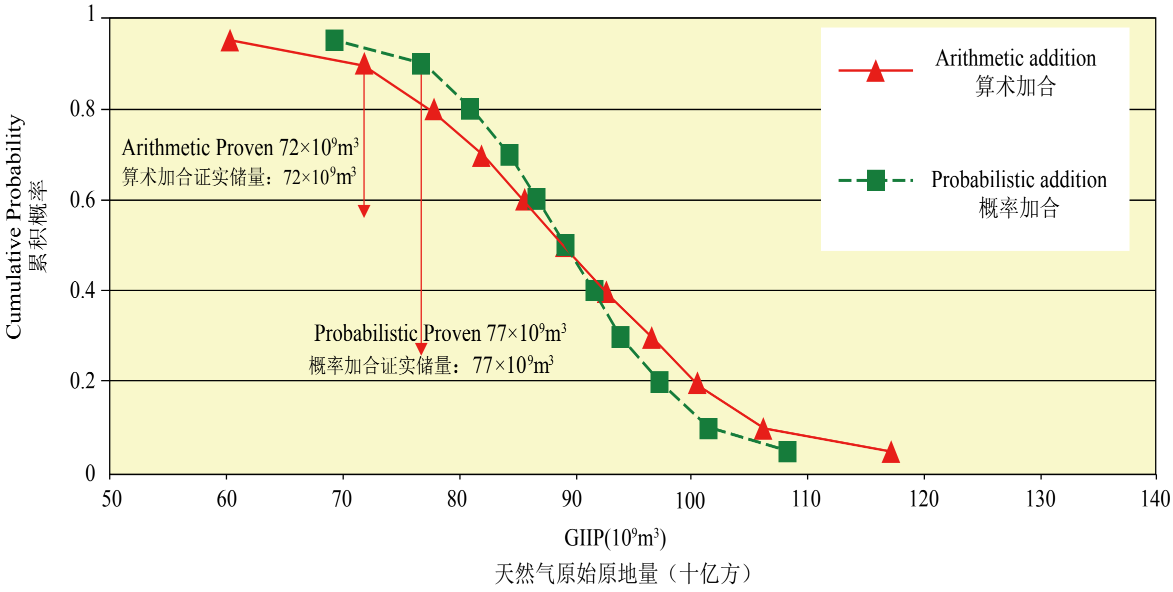

Figure 6.5 Arithmetic and Probabilistic Addition, A and B

图 6.5 断块 A 和 B 气藏储量的算术求和与概率求和曲线分布

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⑥ The mean is used in this discussion as it is the only statistical function that is correctly additive across distributions. However, it should be recalled that the definitional “ best estimate ” case is represented by the median 2P (P50) number.
讨论中使用均值，因为它是在分布曲线中范围内唯一正确加合的统计函数。不过，应重申，定义中的“ 最佳估值 ”情景应指 2P 曲线的中值（P50）。

Applying this approach and making the assumption of complete independence, we can state with 90% certainty that there is at least 77x10^9 m^3 of gas in both reservoir blocks, as opposed to 72x10^9 m^3 of gas using arithmetic summation. In situations where gas contracts are based on Proved Reserves, this may have considerable business implications.

Methods to aggregate volumes independently (assuming no correlation between possible high and low outcomes) are

(1) Scenario trees, representing the possible outcomes as branches of a tree and calculating the overall outcome. This method is treated in Sec. 6.5.

(2) Monte Carlo methods, using a spreadsheet add-in (such as @Risk™ or Crystal Ball™).

(3) Treating the volume estimates as a physical measurement with an associated error and then using error propagation methods.

In the last mentioned method, we approach the uncertainty of the estimate for a reservoir volume by Δ_I = Mean − Proved. We can then calculate the uncertainty for the sum of Reservoirs A and B using the relation $\Delta_{1+2}^2=\Delta_1^2+\Delta_2^2$.

This method is an approximation that holds only for symmetric distributions, but it has the strong advantage of being easy to calculate. It is very suitable for estimating an upper limit for the effects of probabilistic summation. We have to be aware, however, that volumetric estimates, being the product of a number of parameters, tend to be log-normally distributed (i.e., asymmetrical and with a tail of high values).

6.3.4 The Intermediate Case—Using Correlation Matrices

In the previous section, we discussed fully dependent, or arithmetic, summation and fully independent, or probabilistic, summation of Proved Reserves. Most practical situations will be in between these two extreme cases. The reason for this is that some parameters of our estimates will be correlated, while others will be completely independent of each other. Ignoring correlation in these cases will lead to overestimation of Proved Reserves. The rigorous solution in this situation is to calculate probability distributions, specify the correlation between them, and generate the resulting probability distribution for the aggregate. Monte Carlo simulation is the obvious method to achieve this. The overriding problem in this approach is the proper specification of the correlation matrix.

An interesting approach to this problem, illustrated with a real-life example, is presented by Carter and Morales (1998). They describe the probabilistic summation of gas reserves for a major gas development project consisting of 25 fields sharing common production facilities. Each field has a range of gas reserves, expressed at the P90 (Proved), P50, P10, and expectation (mean) levels. The Proved Reserves per field are defined as the volume that has

假定两个断块气藏完全相互独立，通过概率求和可知，两个断块天然气蕴藏量有 90% 的确定性至少有 77×$10^9$$m^3$，而相比之下，其算术求和的数值为 72×$10^9$$m^3$。在天然气合同基于证实储量的情形下，该结果可能会有重要的商业影响。

储量（体积）汇并的非关联（即假定高估值与低估值之间没有相关性）加合方法包括：

（1）情景树法，将各种可能结果作为树的分枝，进而计算整体结果。该方法详见第 6.5 节。

（2）蒙特卡洛法，用电子表格程序（例如 @Risk™ 或水晶球 ™）模拟计算。

（3）将体积估值当作带误差的实际计量值，然后采用误差传播法进行计算。

对于上述最后一个方法，可以用“Δ_I = 均值 − 证实值”来计算单一气藏体积的不确定性。然后，气藏 A 与 B 总体积的不确定性用以下关系式计算：$\Delta_{1+2}^2=\Delta_1^2+\Delta_2^2$。

该方法是一种近似方法，仅适用于对称分布，但其很大的优势是易于计算，非常适合评估概率求和效应的上限。但我们必须知道，容积法估算结果是一系列参数的乘积，倾向于呈对数正态分布（也就是非对称的，尾值高）。

6.3.4 间接方案——关联矩阵法

在前面章节中，我们讨论了证实储量在完全关联情形的算术求和，以及非关联情形的概率求和。而大多数实际情况是处于这两个极端情形之间。原因是我们评估采用的参数有些是相互关联的，有些是完全相互独立的。忽略其相关性会导致证实储量估值偏高。在此情况下，严谨的做法是：计算参数的概率分布，指定参数的相关性，然后生成汇并结果的分布函数。蒙特卡洛模拟是实现这一目标的有效方法。该方法要解决的首要问题是合理确定关联矩阵。

为了解决该问题，Carter 和 Morales（1998）提供了一个有趣方法，并用一个实际案例阐述如下：一个大型天然气开发项目，包含 25 个气田，共享生产设施，采用概率法加合天然气储量。每个气田均有一个天然气储量范围，由 P90（证实）、P50、P10 估值和期望值（均值）表征。每个气田

a 90% chance of being met or exceeded. Adding these volumes arithmetically results in a volume of Proved Reserves across the project that is 15% lower than the stochastically combined P90. Because neither full dependence nor full independence can be assumed, the authors then proceed to analyze the areas of potential dependence between the individual estimates by applying the following procedure:

(1) The areas of dependence are tabulated for individual fields to identify common factors between fields. These areas include technical, methodological, and natural subsurface commonalities between the GIIP estimates of the fields. Commonality is classified as weak, medium, or strong.

(2) An estimate of correlation coefficients is made by assigning values of 0.1, 0.3, and 0.5 for a weak, medium, or strong dependence and combining them into an array suitable for use in a Monte Carlo presentation.

(3) The reserves distribution (for each field) as defined by the P90, P50, and P10 confidence levels is expressed as a double-triangular PDF.

(4) A matrix of correlation coefficients is used to describe the shared risks between fields, with a coefficient for each pair of fields varying from 0 (fully independent) to ± 1 (fully dependent).

(5) The reserves distributions for each field are then probabilistically summed up over the project using the previously defined correlation matrices in the @Risk^{TM} add-in within an Excel^{TM} spreadsheet.

The result of applying this method for the case described was that the gas reserves at the 90% confidence level are some 9% greater than those resulting from arithmetic summation. Not taking the dependencies between the fields into account, the increase would have been 15% over the straightforward arithmetic summation.

Some common-sense measures are described that make the process more practical. The first of these is that fields with the highest level of dependence were added arithmetically into field groups. This ensures a conservative bias in the approach and reduces the size of the correlation matrices to 15 field groups. High dependence occurs between adjacent gas fields believed to be in pressure communication, or between new gas developments sharing structural risk.

Another important measure is a peer review on the semiquantitative process of assigning dependencies. The emphasis in this review process is on identifying factors (such as volumetric uncertainty) that cause full or almost full independence, even if other strong links (such as a shared aquifer) can be demonstrated.

A third simplification of the process was that negative correlation coefficients were disregarded in the analysis. It is possible that a correlation coefficient between two fields can be negative.

证实储量的定义为有 90% 概率达到或超过的体积数量。算术求和各气田证实储量得到项目的证实储量，比随机概率求和的 P90 值低 15%。由于不能假设完全关联或完全独立（非关联），所以作者采用以下步骤来分析单一估算值之间的潜在关联性：

（1）列出各气田相关领域，识别气田间的共有因素。这些领域包括各气田 GIIP 估值之间存在的技术手段、方法原理以及天然储层与流体的共性等。将共性划分为弱、中、强。

（2）根据相关系统评估，给弱、中、强相关性分别赋予相关系数 0.1、0.3 和 0.5，构成适用于蒙特卡洛法的数组。

（3）各气田的储量分布由 P90、P50 和 P10 定义，用双三角概率密度函数描述分布范围。

（4）各气田之间的共享风险用一个关联系数矩阵描述，每一对气田的相关系数在 0（完全不相关）至 ±1（完全相关）之间变化。

（5）然后，应用 Excel^{TM} 中 @Risk^{TM} 插件事先定义的关联矩阵，在项目层级概率求和各气田的储量分布。

该案例应用上述方法的结果表明，90% 置信度的天然气储量比算术求和的结果高 9%。若不考虑各气田之间的相关性，则相应结果比直接算术求和高 15%。

下面介绍一些通用做法，更有利于实际操作。首先，将相关性最高的气田作算术相加，构建气田组。这样确保近似处理的偏差不至于太大，由此相关系数矩阵减少为 15 个气田组。高相关性出现在压力连通的相邻气田，或是共享构造风险的新开发气田。

另一个重要措施，是在相关性半量化过程中进行专家审查。审查重点是确定引起完全非相关或几乎非相关的因素（如容积法的不确定性），即便已经证明存在其他强关联因素（如共享水体）。

简化程序的第 3 个做法，是在分析中忽略负相关系数。两个气田的相关系数出现负值是有可能的。尽管在原则上正相关和负相关都能处理，

While in principle both positive and negative dependencies can be handled, only positive dependencies were identified for the project fields. It was considered during the peer review process that use of a negative coefficient might unduly narrow the range of uncertainty in the final aggregation.

The linked risks resulting from shared surface facilities and constraints are also excluded from the analysis. They are considered to be common (project) risks, and problems with facilities are considered surmountable if they materialize. This type of shared risk can be included in the analysis, if required.

The authors investigated the robustness of their method by changing the dependencies. The result of this sensitivity case supported the general observation that in this type of analysis, the outcome is not very sensitive to changes in individual correlation coefficients.

Use of correlation matrices as described above is similar to other reserve estimation methods in two important aspects:

(1) The figures used are subjective and change when new insights are gained. However, in view of the large number of interrelations (dependencies/independencies) of the fields, major reversals of opinion must occur to change the overall result by a significant amount.

(2) As the established risks are addressed in more detail, specific correlation coefficients will be updated with the proper audit trail. For example, a new seismic interpretation by a new team may result in the dependencies in seismic interpretation being removed after the new interpretation has been accepted.

6.4 Aggregating Over Resources Classes

To achieve business growth and reserves replacement objectives, oil companies identify hydrocarbon volumes in their acreage and execute appraisal and development plans to turn these into Developed Reserves and ultimately into production. To this end, they review EUR targets for existing and newly discovered fields as well as for untested opportunities and identify which activity—exploration, appraisal, development, further study, or new technology development—is required to achieve these targets. As explained in Chap. 2, various classes of resource volumes can be defined in this process.

The volumes thus identified may or may not be ultimately produced, depending on the success of the project. For this reason, it is important not to aggregate Reserves, Contingent Resources, and Prospective Resources “without due consideration of the significant differences in the criteria associated with the classification” ⑦ that

但只列出项目中满足正相关的气田。在审查过程中，专家认为负相关系数可能会过度缩小最终汇并结果的不确定性范围。

分析中，由共享地面设施和限制条件产生的关联风险也被排除在外。该风险被视为（项目）共有风险，如果出现，与共享设施相关的问题是可以克服解决的。若需要，这类风险可以纳入分析之中。

作者通过改变相关性，研究上述方法的稳健性。敏感性分析的结果支持该类分析的总体认识，即单一相关系数的改变对总体结果的影响不大。

如上所述，关联矩阵的应用与其他储量评估方法相似，有两个重要注意事项：

（1）数值的选用带有主观性，当获得新认识时，会相应变化。当然，从油气田大量数据彼此存在关联（相关或非相关）的角度看，只有观点的重大逆转才会导致整体结果的重大改变。

（2）在数据核查跟踪过程中，由于已确定风险的描述更加详实，具体的相关系数会不断适当更新。例如，新技术团队的地震解释新结果被采纳之后，可能会排除地震解释风险的相关性。

6.4 不同类别资源汇并

为了实现商业增长和储量接替目标，油公司需勘查其矿权范围的油气蕴藏数量，并通过实施评价与开发方案，将其转化为已开发储量，并最终变成产量。为此目标，他们需对现有油气田、新发现油气田以及未测试区块进行 EUR 的审查，以确定哪些活动——勘探、评价、开发、进一步研究或新技术开发，可实现预期目标。如第 2 章所述，不同类别资源数量会在该过程核定。

核定的体积数量可能是或不是最终采出的数量，这取决于开发的项目是否成功。因此，未经充分考虑不同资源类别划分标准的显著差异⑦，不要将储量、条件资源量和远景资源量进行汇并，这一点非常重要，否则会包含一些油气聚集体不

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⑦ PRMS Sec. 4.2.1.1

comprise the risk of accumulations not achieving commercial production. In general, this means that the different resources classes should not be included into an aggregate volume. However, a common practice to assess a total portfolio of assets is the use of “risked volumes” calculated by multiplying mean success volumes (MSVs) by the probability of success (PoS). PoS includes both geological chances (presence of hydrocarbons) and probability of commercial development. This is usually deemed to be applicable for a large portfolio of independent projects.

In adding up such volumes, a meaningful total can be defined only by adding the risked volumes (PoS x MSV) resulting in a statistical expectation of the recovery. This will be no problem for a large portfolio of opportunities or for a smaller portfolio where the discounted volumes do not add significantly to the total. Naturally, the range of uncertainty of the aggregate will increase if more speculative categories of resources are included. If such an approach is taken, it is strongly recommended that the resource class components are identified separately and not to report just one single number.

Where many risked volumes are being added, the scenario tree may become a required approach to looking at discrete combinations of possible outcomes; scenario trees are discussed in the next section.

6.5 Scenario Methods

6.5.1 Example of Low Dependence Between Reservoir Elements

A powerful approach to aggregate reserves is the use of scenario methods. To illustrate this approach we discuss two examples: one where we add volumes with a low degree of dependence and one where we aggregate highly correlated volumes.

In the first case, we evaluate three sands (M, N, and S), for which the reservoir parameters and GRVs are relatively independent. The reason for this independence is that the reservoirs occur in different geological formations at very different depths, so there are few factors that cause low and high cases of the sands to coincide. Table 6.3 gives low, median, and high STOIIP for the sands.

To construct a scenario tree for this situation, we have taken the low, median, and high values of STOIIP with equal probability in the sands with the largest volume, the N-sands. We then combine these first with the M-sands and subsequently with the S-sands. This results in a scenario tree with 27 end branches (Figure 6.6).

As can be seen in Figure 6.6, there is some correlation between the occurrence of low, high, and median cases for each of the sands (i.e., the probability that the M-sands have a high value are higher than if the N-sands are high, etc.). At the end branches, we can read off the total STOIIP in each of the 27 possible combinations of N-, M-, and S-sands, as well as the frequency of occurrence.

能商业开发的风险。总之，不同类别的资源不应该进行汇并。但是，对于整个资产组合的评估，通常的做法是采用“风险后油气体积”——成功发现体积均值（MSV）乘以成功几率（PoS）。成功几率包含了地质发现几率和商业开发几率。该方法通常适用于大型独立项目的投资组合。

在此类资源加合中，只有将油气体积进行风险折算（PoS×MSV），得到可采量的统计期望值，然后再加合才能得到有意义的汇并结果。如果风险后的油气数量对总量的影响不大，那么无论是大型或是小型投资组合分析，都不成问题。但自然而然，汇并结果的不确定性范围因为增加了更多推测性资源数量而增大。如果采用这种方法，强烈建议资源类别的数量要单独核定，且不能仅报告一个单一数值。

当多个风险后油气体积进行加合时，可能会使用情景树来分析可能结果的离散组合。下一节将讨论情景树方法。

6.5 情景法

6.5.1 油藏要素呈低关联度的案例

情景树法是汇并储量非常有用的一种方法。我们通过两个案例来说明其用法：一个是低关联度体积加合；另一个是高关联度体积加合。

第 1 种情形案例——油藏参数和 GRV 相互独立的 3 套砂岩储层（M、N 和 S）。其独立性依据是这些油藏分别位于深度完全不同的地层，因而很少有因素会引起这些砂岩储层的低估值和高估值情景同时出现。表 6.3 列出了上述砂岩储层低、中、高估值情景的 STOIIP 估算量。

为了构建该情形的情景树，我们采用等几率选取体积最大 N- 砂岩 STOIIP 的低值、中值和高值，然后逐次与 M- 砂岩、S- 砂岩组合，共得到 27 个分支端点的情景树（参见图 6.6）。

从图 6.6 中可看出，每套砂岩低值、高值和中值的出现存在一定的相关性（即 M 砂岩高值的概率高于 N 砂岩高值的概率等）。在分支末端，可得到由 N- 砂岩、M- 砂岩和 S- 砂岩构成的 27 个可能结果组合的 STOIIP，及其出现的频率。

Table 6.3 STOIIP Uncertainty Range of Three Oil-bearing Sands
表 6.3 三套含油砂岩的原始原地量不确定性范围

Sands 砂岩	Low 低值	Median 中值	High 高值	Mean = Expection 均值 = 期望值
M – Sand M – 砂岩	17	23	30	23.3
N – Sand N – 砂岩	29	41	54	41.3
S - Sand S – 砂岩	10	15	25	16.7

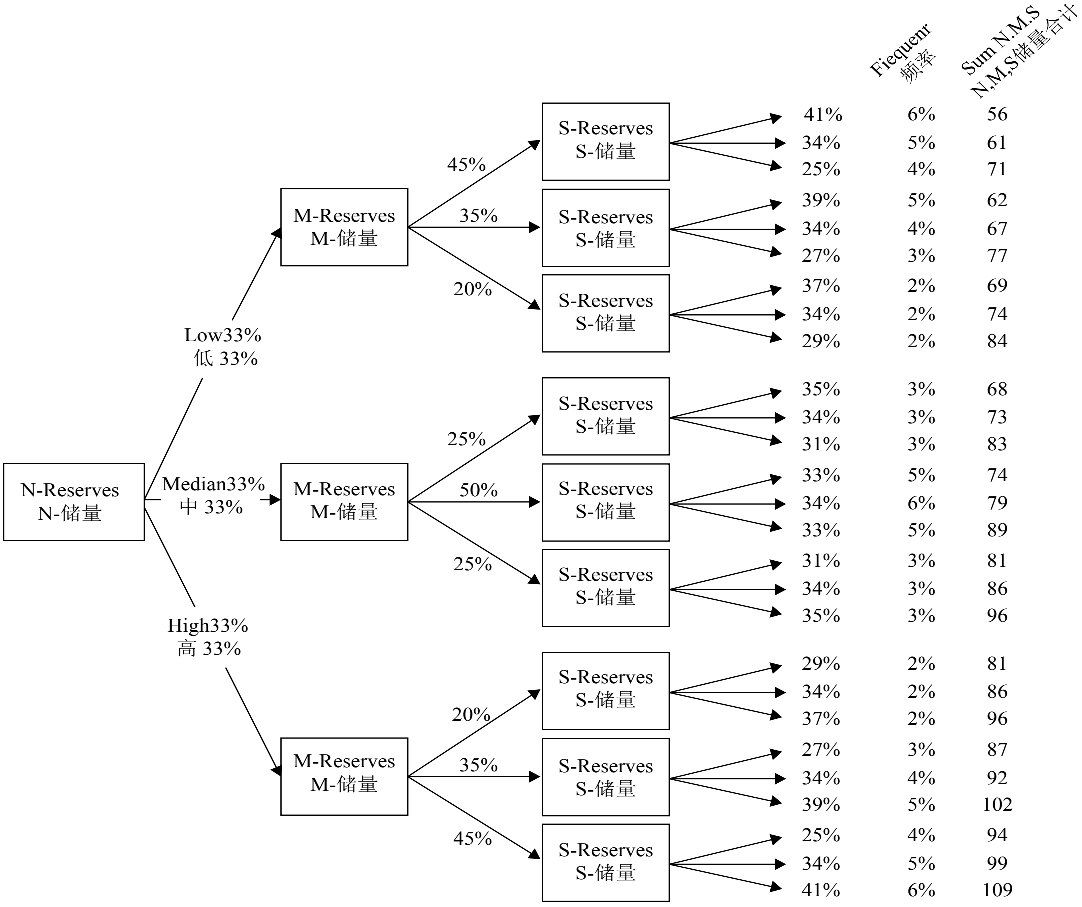

Figure 6.6　Scenario Tree（Low Degree of Dependency）
图 6.6　情景树（低关联度）

It is important to note the low values in this example are not the same as the Proved values for the sands because they are not the 90% probability point in the cumulative probability curve. The probability of the branches and the dependencies between these probabilities, as represented in the tree, should reflect the understanding of the geological processes at work. The resulting STOIIP distribution can then be used as a building block for a resource assessment in PRMS. A plot of these figures is provided in Sec. 6.5.3.

值得注意的要点是，此例中的低值并不代表这些砂岩的证实储量估值，因为它们并不是累积概率曲线上 90% 概率对应的储量值。情景树分支的概率以及这些概率之间的关联关系，应反映工作中的地质认识。那么 STOIIP 结果分布曲线就可作为 PRMS 资源评估的基石。第 6.5.3 节提供了这些数据的交会图。

6.5.2 Example of Dependent Reservoir Elements

In this second example, the sands are on top of each other in a single geological structure; thus, they are all impacted by the same uncertainty in structural dip and the location of the bounding faults. This is a case with high dependencies between the sand volumes because a high volume in the N-sands will increase the likelihood of a high volume in the other sands. We assume that geological parameters, such as porosity or net-to-gross pay play a secondary role and disregard them to keep the number of branches limited. Figure 6.7 shows the scenario tree for this case.

In the scenario tree in Figure 6.7, the dependency between the three sands shows up as a higher probability that high sand volumes are combined with high volumes. A low case in one sand will tend to go together with a low case in another sand. A plot of these figures is provided in Sec. 6.5.3.

6.5.2 油藏要素高度关联的案例

第 2 种情形案例——这 3 套砂岩在同一个地质构造内相互叠置；受到相同构造倾角和边界断层位置的不确定性影响。砂岩体积间存在高度相关性，因为 N- 砂岩出现高值将增加其他砂岩出现高值的可能性。假设地质参数（例如孔隙度或净毛比）只起次要作用，并忽略变化，以限制分支数量。图 6.7 为该情形的情景树。

图 6.7 的情景树中，3 套砂岩之间的关联关系显示，砂岩体积高值与高值组合的几率较高。一套砂岩出现低值，另一套砂岩也趋向于出现低值。第 6.5.3 节提供了以上数据的交会图。

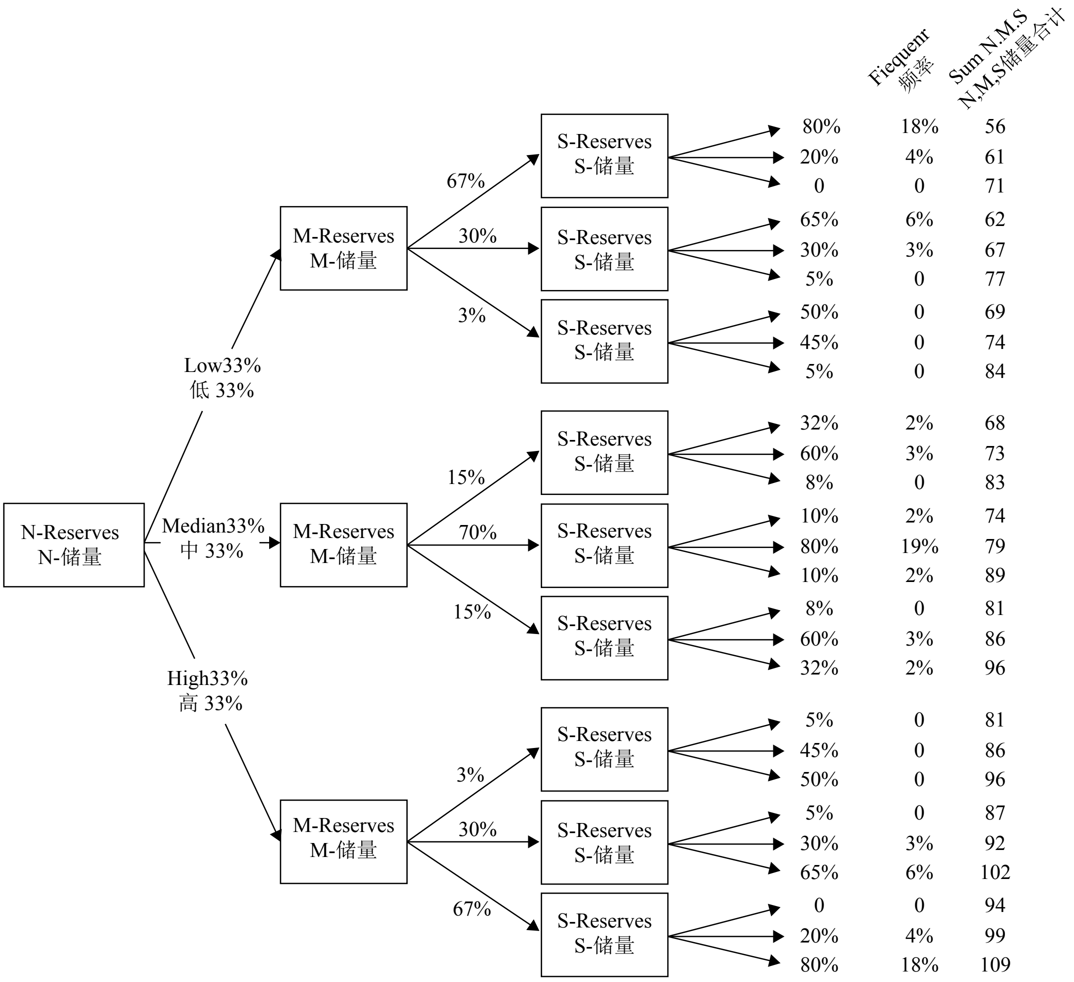

Figure 6.7 Scenario tree with high degree of dependent reservoir elements.

图 6.7 高关联度油藏要素情景树

6.5.3 Comparing Degrees of Dependence

We can go through the same exercise with a similar scenario tree for full independence. This is a straightforward extension from the previous two examples, with the chance factors on the branches of the tree all taken to be one-third (33%). By using the results of the scenario trees, we can construct the pseudoprobability curves for each of the three cases by sorting and calculating cumulative probabilities. Figure 6.8 shows the results. This analysis now results in the summations of the three sands shown in Table 6.4.

6.5.3 关联度对比

采用同样方法，非关联的情形可以构建出类似的情景树。这是前面两个案例的简单延伸：情景树各分支的几率因子一律取三分之一（33%）。利用情景树结果，经排序和计算累积概率，可以构建 3 种情形的视概率曲线（参见图 6.8）。3 套砂岩的分析结果汇总于表 6.4。

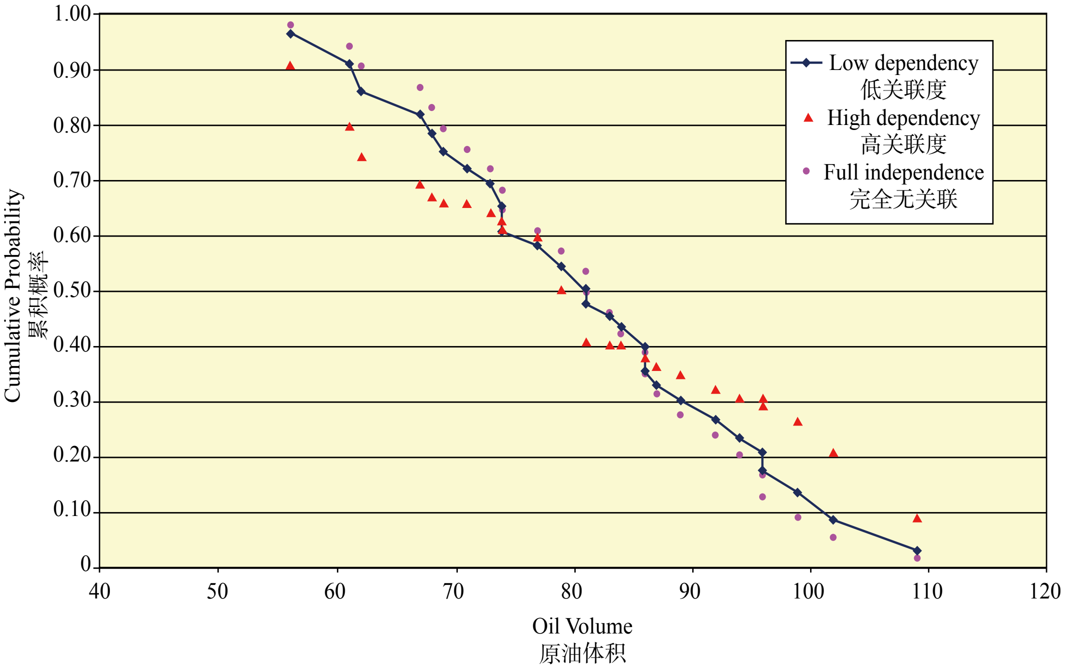

Figure 6.8　Cumulative Probability Curve
图 6.8　累积概率曲线

Table 6.4 Probabilistic Addition with Varying Degrees of Dependency, STOIIP
表 6.4 不同关联度下原始原地量的概率加合

Items 项目	P85=Low P85 = 低值	P50=Median P50 = 中值	P15=High P15 = 高值	Expectaion=Mean 期望值 = 均值
M – Sand M – 砂岩	17	23	30	23.3
N – Sand N – 砂岩	29	41	54	41.3
S – Sand S – 砂岩	10	15	25	16.7
Independent sum 非关联加合	67	81	96	81.3
Low – dependence sum 低关联度加合	64	81	98	81.2
High – dependence sum 高关联度加合	59	79	105	81.1
Fully dependent addition (arithmetic) 完全关联加合（算术求和）	56	79	109	81.3

As expected, the mean values are hardly affected by the assumptions used in the four aggregation procedures. Because the distributions used are almost symmetric, there is also little variation in the value of the median case. For the low and the high values taken at the 15% and 85% levels, respectively, there are some clear differences.

The fully independent case and the low-dependency case closely resemble each other in the cumulative probability representation. As expected, the fully independent case results in a narrower range of volumes than the low-dependency case. Apparently, the result is not very sensitive to the chance factors in the scenario tree.

6.5.4 Comparing Scenario Trees and Correlation Methods

We now have discussed two methods for handling dependencies in aggregating volumes: the use of matrices to describe correlation between parameters (in Sec. 6.3) and the construction of scenario trees in this section. Table 6.5 compares the two methods.

The ease of use and the link with decision-making approaches generally will make the scenario tree method the preferred choice.

与预期相符，4 种汇并方法的均值几乎不受假设条件影响。由于所采用分布近似为对称，中值也仅微弱变化。在低值和高值分别取 15% 和 85% 几率时，不同情形的结果存在明显差异。

非关联与低关联度情形的累积概率曲线上的特征非常相似。正如预期，非关联情形比低关联度情形的体积分布范围更小。显然，在应用情景树时，结果对几率因子并不十分敏感。

6.5.4 情景树与关联矩阵对比

我们已探讨了体积汇并过程中处理相关性的两种方法：用关联矩阵描述参数之间的关联关系（参见第 6.3 节）和本节介绍的构建情景树。表 6.5 对这两种方法进行了比较。

由于使用便捷，且与决策过程紧密结合，使得情景树通常成为首选工具。

Table 6.5 Comparison between Scenario Tree and Correlation Matrix Methods

表 6.5 情景树与关联矩阵法对比

Scenario Trees 情景树	Correlation Matrices 关联矩阵
Natural link with decision making 与决策过程自然结合	Easy link with probabilistic description — allows Monte Carlo approach 易与概率描述关联—可采用蒙特卡洛算法
Dependencies made visible in the diagram 在图中，可查看关联关系	Dependencies shown in matrices 在矩阵中，可直观关联关系
Conditionality depends on ordering of branches-------needs care to construct the tree 条件限制依赖于分支排序 ------- 构建情景树要谨慎	Dependencies independent of ordering 相关性不依赖于排序
Not practical with large number of parameters 参数众多时不实用	Many correlated parameters can be handled 可处理大量相关参数
Intuitively clear 直观清晰	Less intuitive/more abstract 直观性较差 / 更为抽象

6.6 Normalization and Standardization of Volumes

Hydrocarbon volumes can only be added and properly interpreted only if there is no doubt of their meaning. On a global basis, there may be variations in specifications so that for aggregations to be meaningful, we need to normalize volumes. Under PRMS, reserves and resources are measured at the custody transfer point at pressure and temperature, for which agreed values are used. This may lead to small differences between reported volumes in different unit-of-measurement systems. The commonly used reporting conditions for oil and natural-gas-liquid (NGL) field volumes and for fiscalized sales volumes are standard conditions [m^3 or bbl at 15°C, 1 atm (760 mm Hg); m^3 or bbl at 60°F,

6.6 油气体积的规范化与标准化

仅当对油气体积的内涵意义没有疑义时，才能进行加合处理并正确解释。从全球范围看，可能存在不同规范，因此我们需要标准化油气体积，使汇并工作有意义。遵循 PRMS，储量和资源量是在油气交付点温度和压力条件下的计量值——与产品价值相对应。不同单位计量系统的报告数量可能会出现微小差异。通常，石油和天然气液（NGL）在油田和财务销售的计量单位为标准状态 [温度 15℃和压力 1atm（760 毫米汞柱）或温度 60°F 和压力 14.7psia] 下的立方米或桶。当销

14.7 psia). Local deviations from this convention exist where sales gas is measured and reported in other units.

For gas, we can apply two standardization steps:

(1) Conversion to standard pressure and temperature conditions. Unfortunately, various combinations of pressure and temperature in field units as well as SI units are in current use. The pressure and temperature conversion factors for gas are, to some extent, dependent on gas composition, and slightly different values may be used.

(2) Conversion to a volume with an equivalent heating value. Heating value conversion factors:

9,500 kcal/Nm^3 = 39.748 MJ/Nm^3

1,000 Btu/scf (60°F, 30 in. Hg) = 39.277 MJ/Nm^3

The volume equivalent in total combustion heat is

1 Nm^3 (GHV = 9,500 kcal/Nm^3) = 37.674 scf (GHV = 1,000 Btu/scf).

Field gas is usually reported at the composition and heating value it has at the wellhead, and usually at standard conditions. The conversion to an equivalent heating value is not applied for this category.

Sales gas is usually measured and reported in Nm^3 (e.g., m^3 at 0°C, 760 mm Hg) and sometimes converted to an energy equivalent [e.g., the volume at normalized gross heating volume (GHV) of, for example, 9500 kcal/N m^3].

6.7 Summary—Some Guidelines

(1) In summing 2P reserves values, arithmetically add the deterministic estimate of volumes.

(2) Arithmetic summation of Proved Reserves for independent units leads to a conservative estimate for the Proved total. Methods and tools are available to determine a more realistic value (Monte Carlo, probability trees, and customized tools) for summation of independent distributions.

(3) Adding Proved Reserves probabilistically without fully accounting for dependencies could overstate the Proved total.

(4) In calculating reserves volumes from well-performance extrapolation or DCA, always work up from the lowest aggregation level (e.g., well or string). Adding up Proved Reserves from well-based DCA estimates may lead to overly conservative estimates of reserves at the reservoir level of aggregation; hence, always check with an overall reservoir performance extrapolation. Also, carefully review the “history-to-forecast” interface to make sure that the methodology has not introduced any discontinuities.

售气采用其他单位计量和报告时，可能存在单位转换造成的局部偏差。

对于天然气，可采用以下两个标准化步骤：

(1) 转换为标准压力与温度条件。遗憾的是，目前压力和温度的矿场单位和国际标准单位经常混用。某种程度上，天然气压力与温度转换系数取决于天然气组分，采用的系数可能略有不同。

(2) 转换为热值当量体积。热值转换系数为：

9500 kcal/Nm^3 = 39.748 MJ/Nm^3

1000 Btu/scf (60°F, 30 in.Hg) = 39.277 MJ/Nm^3

总燃烧热值当量体积（GHV）：

1 Nm^3 (GHV = 9500 kcal/Nm^3) = 37.674 scf (GHV = 1000 Btu/scf).

在矿区，天然气通常在井口按标准条件计量的组分和热值进行报告，不适用转换为热值当量体积。

销售气的计量与报告通常以标准立方米（Nm^3，温度 0℃和 760 毫米汞柱条件下的立方米）表示，有时转换为能量当量［例如，9500kcal/Nm^3 系数条件下，标准化的总热值当量体积（GHV）］。

6.7 小结

(1) 加合 2P 储量估值时，可采用确定法结果算数求和。·

(2) 对相互独立评估单元的证实储量进行算术加合，会导致总证实储量数据偏于保守。可利用现有的方法和工具（蒙特卡洛法、概率树和其他客户化工具）来确定更接近实际的数值。

(3) 证实储量概率加合时，若没有全面考虑相关性，可能会导致总证实储量过于乐观。

(4) 根据生产动态进行外推或采用递减曲线分析（DCA）估算储量时，总是从最低层级（如单井或井段层级）开始。基于单井递减分析结果进行证实储量的汇并时，可能会导致油气藏层级的数量偏于保守；因此，需用油气藏层级的递减曲线分析进行校验。同样，要仔细审查历史数据和预测结果之间的衔接性，确保所采用的评估方法没有造成数据不连续性。

(5) PRMS allows probabilistic aggregation up to the field, property, or project level. Typically, for reporting purposes, further aggregation uses arithmetic summation by category. Fully probabilistic aggregation of a company's total reserves and risked Contingent and Prospective Resources may be used for portfolio analysis.

(6) For adding volumes with differing ranges of uncertainty and volumes that are correlated, or in situations where discount factors are applied, the scenario method can often be applied.

(7) When adding volumes, make sure they have a common standard of measurement (pressure/temperature, calorific value).

（5）PRMS 允许采用概率法进行油气田、资产或项目层级的汇并。通常，为了披露需要，更高层级的汇并可按级别进行算术加合。在公司层级，完全概率法汇并的总储量、风险后条件资源量与远景资源量可用于资产的投资组合分析。

（6）对于不确定性范围不同、有关联关系或风险折算后的油气数量进行加合时，情景法是常用的方法。

（7）在加合油气数量时，要确保它们具有相同的标准计量单位（压力 / 温度、热值）。

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第 7 章
CHAPTER 7

石油储量与资源量价值评估
Evaluation of Petroleum Reserves and Resources

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7.1 Introduction

The valuation process is about determining value. Commercial evaluation of petroleum reserves and resources is a process by which the value of investing in existing and planned petroleum recovery projects is determined. These results are used to make internal company investment decisions regarding commitment of funds for commercial development of petroleum reserves. Based on a companywide comparative economic analysis of all alternative opportunities available, the company continues to make rational investment decisions to maximize shareholders' value. Results may also be used to support public disclosures subject to regulatory reporting requirements.

These guidelines are provided to promote consistency in project evaluations and the presentation of evaluation results while adhering to PRMS (SPE 2007) principles. In this context, a project evaluation will result in a production schedule and an associated cash flow schedule; the time integration of these schedules will yield an estimate of marketable quantities (or sales) and future net revenue [or net present value (NPV) using a range of discount rates, including the company's]. The estimation of value is subject to uncertainty due not only to inherent uncertainties in the petroleum in place and the efficiency of the recovery program but also in the product prices, the capital and operating costs, and the timing of implementation. Thus, as in the estimation of marketable quantities, the resulting value estimates should also reflect a range of outcomes.

Petroleum resources evaluation requires integration of multidisciplinary "know-how" in both the technical and the commercial areas. Therefore, evaluations should be conducted by multidisciplinary teams using all relevant information, data, and interpretations.

7.2 Cash-Flow-Based Commercial Evaluations

Investment decisions are based on the company's view of future commercial conditions that may impact the development feasibility (commitment to develop) based on production and associated cash flow schedules of oil and gas projects. Commercial conditions reflect the assumptions made both for financial conditions (costs, prices, fiscal terms, taxes) and for other factors, such as marketing, legal, environmental, social and governmental. Meeting the "commercial conditions" includes satisfying the following criteria defined in PRMS Sec. 2.1.2 for classification as Reserves:

(1)A reasonable assessment of the future economics of such production projects meeting defined investment and operating criteria, such as having a positive NPV at the stipulated hurdle discount rate.

(2)A reasonable expectation that there is a market for all or at least some sales quantities of production required to justify development.

7.1 引言

价值评估过程是为了确定价值。通过对石油储量与资源量的商业评估，可确定现有和已规划石油开采项目的投资价值。评估结果将用于公司内部投资决策，确定石油储量商业开发的资金承诺。在对公司所有可选方案进行经济对比分析的基础上，公司做出合理的投资决策，以实现股东价值的最大化。评估结果还可用于公共披露，以满足监管报告要求。

本指南旨在遵循 PRMS (SPE，2007) 的原则，促进项目评估和评估结果报告中的一致性。在此背景下，项目的评估将获得产量预测剖面和相应的现金流剖面；对上述剖面进行时间积分，即可估算出未来可销售量（或销售量）和净收入［或净现值（NPV)，采用一定的贴现率（包括公司贴现率）］。该价值评估结果的不确定性，不仅包括石油原地量与开采效率的固有不确定性，也包括产品价格、资本投资、操作成本和实施的时间节点等方面的不确定性。因此，在评估可销售量时，其价值的估算结果应是一个范围。

石油资源评估需要综合应用多学科的专业技术，既包括技术领域，也包括商务领域。因此，应该由多学科的团队根据所有的相关信息、数据与解释成果来开展评估工作。

7.2 基于现金流的商业评估

公司的投资决策是基于对未来影响项目开发可行性（即承诺开发）的商业条件的判断，而开发可行性分析的基础是油气项目的产量和现金流预测剖面。项目商业化条件体现了对财务因素（成本、价格、合同财税条款、税负）和其他因素（如市场、法律、环境、社会与政府因素）的假设条件。符合商业化条件包括满足 PRMS 第 2.1.2 节储量类别所规定的以下条件：

（1）对于满足规定的投资与运行条件（如按规定的门槛贴现率贴现之后，NPV 为正值）的生产项目，合理评估其未来经济性。

（2）对于全部或部分销售产量（至少支撑项目运行所需），存在可市场销售的合理预期。

(3)Evidence that the necessary production and transportation facilities are available or can be made available.

(4)Evidence that legal, contractual, environmental, and other social and economic concerns will allow for the actual implementation of the recovery project evaluated.

(5)Evidence to support a reasonable timetable for development.

Where projects do not meet these criteria, similar economic analyses are performed, but the results are classified under Contingent Resources (discovered but not yet commercial) or Prospective Resources (not yet discovered but development projects are defined assuming discovery). Value of petroleum recovery projects can be assessed in several different ways, including the use of historical costs and comparative market values based on known oil and gas acquisitions and sales. However, as articulated in PRMS, the guidelines herein apply only to evaluations based on discounted cash flow (DCF) analysis.

Consistent with the PRMS, the calculation of a project’s NPV shall reflect the following information and data:

(1)The production profiles (expected quantities of petroleum production projected over the identified time periods).

(2)The estimated costs [capital expenditures (CAPEX) and operating expenditures (OPEX)] associated with the project to develop, recover, and produce the quantities of petroleum production at its reference point (SPE 2007 and 2001), including environmental, abandonment and reclamation costs charged to the project, based on the evaluator’s view of the costs expected to apply in future periods.

(3)The estimated revenues from the quantities of production based on the evaluator’s view of the prices expected to apply to the respective commodities in future periods, including that portion of the costs and revenues accruing to the entity.

(4)Future projected petroleum production and revenue-related taxes and royalties expected to be paid by the entity.

(5)A project life that is limited to the period of entitlement or reasonable expectation thereof (see Chapter 10) or to the project economic limit.

(6)The application of an appropriate discount rate that reasonably reflects the weighted average cost of capital or the minimum acceptable rate of return (MARR) established and applicable to the entity at the time of the evaluation.

It is important to restate the following PRMS guidance: “While each organization may define specific investment criteria, a project is generally considered to be economic if its best estimate (or 2P) case has a positive net present value under the organization’s standard discount rate.”

(3) 证据表明已有或可获得必需的生产与运输设施。

(4) 证据表明法律、合同、环境以及其他社会与经济关切等各方面，均允许实施评估的开采项目。

(5) 证据表明开发的时间计划合理。

对于未能满足上述条件的项目，也进行类似的经济评估，但其结果划归为条件资源量（已发现，但尚未商业生产）或远景资源量（尚未发现，但假设发现后定义的开发项目）。石油开采项目的价值可通过不同方法进行评估，包括在已知油气项目收购和销售的情况下，采用历史成本法和市场价值对比法。但是，如 PRMS 所述，本指南仅应用贴现现金流（DCF）分析方法进行评估。

按照 PRMS 的规定，项目的净现值计算应反映以下信息与数据：

(1) 产量剖面（指定时间段的石油预测产量）。

(2) 与参照点（SPE 2007 和 2001）所计量的项目石油产量相关的运营、开发和生产的成本——资本支出（CAPEX）和操作费用（OPEX），包括项目应承担的环境维护、废弃与井场复垦成本等，根据评估师对未来成本的评估进行测算。

(3) 预计的产量收入，包括对归属于实体的成本回收部分以及收入，由评估师根据对未来商品价格的预期进行估算。

(4) 实体应支付的与未来预测产量和收入相关的税负和矿费。

(5) 项目的生命周期，不超过份额权益期或合理的预计期限（见第 10 章），或达到项目经济极限的期限。

(6) 采用适宜的贴现率，该贴现率能够合理反映评估时实体的加权平均资本成本或最低回报率（MARR）。

重申以下 PRMS 应用指南很重要：“各机构可以自行规定投资的具体条件要求，但通常情况下，若项目的最佳估值（或 2P）情景按该机构的标准贴现率贴现后净现值为正，则该项目视为是经济的。”

7.3 Definitions of Essential Terms

Understanding of essential definitions and well-established industry practices is necessary when generating and analyzing cash flows for any petroleum recovery project. These include current and forecast economic conditions, economic limit, and use of appropriate discount rate for the corporation.

7.3.1 Economic Conditions

Project net cash flow (NCF) profiles can be generated under both current and future economic conditions as defined in the PRMS. Consistent DCF analyses and resource evaluations may be conducted using the definitions of economic cases or scenarios:

Forecast Case (or Base Case): DCF Analysis Using Nominal Dollars. The "forecast case"(or "base case") is the standard economic scenario for reserves evaluations. Economic evaluation underlying the investment decision is based on the entity's reasonable forecast of "future economic conditions," including costs and prices expressed in terms of nominal (or then-current) monetary units that are expected to exist during the life of the project. Such forecasts are based on changes to "current conditions" projected to any year (t). Estimates of any project cash flow component (price or cost) expressed in terms of base-year or current-year dollars are escalated (to account for their specific annual inflation rates or escalation rates) to obtain their equivalent value in terms of nominal dollars (also known as then-current dollars, or dollars of the day) at any year (t) over its economic life by using the following simple relationship:

$$\text{Nominal\$}(t) = (\text{Current-year\$})EF_{kt} = (\text{Current-Year2010\$})(1+E_k)^t \quad (7.1)$$

Where

$$EF_{kt} = (1+E_k)^t \quad (7.1a)$$

and EF_{kt} is the escalation factor (or the cumulative overall multiplier) at any time t, which ranges from t = 0 (zero or current-year) to t = n (project's economic life in years) for any price or cost component (k = 1, 2, 3…) of project cash flows.

E_k = average and constant annual escalation rate or goods/products and services specific inflation rate (in fraction) for any price and cost component (k) over the entire project life (t = 0 to n). Although generally expressed and used as annual rates, these rates can be expressed over any time period provided that other data are also expressed in the same time unit.

Note that for simplicity alone, periodic escalation rate, E_k, is assumed to remain constant for any individual price or cost component (k = 1, 2, 3, . .) over the entire project life. (Unless specified explicitly, the monetary unit is assumed to be US dollars, designated by $).

7.3 基本术语定义

计算和分析任何石油开采项目的现金流时，需要了解基本的定义和成熟的行业实践，包括当前的和预计的经济条件、经济极限和企业适用的贴现率。

7.3.1 经济条件

按照PRMS规则，可根据当前和未来的经济条件计算项目的净现金流（NCF）剖面。为了使贴现现金流分析（DCF）与资源评估保持一致性，可以使用以下经济评价方案（或情景）定义。

7.3.1.1 预测方案（或基础方案）

按名义美元进行DCF分析。预测方案（或基础方案）是储量评估的标准经济方案。支撑投资决策的经济评估是基于实体对未来经济条件的合理预测，包括以名义货币（或当时货币）单位表示的项目生命期内的成本与价格。而这些预测是建立在任意年（t）的条件与当前条件的变化情况预计基础之上。项目以基础年或当年美元表述的各现金流构成要素（价格或成本）的估算值应进行上浮（考虑年通货膨胀率或上浮率），以获得在经济期限内任意年（t）的以名义美元（即当时美元或当日美元）表述的相应数值，可采用下列简单关系式计算：

$$\text{名义美元}(t) = (\text{当年美元}) \times EF_{kt} = (\text{2010当年美元}) \times (1+E_k)^t \quad (7.1)$$

其中 $EF_{kt} = (1+E_k)^t$ (7.1a)

式中，EF_{kt} 是项目现金流中任意价格和成本构成（k = 1,2,3⋯）在任意时间t的浮动系数（或累计总系数），范围为t=0（0时间点或当年）到t = n（项目经济年限）。

E_k 是项目生命期内（t = 0 ～ n）任意价格与成本构成指标（k）的平均年上浮率或商品/产品与服务特定通胀率常数（小数）。尽管 E_k 多表述为和用作年度比率，但在其他数据也以相同时间单位表述的情况下，该比率可以用任何时间段表述。

请注意，为简便起见，假定整个项目生命期内任何单个价格或成本构成（k=1,2,3,⋯）的阶段上浮率 E_k 保持恒定不变。货币单位假定为美元，用$表示，除非有明确规定。

Constant Case (or Alternative Case). DCF Analysis Using Current-Year Dollars. The “constant case” is an alternative economic scenario in which current economic conditions are held constant throughout the project life. PRMS defines current conditions as the average of those that existed during the previous 12 months, excluding prices defined by contracts or property specific agreements.

PRMS recommended reserves evaluation under Constant Case requires each price and cost component of project cash flows to be expressed in terms of current-year dollars. Evaluation under the Forecast Case uses project cash flows that are expressed in terms of nominal dollars. Table 7.1 illustrates how an example average crude price of USD 50/bbl in current-year 2010 dollars can be expressed in terms of nominal dollars in Years 2011 through 2012 using Eq. 7.1.

For escalation of prices and costs, readers can also refer to SPEE Recommended Evaluation Practices (2002). However, companies may run several additional economic cases based on alternative cost and price assumptions to assess the sensitivity of project economics to uncertainty in forecast conditions.

7.3.1.2 恒定方案（或替代方案）

采用当年美元进行 DCF 分析。恒定方案是一个替代的经济评估方案，其当前经济条件在整个项目的生命期内保持恒定不变。PRMS 将当前经济条件定义为过去 12 个月的平均值，除非项目合同或资产有关协议中对价格有明确的规定。

PRMS 推荐的恒定方案储量评估，要求项目现金流的价格与成本构成以当年美元为单位；采用预测方案评估时，项目现金流使用名义美元为单位表述。表 7.1 阐述了如何通过关系式（7.1）将以 2010 当年美元表述的平均原油价格（每桶 50 美元）转换为 2011 年和 2012 年的名义美元价格。

有关价格与成本浮动的内容，可参见 SPEE 推荐的评估实践（2002）。当然，公司可改变对价格与成本的假设，计算更多经济方案，以评估项目的经济性对预测条件不确定性的敏感程度。

Table 7.1 Oil Price in Different Dollar Units
表 7.1 不同美元单位的原油价格

Year （t） 年（t）	Crude Price ($/bbl) 原油价格（$/bbl）	
	Current-Year 2010 $ 2010 当年美元	Nominal $ 名义美元
2010	50.0	50.00
2011	50.0	52.00
2012	50.0	54.08

*Escalated "Current-Year 2010 $" prices using an annual price escalation rate of 4%.（注：按年度 4% 上浮 “ 2010 当年美元 ” 价格。）

7.3.2 Economic Limit

The economic limit calculation based on forecast economic conditions can significantly affect the estimate of petroleum reserves volumes. SPE recommends using industry standard guidelines for calculating economic limit and associated operating costs required to sustain the operations. For definitions of revenue, costs and cash flow terms used here, readers should refer to Sec. 7.4.1.

Economic limit is defined as the production rate beyond which the net operating cash flows (net revenue minus direct operating costs) from a project are negative, a point in time that defines the project’s economic life. The project may represent an individual well, lease, or entire field. Alternatively, it is the production rate at which net revenue from a project equals “out of pocket” cost to operate that project (the direct

7.3.2 经济极限

根据预测经济条件计算的经济极限对石油储量的估算具有显著影响。SPE 建议采用行业标准规范，来计算经济极限以及维持运营所需的操作成本。这里所用术语定义如收入、成本和现金流，请读者参见第 7.4.1 节。

经济极限是指一个产量极限值，低于该极限值意味着项目（单井、租赁区或整个油田）的净运营现金流（净收入减去直接操作成本）为负值，其对应的时间点即项目的经济年限。或者说，达到该产量时，项目的净收入与运营项目的现金支出成本（维持项目运营的直接成本）相等，如下

costs to maintain the operation) as described in the next paragraph. For example, in the case of offshore operations, the evaluator should take care to ensure that the estimated life of any individual reserves entity (as in a well or reservoir) does not exceed the economic life of a platform in the area capable of ensuring economic production of all calculated volumes. Therefore, for platforms with satellite tiebacks, the limit of the total economic grouping should be considered. Scenario or probabilistic modeling can be used to check the most likely confidence level of making such an assumption.

Operating costs, defined and described in detail in Sec. 7.4.1 and also described in PRMS, should be based on the same type of projections (or time frame) as used in price forecasting. Operating costs should include only those costs that are incremental to the project for which the economic limit is being calculated. In other words, only those cash costs that will actually be eliminated if project production ceases should be considered in the calculation of economic limit. Operating costs should include property-specific fixed overhead charges if these are actual incremental costs attributable to the project and any production and property taxes but (for purposes of calculating economic limit) should exclude depreciation, abandonment and reclamation costs, and income tax, as well as any overhead above that required to operate the subject property (or project) itself. Under PRMS, operating costs may be reduced, and thus project life extended, by various cost-reduction and revenue enhancement approaches, such as sharing of production facilities, pooling maintenance contracts, or marketing of associated nonhydrocarbons. Interim negative project net cash flows may be accommodated in short periods of low product prices or during temporary major operational problems, provided that the longer-term forecasts still indicate positive cash flows.

7.3.3 Discount Rate

The value of reserves associated with a recovery project is defined as the cumulative discounted NCF projection over its economic life, which is the project's NPV. Project NCFs are discounted at the company's discount rate (also known as the MARR desired for and expected from any investment project), which generally reflects the entity's weighted average cost of capital (WACC). Different principle-based methods used to determine company's appropriate discount rate can be found in Campbell et al (2001) and Higgins (2001).

Finally, it may be useful to restate the following PRMS guidance relevant to the petroleum resources evaluation process:

(1)Presentation and reporting of evaluation results within the business entity conducting the evaluation should not be construed as replacing guidelines for subsequent public disclosure under guidelines established by external regulatory and government agencies and any

文所述。例如，对于海上作业，评估师应保持谨慎，确保任何单个储量实体（如一口井或油藏所控）的估算经济年限不超过支撑该区域经济开发的平台的经济年限。因此，对于拥有卫星（周边）回接设施的平台而言，应考虑其整体经济极限。可通过情景法或概率模拟分析来检测所做假设最可能的置信度。

操作成本（第 7.4.1 节有详细定义和说明，在 PRMS 中也有描述）应该与价格的测算方案（或时间运行表）一致。操作成本应只包括那些项目中用于计算经济极限的增量成本。换而言之，在进行经济极限计算时，仅考虑那些若项目停产就会消除的现金成本。操作成本应包含资产的特定管理费（如果是项目的实际成本增量）、生产税和资产税，但在计算经济极限时不含折旧、弃置、恢复成本和所得税，以及任何超出资产评估对象（或项目）自身运营所需的管理费用。根据 PRMS，可通过各种降低操作成本和增加收入的办法（如共享生产设施、联营维修合约或销售伴生的非烃产品等）延长项目生命期。在短期低油价或暂遇重大经营问题期间，但从长远预期看，仍然可以实现正现金流时，则容许项目出现暂时的负净现金流。

7.3.3 贴现率

开采项目的储量价值可定义为其经济年限内的累计贴现净现金流，即项目的净现值（NPV）。项目的净现金流按照公司贴现率（也称投资项目期望的 MARR）进行贴现，主要体现企业的加权平均资本成本（WACC）。各种用于确定公司适宜贴现率的原则性方法，可参见 Campbell 等（2001）与 Higgins（2001）的研究。

最后，重申 PRMS 石油资源评估程序的下列有关指南可能会有所帮助：

（1）实施评估的商业实体在其内部进行评估结果的汇报与报告，不能代替后续按外部监管、政府机构和任何当前或未来的会计准则进行公共披露的指引。因此，由于公司内部业务规划假

current or future associated accounting standards. Consequently, oil and gas reserves evaluations conducted for internal use may vary from that used for external reporting and disclosures due to variance between internal business planning assumptions and regulated external reporting requirements of governing agencies. Therefore, these internal evaluations may be modified to accommodate criteria imposed by regulatory agencies regarding external disclosures. For example, criteria may include a specific requirement that, if the recovery were confined to the technically Proved Reserves estimate, the constant case should still generate a positive cash flow at the externally stipulated discount rate. External reporting requirements may also specify alternative guidance on "current economic conditions."

(2)There may be circumstances where the project meets criteria to be classified as Reserves using the forecast case but does not meet the external criteria for Proved Reserves. In these specific circumstances, the entity may record 2P and 3P estimates without separately recording Proved. As costs are incurred and development proceeds, the low estimate may eventually satisfy external requirements, and Proved Reserves can then be assigned.

(3)While the PRMS guidelines do not require that project financing be confirmed prior to classifying projects as Reserves, financing may be another external requirement. In many cases, loans are conditional upon the project being economic based on Proved Reserves only. In general, if there is not a reasonable expectation that loans or other forms of financing (e.g., farm-outs) can be arranged such that the development will be initiated within a reasonable time frame, then the project should be classified as Contingent Resources. If financing is reasonably expected but not yet confirmed, and financing is an external requirement for reporting in that jurisdiction, the project may be internally classified as Reserves (Justified for Development), but no Proved Reserves may be reported.

7.4 Development and Analysis of Project Cash Flows

This section describes how project cash flows are developed. Definitions of different cash flow terms are followed by an overview of its major components (production rates, product prices, capital and operating costs and other key definitions of ownership interests, royalties, and international fiscal agreements), including the uncertainties (or accuracy) associated with them that change over time. The next subsection provides the technical basis and a brief description of how project DCFs analysis is carried out to establish its value.

7.4.1 Definitions and Development of Project Cash Flows

The cash-flow valuation model estimates money received (revenue) and deducts all royalty payments, costs (OPEX and

设和政府监管机构规定的对外披露要求之间的差异，公司内部使用的石油储量评估结果可能与对外报告和披露的数据有所不同。所以，公司内部评估结果可以根据监管机构对外披露的规则要求进行调整。例如，可能会有这样的特定要求：若可采量限定为证实可采储量，则其恒定方案在外部规定的贴现率下仍应当产生正现金流。对外披露也可能对“当前经济条件”有其它的特定要求。

（2）可能会出现这种情况：按照预测方案，项目能够满足储量划分标准，但尚不满足对外披露的证实储量标准。在这种具体情况下，实体可以登记 2P 和 3P 储量而不单独登记证实储量。随着成本实际发生和开发的进行，低估值情景最终会完全满足对外披露规定的标准，这时再登记证实储量。

（3）PRMS 指南虽不要求项目在登记储量前确认融资，但融资可能是另一外部要求。在许多情况下，贷款是有条件的，要求项目仅基于证实储量，即具有经济性。总的来说，如果不能对贷款或其他形式的融资（例如招标出售）有合理预期，以便在合理期限内启动项目，那么项目要划归为条件资源量。如果融资可合理预期，但尚未确定，而当地管辖区要求将融资情况对外披露，那么该项目可在公司内部划归为储量类别（已论证可开发），但不能报告证实储量。

7.4 项目现金流的生成与分析

本节叙述了如何生成项目现金流。在对不同现金流术语进行定义之后，概述了现金流的主要构成部分（产量剖面、产品价格、投资成本与操作成本，以及所有权权益、矿费、国际财税协议）及其随时间变化的不确定性（或精确度）。下一节将为项目进行现金流分析获得价值评估结果提供技术依据，并简要说明。

7.4.1 项目现金流的定义与生成

现金流价值评估模型将估算获得的资金（收入），然后扣减所有矿费、成本（操作成本和资

CAPEX), and income taxes, yielding the resulting project NCFs. Detailed definitions, basis, and description of the key project cash-flow components are provided amply for in Campbell et al. (2001), Newendorp and Schuyler (2000), and Schuyler (2004). However, even though some terms may not exist or new terms may appear in different countries, in the basic and simplified format that works in any country, the project annual NCF at any year t can be expressed in terms of the following relationship:

$$NCF(t)=REV(t)-ROY(t)-PTAX(t)-OPEX(t)-OH(t)-CAPEX(t)-ITAX(t)+TCR(t) \tag{7.2}$$

All affected annual terms above are expressed in applicable working interest (WI) portions are defined as follows:

NCF(t) = NCF,

REV(t) = revenue = annual production rate (t) times price (t),

ROY(t) = royalty payments = REV(t) times effective royalty rate (t),

PTAX(t) = production tax payments = [REV(t) - ROY(t)] times effective production tax rate (t),

OPEX(t) = OPEX (includes all variable and fixed expenses),

OH(t) = overhead expense (includes all fixed expenses related to management, finance and accounting and professional fees, etc.),

CAPEX(t) = capital expenditures (tangible and intangible),

ITAX(t) = income tax payments = taxable income (t) times effective income tax rate (t), and

TCR(t) = tax credits received.

Note that the use of word “effective” in the above terms is meant to represent the composite rate of several applicable factors. For example, production taxes in the US may include severance and ad valorem taxes, and income tax may include federal and state taxes. It does not mean to eliminate the need for their inclusion and calculations separately.

To complete the process of generating the project annual net cash flows given by Eq. 7.2, net revenue, taxable income and income tax payments during any year t are given by the following definitions:

(1)Calculation of annual net revenue (NREV):

$$NREV(t)=REV(t)-ROY(t)-PTAX(t) \tag{7.2a}$$

(2)Calculation of annual taxable income (TINC):

$$TINC(t)=NREV(t)-OPEX(t)-OH(t)-EXSI(t)–DD\&A(t)-OTAX(t) \tag{7.2b}$$

where new annual terms not defined previously are

NREV(t) = net revenue defined by Eq. 7.2a,

TINC(t) = taxable income defined by Eq. 7.2b,

EXSI(t) = expensed investment capital,

DD&A(t) = capital recovery or allowance in terms of depreciation,

本成本）和所得税，得到项目的净现金流（NCF）。有关项目现金流主要构成的详细定义、依据以及描述，在 Campbell 等（2011）、Newendorp 和 Schuyler（2000）以及 Schuyler（2004）的著作中有详细叙述。但是，尽管在不同的国家可能有一些术语不存在或者有一些新术语，均可使用下面列出的最基本和简洁的关系式描述任意年度（t）的项目净现金流。

$$NCF(t)=REV(t)-ROY(t)-PTAX(t)-OPEX(t)-OH(t)-CAPEX(t)-ITAX(t)+TCR(t) \tag{7.2}$$

上述所有以适用工作权益（WI）来体现的术语定义如下：

NCF(t)= 年度净现金流；

REV(t)= 年度收入 = 年产量 (t)× 价格 (t)；

ROY(t) = 年度矿费 = 年度收入 REV(t)× 实际矿费费率 (t)；

PTAX(t) = 年度生产税 =[年度收入 REV(t)–年度矿费 ROY(t)]× 实际生产税率 (t)；

OPEX(t)= 年度操作成本（包括所有可变与固定费用）；

OH(t)= 年度管理费（包括与管理、财会和与专业费用等有关的固定费用）；

CAPEX(t)= 年度资本支出（有形的和无形的）；

ITAX(t)= 年度所得税 = 应纳税收入 (t)× 实际所得税率 (t)；

TCR(t)= 已获得的年度税收抵免。

请注意，上述术语中的“实际”一词表示的是若干适用因素的综合，即用各适用税种分别计算再合并。例如，美国的生产税可能包含采掘税与从价税，而所得税可能包含联邦税与州税；将其归类合并并不意味着不需要包含这些税种并分别进行计算。

要根据式（7.2）得出项目年度净现金流，还需通过下列定义得到任意年（t）的净收入、应纳税收入和所得税。

（1）年度净收入（NREV）计算：

$$NREV(t)=REV(t)-ROY(t)-PTAX(t) \tag{7.2a}$$

（2）年度应纳税收入（TINC）计算：

$$TINC(t)=NREV(t)-OPEX(t)-OH(t)-EXSI(t)–DD\&A(t)-OTAX(t) \tag{7.2b}$$

其中，前面未定义的新术语为：

NREV(t)= 由式（7.2a）定义的年度净收入；

depletion and amortization (of allowed nonexpensed investment capital), and

OTAX(t) = other tax payments.

(3) Calculation of annual ITAX:

$$\mathrm{ITAX}(t) = \mathrm{TINC}(t)\times\mathrm{ITR}(t) \qquad (7.2c)$$

where the ITR(t) is the annual effective income tax rate of the corporation.

The revenue and costs components of any term described above (including all other relevant economic and commercial terms) must be accounted for when deriving project NCF even if they are defined differently by each entity (e.g., company or government). Definitions of these terms may differ from country to country due to the fiscal arrangements made between operating companies and host governments, which allocate the rights to develop and operate specific oil and gas businesses. Common forms of international fiscal arrangements are concessions (through royalties and/or taxes) and contracts as described in Chapter 10 and elsewhere (Campbell et al. 2001 and Seba 1998). In general, these agreements define how project costs are recovered and profit is shared between the host country and the operator. Detailed knowledge of these governing rules (in royalty, tax, and other incentives) is critical for a credible project reserves assessment and evaluation process.

Although the generation of these annual project cash-flow components is straightforward, the accuracy of the estimates (magnitude and quality) is dependent on the property-specific input data and forecasting methods used (deterministic or probabilistic) and the expertise of and effective collaboration among the multidisciplinary valuation team members.

Each component of project NCF terms (such as production rate, product price, CAPEX, OPEX, inflation rate, taxes, and interest rate) briefly described in Eq. 7.2 has some uncertainty that changes over time. The terms with significant impact on project NCF are briefly reviewed below.

Reserves and Production Forecasts. The uncertainty in reserves and associated production forecasts is usually quantified by using at least three scenarios or cases of low, best and high. For many projects, these would be the 1P, 2P, and 3P reserves. They could have been generated deterministically or probabilistically. Many companies, even if the reserves uncertainty is quantified probabilistically, choose specific reserves cases (as opposed to a Monte Carlo cash-flow approach) to run cash flows because this allows a clear link between reserves and associated development scenarios and costs. In projects with additional Contingent Resources and exploration upside,

TINC(t) = 式（7.2b）定义的年度应纳税收入；

EXSI(t) = 费用化资本投资；

DD&A(t) = 以折旧、折耗与摊销计入的未费用化资本回收或备抵额；

OTAX(t)= 其他税负。

（3）所得税（ITAX）的计算：

$$\mathrm{ITAX}(t) = \mathrm{TINC}(t)\times\mathrm{ITR}(t) \qquad (7.2c)$$

其中，ITR(t) 为公司的年度企业实际所得税率。

计算项目净现金流时，必须考虑到上述术语（包括所有其他相关经济和商业术语）涉及的收入与成本构成，即便不同的实体（例如公司或政府）对这些术语的定义不同。根据作业公司与主管油气具体业务开发与作业权的政府所达成的财税协议，不同国家对这些术语的定义也可能有所不同。国际上常见的财税合约包括租让制（含矿费和 / 或税）和合同制，这些内容将在第 10 章和其他文献（Campbell 等，2011；Seba，1998）中介绍。总体上，这些协议定义了如何回收成本和分配资源国与作业者之间的利润。充分了解相关管理规则（矿费、税负和其他优惠政策）的细节对合理可靠地开展项目储量评估和评价十分重要。

尽管项目年度现金流的各构成要素可以直接计算，但其结果的精确度（数量与质量）取决于所采用的特定合同区油气资产输入数据、预测方法（确定法或概率法）以及多学科评估小组的专业知识和成员间的有效合作。

项目净现金流关系式（7.2）中的各术语（如产量、产品价格、资本成本、操作成本、通货膨胀率、税和利率等）具有随时间变化的不确定性。对项目净现金流具有重要影响的术语概述如下。

7.4.1.1 储量与产量预测

储量与相关产量预测的不确定性通常至少用低估值、最佳估值、高估值 3 种情景来量化。对于多数项目而言，也就是 1P、2P 和 3P 储量，可采用确定法或概率法进行估算。很多公司即使选用概率法量化储量的不确定性，仍采用具体的储量情景（而不是蒙特卡洛法）进行现金流计算，这样可在储量和相应的开发情景与成本间形成清

companies frequently layer these forecasts on top of the Reserves. This can lead to overly optimistic evaluations unless the appropriate risks of discovery and development are applied correctly.

Product Prices. It is important to use the appropriate product prices taking into account the crude quality or gas heating value. Whatever the method of predicting future oil prices (be it forward strip or internal company estimates), the differential with a recognized marker crude (such as West Texas Intermediate or Brent) should be applied. Ideally, it is best to use actual historical oil price differentials. For new crude blends, a market analyst should review a sample assay. If the oil is being transported through a pipeline with other crude, the average price for the blend should be considered, and the evaluator should understand whether a crude banking arrangement exists or not to allow individual crudes to receive separate price differentials based on quality (usually API gravity and sulfur content).

For gas, it is important to look at the final sales gas composition after liquids processing to ensure that the correct differentials are being applied. Each byproduct (e.g., propane, butane, and condensate) should be evaluated with the appropriate price forecast. Shrinkage of the raw gas caused by removing liquids and the presence of nonhydrocarbon gases such as CO_2 should be accounted for. Fuel gas requirements should be subtracted from the sales gas reserves.

The transportation costs for both oil and gas should be identified either as part of the operating costs or as a reduction of the sales price if the sales point is not at the wellhead.

Project Capital Costs. The major components of CAPEX for a typical oil and gas development project are land acquisition, exploration, drilling and well completion, surface facilities (gathering infrastructure, process plants, and pipelines), and abandonment.

Drilling and completion well costs are categorized in terms of tangible (subject to depreciation allowance) and intangible (expensed portion and portion subject to amortization) well costs.

Surface facility costs are subjected to facility-specific depreciation allowances used in calculating taxes and various incentives.

Total capital investment cost required for any process equipment (or plant with several units of equipment) is generally recognized under four categories (Clark and Lorenzoni 1978 and Humphreys and Katell 1981). Direct costs include all material and labor costs associated with a purchased physical plant or equipment and its installation. They include the costs of all material items that are directly incorporated in the plant itself as well as those bulk materials (such as foundation, piping, instrumentation, etc.) needed to complete

晰的对应关系。对于还拥有条件资源量和勘探前景的项目，公司经常会将其预测结果与储量累加；但除非确实正确考虑了适当的发现与开发风险，否则会导致评估过于乐观。

7.4.1.2 产品价格

考虑原油品质或天然气热值对合理确定产品价格十分重要。无论未来原油价格采用何种预测方法（远期剥离价格或公司内部估算价格），均应考虑与公认基准原油价格（如西得克萨斯中质油或布伦特原油）的差异。理想情况下，最佳的方式是采用实际的历史油价差异。对于新的混合油产品，市场分析师应对样品进行检测；若该油品通过管线与其他原油混输，则应当考虑混合后的平均价格，并且评估师应当了解是否存在银行账务处理细则，允许单种油品按其品质（通常为API重度和含硫量）考虑不同的价格差异。

对于天然气而言，重要的是依据其脱液处理后销售气的最终组分来确定合理价差。每种副产品（如丙烷、丁烷、凝析油）都应当按适当价格进行评估。原料气由于脱液处理和非烃气体（如CO_2）等造成的损耗，应予以体现。燃料气量应从销售气储量中扣减。

如果井口不是销售点，油气的运输成本应当视为操作成本的一部分，或者在销售价格中扣减。

7.4.1.3 项目资本成本

对于典型油气开发项目而言，其资本成本的主要构成包括：土地租用、勘探、钻井与完井、地面设施（油气集输基础设施、处理厂与管线）以及弃置。

钻井与完井的成本可分为有形成本（可形成折旧备抵额）和无形成本（费用化部分与可摊销部分）。

地面设施的成本可产生设施折旧抵扣，用于计算税负和各种优惠。

处理设施（或有多台装置的处理厂）的资本投资大体上分为四类（Clark和Lorenzoni，1978；Humphreys和Katell，1981）。直接成本（Direct Costs）指与采购的处理厂或设施实体及其安装启动相关的所有物料和人工成本，包括直接构建处理厂的所有物料，以及完成安装所需散装物料（如地基、管线、基础设施等）的成本。间接成

the installation. Indirect costs represent the quantities and costs of items that do not become part of, but are necessary costs involved in, the design and construction of process equipment. Indirect costs are generally estimated as “percentage of direct costs.” Indirect costs are further subcategorized as engineering, constructor’s fee (covering administrative overhead and profit), field labor overhead (FLOH), miscellaneous others and owner’s costs (such as land, organization, and startup costs). Engineering indirects include the costs for design and drafting, engineering and project management, procurement, process control, estimating and construction planning. FLOH includes costs of temporary construction consumables, construction equipment and tools, field supervision and payroll burden, etc. Miscellaneous others include freight costs, import duties, taxes, permit costs, royalty costs, insurance and sale of surplus materials. Contingency is included to allow for possible redesign and modification of equipment, escalated increases in equipment costs, increases in field labor costs, and delays encountered in startup. Finally, working capital is needed to meet the daily or weekly cost of labor, maintenance, and purchase, storage and inventory of field materials.

Equipment sizing and pricing requires a reasonably fixed basic design for budget estimates and a detailed design for definitive estimates. For equipment sizing and design of oil and gas handling facilities (in addition to contractor or company-developed standard and analogous designs), the readers may review a fine reference by Arnold and Stewart (1989, 1991).

There are two fundamental approaches to project cost estimating, the “top-down” and the “bottom-up.” The top-down approach uses historical data from similar engineering projects to estimate the costs for the current project by revising and normalizing these data for changes in time (inflation or deflation), production size, or plant capacity and location and other factors (such as activity level, weight, and energy consumption). It uses a simple “percentage-of-cost basis” established from the review of historical or current data. The bottom-up approach is a more detailed method of cost estimating and requires a detailed design that breaks down the process plant equipment into small, discrete, and manageable parts (or units). The smaller unit costs are added together (including other associated costs) to obtain the overall cost estimate for the process equipment and the plant.

As illustrated by Figure7.1, a typical project development life (for surface facilities, plants, or pipelines) encompasses the four phases of initial planning and evaluation, designing and engineering (conceptual and detailed), construction, and startup, which could take several years to complete. It represents a series of steps leading to decision points (or

本（Indirect Costs）是指尽管不是处理设施设计和建设的部分成本，但仍有必要支出并计入成本的款项。间接成本通常按直接成本的百分比来进行估算。间接成本可进一步细分为工程管理、施工人员费（含上层管理费和薪金）、现场用工管理费（FLOH）、其他杂项及业主成本费用（如土地、组织管理和启动成本）。工程管理类的间接成本包括工程项目设计、工程和项目管理、采办、过程控制、评估和建设规划等所需的成本费用；现场用工管理费包括临时建材、施工设备及工具、现场监督和薪金总额等；其他杂项包括运费、进口税、税负、许可证成本、矿费成本、保险和剩余物资处置费用等。备用金（Contingency）是为了应对可能出现的设备重新设计与修改、设备成本上浮、现场人工成本增加，以及项目建设的启动延迟等情况。最后，运营资本（Working Capital）需要满足每天或每周的人工、维护和现场物料的购买、保管和库存成本。

设备的选型与定价工作需要针对资金计划做一个合理确定的基础设计，并对最终确定参数做详细设计。对于油气处理设施的设备选型及设计（除了承包商或公司制定有标准和类似设计以外的情形），读者可参见 Arnold 和 Stewart（1989，1991）等的文献。

项目成本的估算有两种基本方法，即“自上而下”和“自下而上”法。自上而下法采用类似工程项目的历史数据，通过数据修正和归一化来估算当前项目的成本随时间（通货膨胀或紧缩）、生产规模或者处理厂能力和位置以及其他因素（如活跃等级、权重以及能源消耗情况等）的变化。该方法将分析历史或现有数据建立的简单“成本百分比”作为其基础。自下而上法则是一种更为详细的成本估算方法，要求有详细设计，把处理厂设施分解为小的、单个和可控部件（或元件）。将上述小部件的成本相加（包括其他相关成本）即可得到处理设施和工厂的总成本。

如图 7.1 所示，一个典型项目（地面设施、工厂或管线）的开发周期主要包括四个阶段，即初期规划与评估、工程设计（概念与详细）、开发建设以及启动运行，可能需要多年才能完成。每个阶段的结束点都是经过一系列步骤之后的决

gateways) at the end of each phase where cost estimates are made to determine whether it is economically viable to proceed to the next step or project phase.

策点（或关口），需进行成本估算，明确继续进入下一步骤或项目阶段是否具有经济可行性。

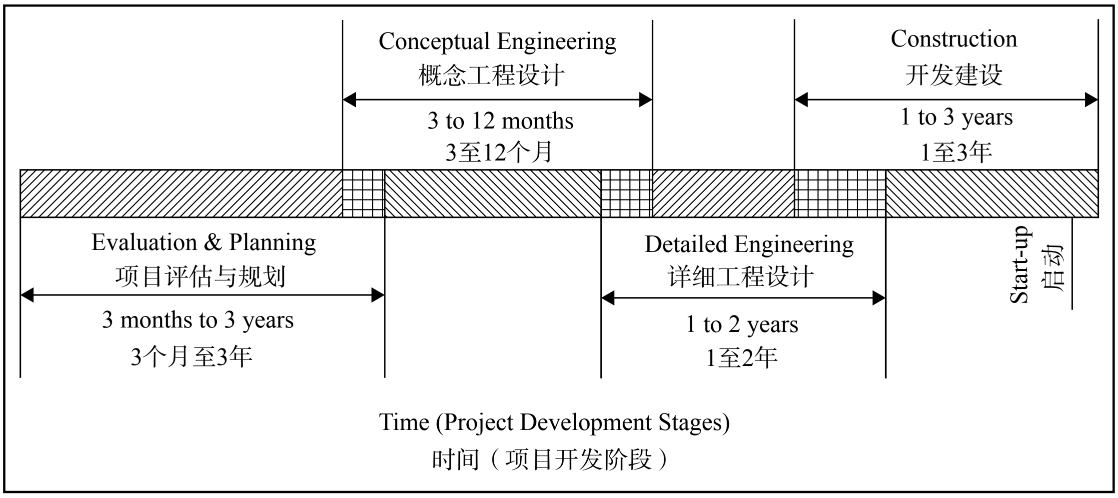

Figure 7.1 Typical project phases [adapted from Clark and Lorenzoni (1978)].
图 7.1 典型项目阶段 [据 Clark 和 Lorenzoni (1978) 改编]

Although they may be known or defined by different names, the American Association of Cost Engineers (Humphreys and Katell 1981) recommends three basic categories of project cost estimates according to detail and accuracy required by their intended use (during project phases illustrated in Figure 7.1), which are approximately defined as follows:

(1)Order of magnitude estimate is considered accurate within - 30% to + 50%. Based on cost-capacity curves and ratios, this cost estimate is made during the initial planning and evaluation stage of a project, and used for investment screening purposes.

(2)Preliminary estimate is considered accurate within - 15 to + 30%. Based on flow sheets, layouts, and equipment details, the semidetailed cost estimate is made during the conceptual-design stage of a project, and is used for budget proposal and expenditure approval purposes.

(3)Definitive estimate is considered accurate within - 5 to + 15%. Based on detailed and well-defined design and engineering data (with complete sets of specifications, drawings, equipment data sheets, etc.), this estimate is made during the detailed engineering and construction stage of a project and is used for procurement and construction.

Project Operating Costs. Similar to capital costs, estimation and treatment of OPEX in various categories could also be important for the purpose of calculating tax and project profitability. Estimates of OPEX in base-year, or current-year, dollars are generally based on an

尽管我们所知或定义的术语名称可能有所不同，但美国成本核算工程师协会 (Humphreys 和 Katell，1981) 根据不同用途（如图 7.1 项目各阶段所示）的具体细节与精度要求，建议将项目的成本估算大致分为：

（1）数量级估值：精度介于 -30% ～ +50% 之间。在项目初期规划与评估阶段，基于成本 / 产能关联曲线和比率估算成本，用于投资筛选。

（2）初步概算值：精度介于 -15% ～ +30% 之间。在项目的概念设计阶段，基于工艺流程图、设计和设备的详细信息进行较详细的成本估算，用于资金预算计划与经费审批。

（3）最终预算值：精度介于 -5% ～ +15% 之间。在项目详细工程设计与施工建设阶段，基于详细与明确的设计和工程数据（含整套的规范、图纸、设备数据表等）进行估算，用于采办与施工建设。

7.4.1.4 项目操作成本

与资本成本类似，各种操作成本的评估与处理对税负和项目利润的计算也是非常重要的。操作成本（按基准年美元或当年美元）的估算通常以工程项目的类比作为基础，再根据产能、人工

analogous operations, adjusted for the production capacity, manpower, and appropriate cost-escalation (or cost-component specific inflation) rates. Operating cost estimates are generally performed on a unit-of-production, monthly, or annual basis.

OPEX are generally recognized under five categories (Humphreys and Katell 1981). Direct costs are considered to be dependent on production and include variable and semivariable components. At production shutdowns (with zero production or throughput), direct costs are generally represented at a reasonable minimum basis of about 20% or greater of the semivariable costs estimated for an operation at full capacity. Indirect costs are considered independent of production and include plant overhead, or burden, and fixed costs such as property taxes, insurance and depreciation. General and administration expenses (G&A), or simply overhead expenses, are those costs incurred above the factory or production level and are associated with home office or headquarters management. This category includes salaries and expenses of company officers and staff, central engineering, research and development, marketing and sales costs, etc. Distribution costs are those operating and manufacturing costs associated with shipping the products to market, like pipelines for crude oil, gas sales, and natural gas liquids. They include the cost of containers and packages, freight, operation of pipelines, terminals, and warehouses or storage tanks. Contingencies constitute an allowance made in an operating cost estimate for unexpected costs or for error or variation likely to occur in the estimate. A contingency allowance is just as important in the OPEX as it is in the CAPEX. However, it must be pointed out that companies may define and categorize their operating costs differently and may not even include some of the components in their project economic analysis.

Other Key Terms and Definitions. Ownership Interest represents the share, right, or title in property (a lease, concession, or license), project, asset, or entity. The most commonly known type of ownership (or economic) interests are: WI, net WI, mineral interest, carried interest, back-in interest, and reversionary interest.

Royalties are the payments made to the landowner or the mineral interest owner for the right to explore and produce petroleum after a discovery. They are made to the host government or mineral owner (lessor) in return for depletion of the reservoirs and granting the producer (lessee/contractor) access to the petroleum resources. Many agreements allow for the producer to lift the royalty volumes, sell them on behalf of the royalty owner, and pay the proceeds to the owner. Some agreements provide for the royalty to be taken only in kind (e.g.,

以及适当的成本浮动（或成本构成的具体通胀情况）进行调整。项目操作成本的估算通常以月度或年度计量的产量作为基础单位进行估算。

操作成本通常分为 5 类（Humphreys 和 Katell，1981）。直接成本（Direct Costs）是指与产量相关联的部分，包括可变和半可变成本。通常，在停产（产量或生产能力为零）时，直接成本的合理下限应为满负荷生产时半可变成本的 20% 或以上。间接成本（Indirect Costs）指与产量无关的部分，包括处理厂的管理费或杂费、以及资产税、保险和折旧等固定费用。总务行政管理费用（General and Administration Expenses, G&A），或简化为管理费，是整个工厂或生产层面以上发生的与总部管理相关的成本。该类成本包括公司高管与员工的薪水和费用、中枢工程、研发、市场和销售成本等。分销成本 (Distribution Costs)，指将产品运输至市场的相关运营和建造成本（如原油、销售气和天然气液的运输管线）。该类成本包括集装箱与封装、货运、管线运行、集输终端，以及仓库或储罐等的费用。备用金（Contingencies）用于操作成本中的不可预见费用，或者应对成本估算可能的误差或变动。备用金在操作成本中的作用与在资本成本中的作用同样重要。然而须指出，各公司对操作成本的定义和分类可能不尽相同，甚至部分构成可能没包含在其项目的经济评价分析中。

7.4.1.5 其他关键术语与定义

所有权权益（Ownership Interest）指在合同区（租赁区、租让区或许可证区）、项目、资产或实体中所拥有的份额、权利和地位。最常见的所有权（或经济）权益类型包括：工作权益、净工作权益、矿产权益、干股权益、留存权益和可复归权益。

矿费（Royalties）指在油气发现后，向地主或矿权主支付的费用，以获取石油资源的勘探与开采权。这笔费用将支付给资源国政府或矿权主（出租人），作为油气藏开发和准许生产商（承租人 / 合同者）动用石油资源的回报。许多协议允许生产商在采出与矿费相当的油气数量后，代表矿费所有者销售，再将收入支付给矿费所有者。一些协议规定，矿费所有者仅以实物（如产量）

in terms of production) by the royalty owner.

Royalty Interest is a mineral interest that is not burdened with a proportionate share in investment and operating costs. Royalty owners are responsible for their share of production and ad valorem taxes (i.e., taxes imposed based on production value and/or value of equipment necessary to produce petroleum). Royalty interest may also be defined as the share of minerals reserved in money, or in kind, free of expense, by the owner of mineral interest or a fee received when leasing the property to another party for exploration and production.

Overriding royalty interest is a fraction of wellhead production owned free of any cost obligation. It is an economic interest created in addition to the royalty stated in the basic lease.

International Fiscal Arrangements made between the producer and the host government may include concession agreements, joint venture agreements and contracts (production sharing and service [refer to Chap. 10, PRMS (SPE 2007), Campbell et al. (2001), and Seba (1998)].

7.4.2 Analyzing Project Cash Flows and Establishing Value

The generally accepted figure of merit or value for any petroleum recovery project is defined by cumulative discounted NCF or the NPV generated over its economic (or contractual) life cycle illustrated by Figure 7.2.

的形式收取矿费。

矿费权益（Royalities Interest）是一种无需在投资与操作成本中按比例分摊的矿产权益。矿费所有者收取其产量份额对应的矿费并支付从价税（即基于产量价值和 / 或石油生产所需设备价值而征收的税负）。矿费权益也可以定义为矿权主以货币或实物形式所保留的矿产份额（与费用无关），或者是矿权主将合同区租赁给其他方进行勘探与开发所收取的费用。

优先矿费权益（Overriding Royalty Interest）指免费拥有一定比例的井口产量，不承担任何成本义务，是基本租约中矿费之外的一种经济权益。

生产商与资源国政府之间签署的国际财税合约（International Fiscal Arrangements），包括租让协议、合资协议和合同制［产品分成合同和服务合同参见 PRMS（SPE，2007）第 10 章；Campbell 等，2001；Seba，1998 等文献］。

7.4.2 项目现金流分析和价值确定

石油开采项目的价值通常用其经济（或合同）生命周期的累计贴现净现金流或净现值来表示，如图 7.2 所示。

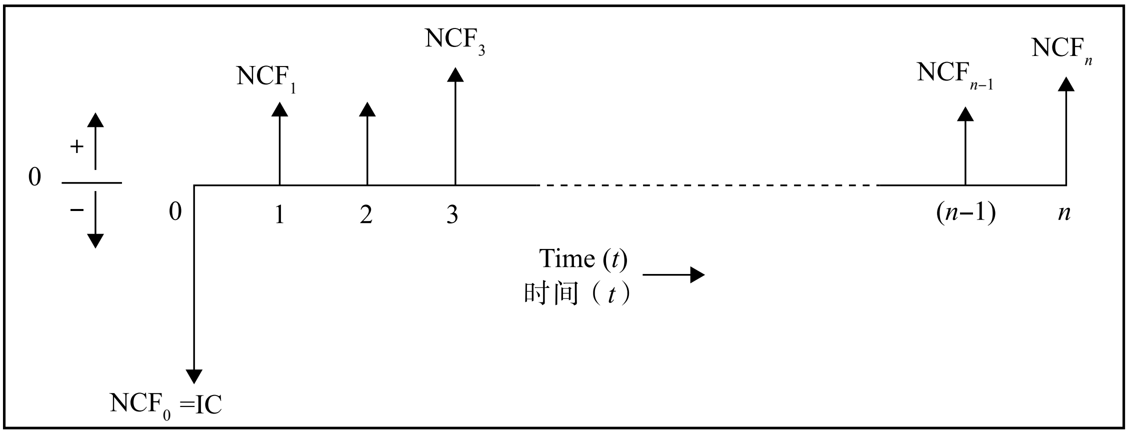

Figure 7.2　A typical project net cash flow diagram.
图 7.2　典型的项目净现金流图

The value of any project can be expressed mathematically by the following DCF-based valuation model or the NPV equation:

$$\mathrm{Npv}(t,\mathrm{MARR})=\sum_{t=0}^{n}\frac{\mathrm{NCF}_t}{(1+\mathrm{MARR})^t}=\sum_{t=0}^{n}\mathrm{NCF}_t\cdot\mathrm{DF}_t \qquad (7.3)$$

and can also be rewritten in the following open form:

项目的价值可以数学表达为下列基于贴现现金流的价值模型或净现值关系式：

$$\mathrm{Npv}(t,\mathrm{MARR})=\sum_{t=0}^{n}\frac{\mathrm{NCF}_t}{(1+\mathrm{MARR})^t}=\sum_{t=0}^{n}\mathrm{NCF}_t\cdot\mathrm{DF}_t \qquad (7.3)$$

或以展开形式表示：

$$NPV(t,MARR)=NCF_0+NCF_1\cdot DF_1+NCF_2\cdot DF_2+NCF_n\cdot DF_n \tag{7.3a}$$

where

NCF_t = annual year-end NCF (revenue minus cost) at any year (t) ranging from 0 to n and

NCF_0 = the initial investment capital (IC) made as a single lump sum in the first or “0” year-end for the most projects. However, for large projects, the initial CAPEX profile does span more than one year and thus, the NCF_t's for (t) ranging from initial (0) to say (m) years would be negative during these early years. They are actually spent as nominal dollars during these earlier m years and are also equivalent to their future value (FVI) assumed to be spent only in zero-year (or current-year) as a lump-sum initial investment capital (IC or NCF_0) and can now be defined as follows:

$$IC = NCF_0 = FVI(\mathrm{t}, \mathrm{MARR}) = \sum_{\mathrm{t}=0}^{\mathrm{m}} \mathrm{IC}_t(1+\mathrm{MARR})^t$$

$$= \sum_{t=0}^{m} \mathrm{IC}_t/\mathrm{DF}_t \tag{7.3b}$$

This manipulation is necessary not to discount future project cash flows for another m years and thus provide the same comparative basis for all projects included in a company's investment portfolio. As a result, each project will show the positive cash flow in the actual year where revenue begins, and this ensures consistent discounting of future cash flows among all competing investment projects. Variables in Eqs.7.3 through 7.3b are defined as follows:

MARR = Minimum acceptable rate of return desired or the company's annual discount rate,

t = time starting from zero (0) or current-year to (n) years in the future,

n = project economic (or contractual) life in years,

m = number of years (usually 2 to 5 for megaprojects) during which initial project capital is actually spent,

DF_t = discount factor at any year (t) defined as follows:

$DF_t=1/[1+MARR]^t$ for the year-end cash receipts (7.3c)

$DF_t=1/[1+MARR]^{(t-0.5)}$ for the mid-year cash receipts (7.3d)

Eqs.7.3 through 7.3c assume project annual NCFs are received only at year-end. However, if they are received at mid-year then the appropriate discount factor (DF_t) defined by Eq. 7.3d must be used. For discounted cash-flow analysis, readers can also refer to SPEE (2002).

According to PRMS guidelines, a discovered petroleum development project is considered commercial and its recoverable quantities are classified as Reserves when its evaluation has established

$$NPV(t,MARR)=NCF_0+NCF_1\cdot DF_1+NCF_2\cdot DF_2+NCF_n\cdot DF_n \tag{7.3a}$$

其中，NCF_t= 0 到 n 之间任一年度（t）的年终净现金流（收入减去成本）；

NCF_0= 初始资本投资（IC），即大多数项目首年或第 0 年底的投资总额。然而对大型项目而言，初始资本成本剖面会持续超过一年，因此，在早期阶段（从初始 0 年到 m 年）中任意年（t）的 NCF_t 为负值。在早期 m 年间的 NCF_t 实际按名义美元支付，假设仅在第 0 年（或当年）作为初始资本投资总额（IC 或 NCF_0）一次性支出，也可以等价于其未来价值（FVI），用下面关系式表示：

$$IC = NCF_0 = FVI(\mathrm{t}, \mathrm{MARR})$$

$$= \sum_{\mathrm{t}=0}^{\mathrm{m}} \mathrm{IC}_t(1+\mathrm{MARR})^t = \sum_{t=0}^{m} \mathrm{IC}_t/\mathrm{DF}_t \tag{7.3b}$$

不对项目现金流进行 m 年贴现的规定是有必要的，可以为公司投资组合中所有的投资项目提供相同的可对比基础。因此，各项目将在有收入的当年呈现正现金流，并确保对所有竞争性投资项目的未来现金流进行一致的贴现测算。式（7.3）到式（7.3b）的变量定义如下。

MARR= 期望的最低回报率或公司年度贴现率；

t= 从 0 年或当年至未来 n 年间的任意时间点；

n= 项目经济（或合同）生命年限；

m= 项目实际初始资本投资支出的年数（大型项目通常为 2 ～ 5 年）；

DF_t= 任意年（t）的贴现率，定义如下：

对于年终现金收入：

$$DF_t=1/[1+MARR]^t \tag{7.3c}$$

对于年中现金收入：

$$DF_t=1/[1+MARR]^{(t-0.5)} \tag{7.3d}$$

式（7.3）至式（7.3c）假定项目仅在年底获得年度净现金流。若项目净现金流为年中获得，则需采用式（7.3d）定义的贴现率（DF_t）。有关贴现现金流分析的内容，可参见 SPEE（2002）。

根据 PRMS 指南，一个已发现石油开发项目经过评价能获得正净现值（NPV），且不存在影

a positive NPV and there are no unresolved contingencies to prevent its timely development. If the project NPV is negative and/or there are unresolved contingencies preventing the project implementation within a reasonable time frame, then technically recoverable quantities must be classified as Contingent Resources.

Finally, in addition to project NPV described above, there are other important measures of profitability [such as the internal rate of return, profitability index (dollar generated per dollar initially invested), payout time, or payback period] that are routinely used in project economic evaluations (Campbell et al. 2001, Higgins 2001, Newendorp and Schuyler 2000, Seba 1998, and COGEH 2007).

7.5 Application Example

A relatively small but prolific international oil field (with its associated gas) is jointly owned by several independent North American producers. The company in this example evaluation has a one-third WI ownership in the property.

The PRMS guidance on evaluations states that: “While each organization may define specific investment criteria, a project is generally considered to be ‘economic’ if its ‘best estimate’ (2P or P50 in probabilistic analysis) case has a positive NPV under the organization’s standard discount rate. It is the most realistic assessment of recoverable quantities if only a single result were reported.” Therefore, it is judged to be prudent and useful to generate the results of economic evaluation reserves for this example petroleum-development project using production profiles based on the low estimate (Proved, or 1P), the best estimate (Proved plus Probable, or 2P), and the high estimate (Proved plus Probable plus Possible, or 3P) of oil reserves. Moreover, similar to reserves assessment using probabilistic approach in Chapter 5, an economic evaluation of these three scenarios may also be carried out using stochastic (probabilistic) decision analysis, which is briefly described at the end of this chapter, including its application to the PRMS Forecast Case economic evaluation of the example oil project.

7.5.1 Basic Data and Assumptions

The example petroleum recovery project is developed at an initial annual depletion rate of about 11% of the respective estimated ultimate recovery (EUR) values of 1P, 2P, or 3P Reserves. The project has been producing under an effective pressure maintenance scheme supported by downdip water injection. Figure 7.3 presents oil production profiles based on the low (1P), best (2P), and high (3P) estimates of oil reserves (i.e., the company's WI share only).

响其及时开发的不可解决的或有因素，则可视为具有商业性，其可采量可归类为储量。如果项目净现值为负和 / 或在合理时间段内存在影响其实施的不可解决的或有因素，那么其技术可采量必须被划分为条件资源量。

最后，除上述项目的净现值外，项目经济评价中通常还有其他一些评价项目盈利能力的重要指标，如内部收益率、盈利指数（每美元初期资本投资所产生的价值）、资金偿还期或投资回收期（Campbell 等，2001；Higgins，2001；Newendorp 和 Schuyler，2000；Seba，1998；COGEH，2007）。

7.5 应用案例

某油田，规模小，但产量高（有伴生气），由几家北美独立生产商联合拥有。评估本案例的公司拥有该资产三分之一的工作权益。

PRMS 评估指南规定：“虽然各机构可以定义具体投资指标，但若项目最佳估值（2P 情景或概率法 P50 估值）按该机构标准贴现率贴现后为正净现值，那么通常视该项目为经济的。如果只报告一个结果，那么这是最现实的可采量评估结果。”因此，可根据该案例石油开发项目的原油储量低估值（证实储量或 1P）、最佳估值（证实储量 + 概算储量，或 2P）、高估值（证实储量 + 概算储量 + 可能储量，或 3P）对应的产量剖面，得到其多情景的经济储量评估结果，这样做是谨慎且有效的。此外，与第 5 章概率法储量评估类似，上述 3 种情景同样可采用随机（概率）决策分析方法来进行经济评价，该方法在本章最后部分简要介绍，包括其在本案例 PRMS 预测方案经济评价中的应用。

7.5.1 基础数据与假设

该石油开采项目案例分别以 1P、2P 和 3P 情景最终可采量（EUR）的 11% 作为初始开采速度。项目以储层下倾部位注水以保持压力维持生产。图 7.3 是原油储量低估值（1P）、最佳估值（2P）以及高估值（3P）情景对应的产量剖面（仅公司工作权益部分）。

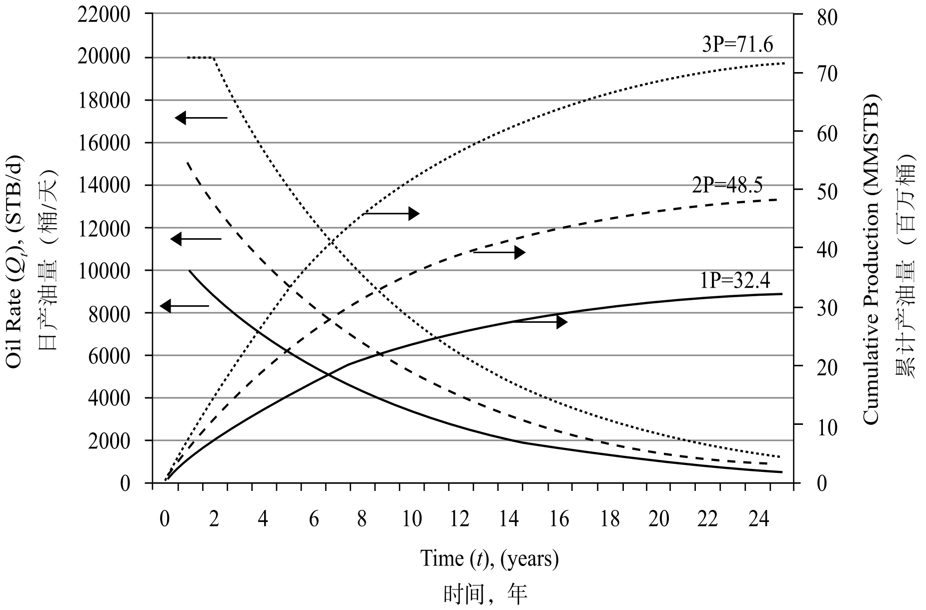

Figure 7.3　Example Evaluation: Production rate profiles and reserves.
图 7.3　评估案例：产量剖面和储量

It is important to emphasize that production profiles are independently developed based on different oil initially-in-place (OIIP) estimates and hence the reserves categories represent the low, best, and high scenarios. Table 7.2 summarizes key parameters defining current and future economic conditions.

重要的是要强调，产量剖面是分别根据不同原油原始原地量（OIIP）估值单独计算的，因而其储量级别分别对应低估值、最佳估值与高估值情景的估算结果。表 7.2 汇总了当前和未来经济条件的关键参数。

Table 7.2　Example Evaluation:Key Economic Parameters
表 7.2　评估案例的关键经济参数

Key Economic Parameters 关键经济参数			Estimate 估值
Current Economic Conditions 当年经济条件		Current-year 2010 Oil Price ($/bbl) 2010 当年油价（美元 / 桶）	60
		Current-year 2010 Gas Price ($/MMBtu) 2010 当年气价（美元 /MMBtu）	5
Future Economic Conditions (beyond the current-year 2010 and over the project life) 未来经济条件 (2010 当年之后至项目生命期)	Average Annual Product Price & Cost Escalation Rates (%) 产品年平均价格与成本上浮率 (%)	Oil Prices 油价	3
		Gas Prices 气价	3
		Operating Expenditures (OPEX) 操作成本（OPEX ）	3.5
		Capital Expenditures (CAPEX) 资本成本（CAPEX ）	4
		Average Annual Inflation Rate (f) 年平均通货膨胀率 (分数)	3
		Average Nominal Discount Rate (ANDR) 平均名义贴现率 (ANDR)	10

Furthermore, Table 7.3 summarizes the cost estimates and other relevant company-specific data assumed and necessary to carry out the example oil project evaluation for all three reserves scenarios.

Key economic assumptions and project cost estimates (Tables 7.2 and 7.3) are considered reasonable. Although the quality of input data is very important for assessment of reserves volumes and project value, it does not impact the methodology of the evaluation process described here.

Finally, based on the project basic economic data summarized in Tables 7.2 and 7.3, the projected oil and gas production rates, and forecasts of product prices and costs, the cash flow development process (described in Sec. 7.4) is used to generate the relevant project NCF projections over its 25-year economic life for the following two PRMS economic scenarios:

(1) Forecast Case (Base Case) Economic Scenario: All project cash flows are expressed in terms of nominal dollars calculated by escalating the project cash flows in terms of current-year 2010 dollars using the appropriate annual price and cost escalation and inflation rates in Table

此外，表 7.3 汇总了评估案例中 3 个储量情景所需的成本估值和其他相关数据。

评估案例的关键经济假设与成本估算（表 7.2 与表 7.3）被认为是合理的。尽管输入数据的质量对于储量和项目价值评估十分重要，但不会影响评估方法。

最后，根据表 7.2 和表 7.3 列出的项目基础经济数据、设计的油气产量、预测的产品价格和成本，可进行现金流计算（如第 7.4 节所述）来得到下面两种 PRMS 经济方案所对应的项目 25 年经济生命期的净现金流。

（1）经济预测方案（基础方案）：项目所有现金流均按名义美元表示，可采用表 7.2 中适用年度价格与成本的上浮率和通货膨胀率对以 2010 当年美元表示的项目现金流进行浮动计算而

Table 7.3 Example Evaluation: Basic Reserves and Cost Data

表 7.3 评估案例的储量和成本基础数据

<table>
<tr><th colspan="2">Type of Basic Data Required
基础数据</th><th>Low Estimate
(1P)
低估值</th><th>Best Estimate
(2P)
最佳估值</th><th>High Estimate
(3P)
高估值</th></tr>
<tr><td colspan="2">Oil Reserves (MMSTB)
原油储量（MMSTB）</td><td>32.4</td><td>48.5</td><td>71.6</td></tr>
<tr><td colspan="2">Solution GOR (scf/STB)
溶解气油比（scf/STB）</td><td>600</td><td>600</td><td>600</td></tr>
<tr><td colspan="2">Solution Gas Reserves (Bscf)
溶解气储量（Bscf）</td><td>19.4</td><td>29.1</td><td>42.9</td></tr>
<tr><td colspan="2">Gross Heating Value of Gas (Btu/scf)
天然气总热值（Btu/scf）</td><td>1330</td><td>1330</td><td>1330</td></tr>
<tr><td colspan="2">Initial Oil Rate (MSTB/D)
初始产油量（MSTB/D）</td><td>10</td><td>15</td><td>20</td></tr>
<tr><td colspan="2">Initial Investment Capital, IC (MM$)
初始资本投资，IC（百万美元）</td><td>140</td><td>180</td><td>230</td></tr>
<tr><td rowspan="2">Annual Future Expenses and Capital (2010 MM$)
未来年度费用与资本成本（2010 当年百万美元）</td><td>OPEX
操作成本</td><td>8</td><td>10</td><td>12</td></tr>
<tr><td>CAPEX (only in 5th/10th/15th years)
资本成本（仅在第 5/10/15 年产生）</td><td>8</td><td>12</td><td>18</td></tr>
<tr><td colspan="2">Effective Royalty Rate
实际矿费费率（%）</td><td>20</td><td>20</td><td>20</td></tr>
<tr><td colspan="2">Effective Production Tax Rate
实际生产税率（%）</td><td>10</td><td>10</td><td>10</td></tr>
<tr><td colspan="2">Annual Declining Balance Depreciation Rate
年度余额递减折旧率（%）</td><td>25</td><td>25</td><td>25</td></tr>
<tr><td colspan="2">Effective Income Tax Rate
实际所得税率（%）</td><td>35</td><td>35</td><td>35</td></tr>
</table>

7.2.

(2) Constant Case (Alternative Case) Economic Scenario: Project cash flows are expressed in terms of current-year 2010 dollars, and all future annual price and cost escalation and inflation rates are assumed to be zero during the entire project life of 25 years.

It is a good practice to test for the economic limit as a project approaches the end of its productive life. In this example, the net cash flows for the three profiles remain positive at the end of the 25 year project period.

7.5.2 Summary of Results.

Due to its relatively small size and the availability of analog projects completed in the same producing area, the project is expected to be completed by a reputable contractor in less than 18 months from its approval. It is further assumed that contract drilling rigs and the off-the-shelf design details on the required gas/oil separator, water injection plants, and related pipelines are readily available. Figure7.4 illustrates the example project's CAPEX profiles for the initial investment spent in terms of 2010 dollars during 2 years for these three reserves scenarios evaluated.

得到的。

（2）经济恒定方案（替代方案）：项目现金流以 2010 当年美元表示，项目未来整个 25 年生命期内的所有产品年度价格和成本的浮动与通货膨胀率均假定为 0。

在项目接近生产末期时进行经济极限测试是很好的做法。在该案例中，3 个剖面的净现金流在 25 年末项目结束时仍保持为正值。

7.5.2 结果汇总

由于项目的规模相对较小，且同一产区有已完成的可类比项目，因此可预期该项目由有信誉的合同者在批准后 18 个月内完成开发工作。此外，假设签约钻机和所需油气分离器、注水站、相关管线的详细设计已完成。图 7.4 是案例项目 3 个储量情景在两年期间以 2010 年美元支出的初始资本投资剖面。

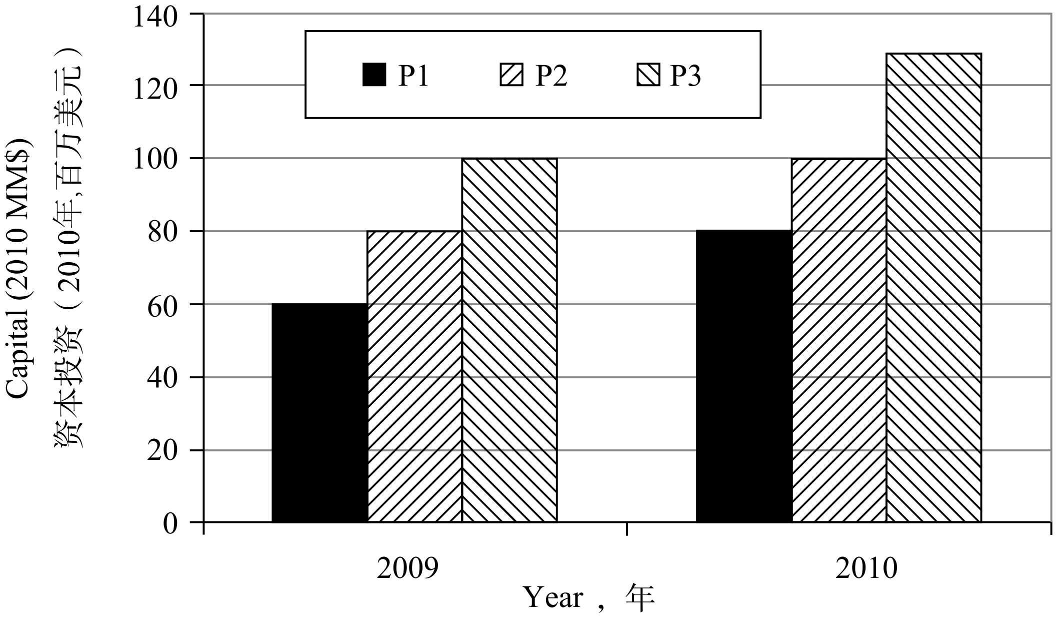

Figure 7.4　Evaluation Example: Expenditure profiles of initial capital investment.
图 7.4　评估案例：初始资本投资剖面

The value of the example petroleum project owned by an independent producer (with a one-third WI) is evaluated using its appropriate annual discount rate assumed to be at 10%/yr.

Based on development of three plausible reserves estimates and associated production profiles presented in Figure7.3, discounted annual

该案例石油项目中独立生产商（有项目三分之一工作权益）所获得的价值，采取适用的贴现率 10%/ 年来进行估算。

通过对 3 个假定情景的储量估值的开发和图 7.3 所示产量剖面，可以得到每个储量情景所对

and cumulative NCF profiles under PRMS Forecast Case and Constant Case assumptions can be generated for each reserves scenario. Figure7.5 illustrates these profiles only for the 2P reserves scenario.

Table 7.4 provides a comparative summary of results based on 1P, 2P, and 3P reserves scenarios and associated project profitability measures estimated under both economic cases.

应的 PRMS 预测和恒定方案贴现年度净现金流与累计净现金流剖面。图 7.5 仅是 2P 储量情景的剖面。

表 7.4 提供了 1P、2P 和 3P 储量情景方案的对比数据，以及在恒定经济条件下的项目盈利性测算结果。

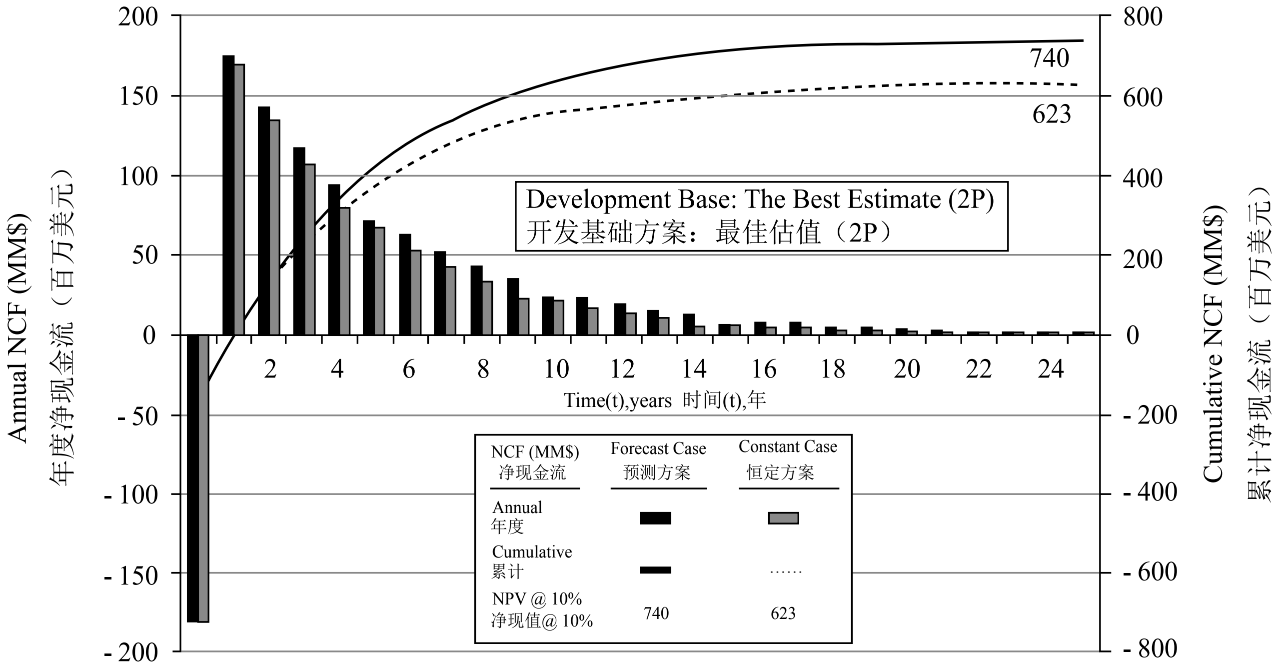

Figure 7.5 Evaluation example using the best reserves estimate (2P): Discounted Net Cash Flow (NCF) projections (million $) at 10%.

图 7.5 评估案例储量最佳估值（2P）方案的贴现净现金流预测剖面（贴现率 10%，百万美元）

As summarized in Table 7.4, the project's NPV profit (or value of its petroleum reserves) estimated using the Forecast Case (with higher project NCFs in nominal dollars) is determined to be greater than that obtained using the Constant Case (with lower project NCFs expressed in current-year 2010 dollars) when both project NCFs are discounted at the same company annual nominal discount rate of 10%.

Under the price and cost estimates (including their future projections) and assumptions used, the example petroleum project is determined to be a very attractive investment opportunity for the corporation with an estimated annual DCF rate of return exceeding 75% for all economic scenarios studied, providing a substantial margin of safety (or degree of certainty) over the desired annual MARR of 10%. However, whether this particular project is finally included in the company's current investment portfolio or not will strictly depend on both the relative economic merits of other competing investment opportunities and the amount of investment capital available.

如表 7.4 所示，当采用相同的公司年度名义贴现率 10% 进行贴现时，预测方案（按名义美元计算的较高项目净现金流）得到的项目净现值利润（或石油储量价值）要高于恒定方案（按 2010 年美元计算的较低项目净现金流）的项目净现值利润。

根据价格与成本估值（包括对未来的预测）和采用的假设条件，实例中的石油项目应该是公司很有吸引力的投资机会，研究的所有经济方案的年度 DCF（贴现现金流）回报率都超过了 75%，远高于年度最低回报率（MARR）期望值 10%，提供了明显的安全边际（或确定性程度）。但是，该项目是否最终会进入公司目前的投资组合，还要严格取决于其他竞争性投资机会的经济效益以及公司拥有的投资额度。

Table 7.4—Evaluation Example: Basis and Estimated Project Profitability Measures
表 7.4 评估案例的基础数据与项目盈利性测算结果

Parameters 参数		Low Estimate (1P) 低估值	Best Estimate (2P) 最佳估值	High Estimate (3P) 高估值
Key Parameters (in 2010$' s) 关键参数（2010 当年美元）	Oil Reserves (MMSTB) 原油储量（MMSTB)	32.4	48.5	71.6
	Associated Gas Reserves (Bscf) 伴生气储量（Bscf)	19.4	29.1	42.9
	Initial Oil Rate (MSTB/D) 初始日产油量（MSTB/D)	10	15	20
	Initial Investment Capital, IC (MM$) 初始资本投资 , IC（百万美元）	140	180	230
Value of Petroleum Reserves or Net Present Value, NPV@10% 石油储量价值或净现值，净现值 @10%	Forecast Case 预测方案	467	740	1139
	Constant Case 恒定方案	392	623	958
DCF Rate of Return, DCF-ROR (%) 贴现现金流回报率，(%)	Forecast Case 预测方案	81	96	107
	Constant Case 恒定方案	76	90	101
Profitability Index ($, Returned per $ Initially Invested) 盈利指数（美元，每美元初始投资回报）	Forecast Case 预测方案	4.3	5.1	6.0
	Constant Case 恒定方案	3.8	4.5	5.2

Finally, Figure7.6 shows the results of a sensitivity analysis in a typical tornado diagram form:

The tornado diagram illustrates the impact on project NPV (based on 2P scenario) of predefined constant ± 30% (positive and negative percent) changes in major cash-flow components, including the discount rate. Similar charts also could be constructed to illustrate the sensitivity of other project profitability measures, such as rate of return, profitability index, and payout time, etc. Sensitivity analysis clearly demonstrates that project NPV is more sensitive to revenue (oil price and similarly to production rate) than it is to costs, especially the operating costs.

图 7.6 用典型龙卷风图展示了敏感性分析结果。该图描述了现金流的主要参数（包括贴现率）恒定变化 ±30%（正负百分比）时，对项目净现值（基于 2P 情景）所产生的影响情况。对于项目的其他盈利性指标也可以进行类似的敏感性分析，如回报率、盈利指数以及资金偿还期等。敏感性分析明确地表明项目净现值对于收入（油价以及产量）的敏感性要远远高于其对于成本（尤其是操作成本）的敏感性。

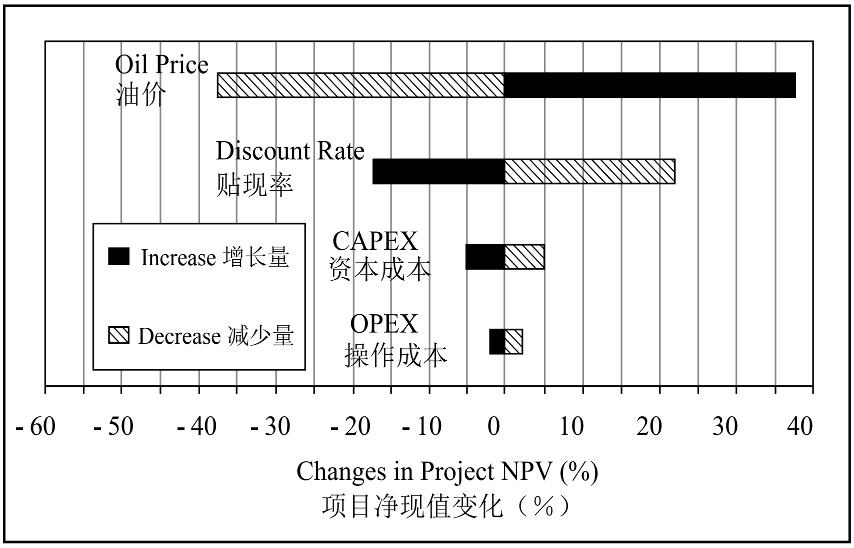

Figure 7.6 Results of sensitivity analysis.
图 7.6 敏感性分析结果

A constant ± 30% change in the selected major parameters would change this example project NPV (also approximately valid for the development of any reserves or resources category) as follows:

(1) Oil price (and production rate) would change it by ± 37%, with a direct relationship.

(2) Other parameters impact the NPV inversely, as expected [e.g., (+) changes resulting in (–) changes in NPV and vice versa]. It follows that

① Discount rate would change it by -17% and +22%, respectively,

② CAPEX would change it by -5% and +5%, respectively, and

③ OPEX would change it by -2% and +2%, respectively.

However, although impact of capital, and especially the operating expenditures, on project economics appears to be relatively minor, the need for consistency and accuracy in their estimates cannot be overemphasized as they are routinely used to estimate company's unit annual development and operating costs (in $/bbl) both on a project and a companywide basis.

7.5.3 Decision Analysis Based on Expected Value (EV) Concept

(Campbell et al. 2001, Newendorp and Schuyler 2000, Schuyler 2004)

Decision Analysis is a structured process based on a clear objective(s) and criteria that are used to evaluate, compare, and make rational decisions on many definable problems, including investment projects.

In deterministic analysis, investment decisions are generally made by evaluating and comparing the project NPVs in a portfolio of projects competing for capital funds. In the Forecast Cases of the example recovery project, NPV was deterministically estimated to be about USD 467 million, USD 740 million and USD 1,139 million, respectively, for

可见，选定的主要参数恒定变化 ±30%，该例中的项目净现值产生了如下变化（对其他储量或资源量级别的效果大致类似）。

（1）油价及产量的变化将使项目净现值增减 37%，呈直接线性关系。

（2）其他参数对净现值的影响是反向的，与预期一致（例如，参数数值的增加会导致净现值的降低，反之亦然）：

①贴现率将使项目净现值分别降低 17% 和增加 22%；

②资本成本将使项目净现值分别减少 5% 和增加 5%；

③操作成本将使项目净现值分别减少 2% 和增加 2%。

当然，尽管资本支出，特别是操作成本支出，对项目的经济性影响较小，但仍需要进行一致性的和准确的估算，因为它们经常会被用来估计项目和公司的年度开发和运营单位成本（美元/桶）。

7.5.3 基于期望值（EV）概念的决策分析

决策分析（Campell 等，2001；Newendorp 和 Schuyler，2000；Schuyler，2004）是一种基于明确目标与条件要求的结构化分析流程，可用于许多可界定性问题的评价、对比以及理性决策，包括项目投资。

投资决策一般是通过评价和对比竞争资本金的投资组合的项目净现值来进行的。在该案例项

the 1P, 2P, and 3P estimates of petroleum reserves.

In stochastic analysis, on the other hand, the EV concept is used to probabilistically estimate project profitability measures. EV is the probability-weighted value of all possible outcomes, which is the sum of all outcome values X_i times their respective probabilities of occurrence $p(x_i)$ [where subscript (i) could range from 1 to n], and can be mathematically expressed by

$$EV = \sum X_i \bullet p\,(x_i) \qquad (7.4)$$

where the summation is taken over (n) outcomes irrespective of whether the outcomes represent different categories of petroleum resources, monetary values, DCF rates of return or any other values of a random occurrence.

Two most common methods used to stochastically assess petroleum resources and/or evaluate project economics are briefly described below.

Decision Tree Analysis (DTA). Using Eq. 7.4 at each successive node, DTA can be used to derive the expected monetary value (EMV) of the project at any discount rate (or MARR), which now replaces the project NPV deterministically determined earlier (see Eqs. 7.3), as follows:

$$EMV@MARR = \sum EMV_i \times p\,(x_i) \qquad (7.5)$$

where EMVi represent the EMV for ith outcome, etc.

In the simplest possible application of DTA and for illustration purpose only, let us assume that the deterministically estimated incremental project reserves with varying degrees of uncertainty and their associated NPVs have average probabilities of occurrence of 97% (for Proved), 70% (for Probable instead of being ≥ 50% as a range for 2P, etc), and 30% (for Possible). They represent generalized approximations, or "weighting factors," that are valid for the majority of cases using a log-normal "cumulative probability distribution curve," which is also known as an "expectation curve" (EC). The expected (or mean) value for any random variable is equivalent to and defined by the area under its specific EC. Therefore, using Eqs. 7.4 and 7.5, the expected reserves volume (ERV) and the EMV for the example petroleum project can be calculated as follows:

ERV = (0.97) x32.2 + (0.7) x (48.5-32.2) + (0.3) x (71.6-48.5) = 50.1 MMSTB

EMV at 10% = (0.97) x 467 + (0.7) x (740-467) + (0.3) x (1,139-740) = USD 763 million

These expected values would approach their best estimates or 2P values (of 48.5 MMSTB and USD 740 million for the Forecast Case) if their expectation curves were normally distributed.

7.5.3.2Monte Carlo Simulation (MCS) Technique

It uses a simple sampling technique that amounts to integrating

目预测方案下，石油储量1P、2P和3P的净现值分别用确定性方法估算为约4.67亿美元、7.4亿美元和11.39亿美元。

另一方面，可用随机分析中的期望值（EV）概念来进行项目盈利指标的概率评估。期望值是所有可能结果的概率加权值，等于结果X_i乘以其发生概率$p(x_i)$（下标i的变化范围为1至n）的总和，数学表达式为：

$$EV = \sum X_i \bullet p\,(x_i) \qquad (7.4)$$

其中，总和是n个结果相加，这些结果可以是不同级别的石油资源量、货币价值、贴现现金流回报率或是任何其他随机产生的数值。

两种最常用的石油资源和/或项目经济随机评估方法简要介绍如下。

7.5.3.1 决策树分析（DTA）

通过在各连续的分析节点应用式（7.4），决策树分析法(DTA)可以得到项目在任何贴现率(或MARR）下的货币期望值（EMV），来替代前面用确定法得到的项目净现值［参见式（7.3）］，数学表达式如下：

$$EMV@MARR = \sum EMV_i \times p\,(x_i) \qquad (7.5)$$

其中，EMV_i表示第i种结果的货币期望值。

仅为了演示的目的，我们来作一个最简单的决策树分析，假定用确定法估算的各种不确定性程度的储量增量及其净现值的平均发生概率为97%（证实储量）、70%（概算储量，而不是2P的概率范围≥50%）以及30%（可能储量）。这些数值是广义逼近值或权重因子，对于大多数情景的累积概率对数正态分布曲线（即我们所知的期望曲线EC）是有效的。任意随机变量的期望值（或均值）等于其期望曲线下方圈定的面积。因此，案例项目的储量期望值（ERV）和货币期望值（EMV）可采用等式（7.4）与式（7.5）计算：

ERV=0.97×32.2+0.7×(48.5-32.2)+0.3×(71.6-48.5)=50.1MMSTB

EMV@10%=0.97×467+0.7×(740-467)+0.3×(1139-740)=763百万美元

若期望曲线呈正态分布，则上述期望值与最佳估值或2P值（4850万桶，预测方案7.4亿美元）十分接近。

7.5.3.2 蒙特卡洛模拟（MCS）技术

该技术采用简单的采样技术，再汇到等式

Eq. 7.4. It is based on the DCF model defined by Eq. 7.3. and specific probability distribution curves similar to those presented in Figure 7.7, which are defined for each key random variable with significant ranges of uncertainty.

In a simplified cash-flow model, project NCF at any time (t), defined earlier by Eq. 7.2 and required by Eqs. 7.3 through 7.3b, may be expressed in terms of these key probabilistic (or random) variables as

$$NCF_t = [Volume(t) – Royalty(t)](t) \times Price(t) - CAPEX(t) – OPEX(t) – Taxes(t) \quad (7.6)$$

Uncertainty around each random variable in Eq.7.6 may be represented by one of the following common probability-density functions (or probability distribution curves) presented in Figure7.7. The selection of a distribution curve appropriate for any random variable should be based on the judgments of the subject-matter experts.

（7.4）进行积分。该方法是基于等式（7.3）所定义的贴现现金流（DCF）模型，具体的概率分布曲线与图 7.7 类似，每个主要随机变量有不同的不确定性分布范围。

对于简化的现金流模型，如式（7.2）所定义、式（7.3）至式（7.3b）所要求，项目在任意时间（t）的净现金流（NCF）可以用以下关键概率（或随机）变量来表述：

$$NCF_t = [Volume(t) – Royalty(t)](t) \times Price(t) - CAPEX(t) – OPEX(t) – Taxes(t) \quad (7.6)$$

式（7.6）中每个随机变量的不确定性可以由图 7.7 中的常用概率密度函数（或概率分布曲线）之一来描述。任意随机变量的适宜分布曲线的选择应该以该领域专家的判断为基础。

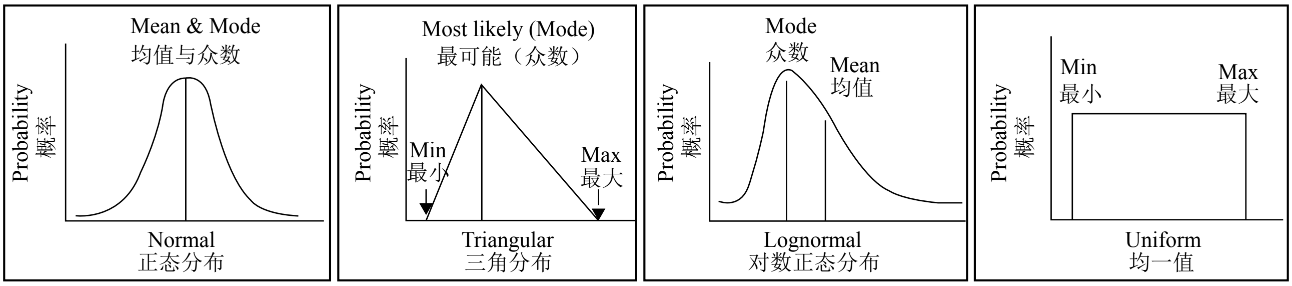

Figure 7.7 Common probability distribution curves.
图 7.7 常用概率分布曲线

Selecting and using the probability distribution curve [or probability-density function (PDF)] appropriate for each random variable and accounting for other fixed input parameters in the cash-flow model (see Eqs. 7.3 and 7.6), MCS sampling technique randomly generates the estimates of project annual NCFs over the study period and the resulting single EMV at each trial. After hundreds or thousands of trials, it can generate the project NCF profiles representing different confidence bands, associated EMVs, and hence the resulting EMV profile (or profiles for other profitability measures as well). Results are usually presented in terms of both PDFs (approximately bell-shaped distribution curves) and ECs, as illustrated for the EMV profiles of the example evaluation project on the right side of Figure 7.8.

Based on the assumptions made and input data (given in terms of probability distribution curves and as fixed parameters illustrated in the left side of Figure7.8) used for the example petroleum project, the data for the simulated EMV profiles are generated by using the MCS technique and plotted in the right side of Figure 7.8. As a result, the stochastically established P90, P50, and P10 values of the project EMVs (discounted at 10%) for the Forecast Case are estimated to be about

选择应用每个随机变量的适用概率分布曲线（或概率密度函数 PDF）和现金流计算模型的其他固定输入参数［参见式（7.3）和式（7.6）］时，蒙特卡洛模拟（MCS）取样技术可随机生成项目研究期的年度净现金流，并在每一次计算中产生一个货币期望值（EMV）。成百上千次运算后，就可以得到不同置信度区间的项目净现金流剖面及其相应 EMV，从而最终得到 EMV 剖面（或其他盈利指标的剖面）。通常，结果用 PDF（大致为钟形分布曲线）和 EC 两种形式体现，如图 7.8 右侧所示的案例评估项目 EMV 剖面。

根据项目实例所使用的假设和输入参数（形式为概率分布曲线和图 7.8 左边所示的固定参数），采用 MCS 技术生成模拟 EMV 剖面的数据，如图 7.8 右侧所示。结果，随机生成的项目预测方案的 P90、P50 和 P10 货币期望值（10% 贴现率）约分别为 5.0 亿美元、7.05 亿美元和 9.95 亿美元。与

USD 500, USD 705, and USD 995 million, respectively. They compare with the deterministic NPVs (also discounted at 10%) of about USD 467 million (1P), USD 740 million (2P), and USD 1,139 million (3P), respectively. Moreover, the mean monetary value of the project (EMV at 10%), is equivalent to the area under either of its EMV profiles shown on the right side of Figure 7.8 and is estimated to be USD 846 million as compared with USD 763 million estimated using DTA (or EV analysis) applied to deterministic estimates. It must be noted that only the mean values of probabilistic estimates (Reserves or associated EMVs) may be added together among projects (refer to Chapter 6 for more details).

It is important to point out that MCS technique provides the evaluator with a significant advantage over the deterministic analysis using the scenario approach and especially over traditional sensitivity analysis. MCS provides not only the project's expected profitability measures like EMV, expected DCF rate of return, and expected profitability index etc., but also their profiles over a wide range of uncertainties quantified in terms of PDFs and ECs similar to the ones presented for the example project's EMV on the right side of Figure 7.8.

之相比，确定性评估的 NPV（也用 10% 贴现率）分别为 4.67 亿美元（1P）、7.40 亿美元（2P）和 11.39 亿美元（3P）。此外，项目的平均货币期望值（贴现率 10%）等于图 7.8 右边 EMV 剖面下方的面积，为 8.46 亿美元，与之相比，使用 DTA（或 EV 分析）的确定性评估的结果为 7.63 亿美元。必须注意，只有概率评估的平均值（储量或相应 EMV）可以进行项目间的汇并（详见第 6 章）。

有必要指出，蒙特卡洛模拟技术比使用情景法研究的确定性分析（尤其是传统的敏感性分析）技术优势更明显。蒙特卡洛模拟不仅可提供预期的盈利指标（如货币期望值、贴现现金流回报率期望值和盈利指数期望值等），还可以提供其剖面，并以概率密度函数（PDF）和期望曲线来量化不确定性范围（与图 7.8 右侧评估实例的 EMV 曲线类似）。

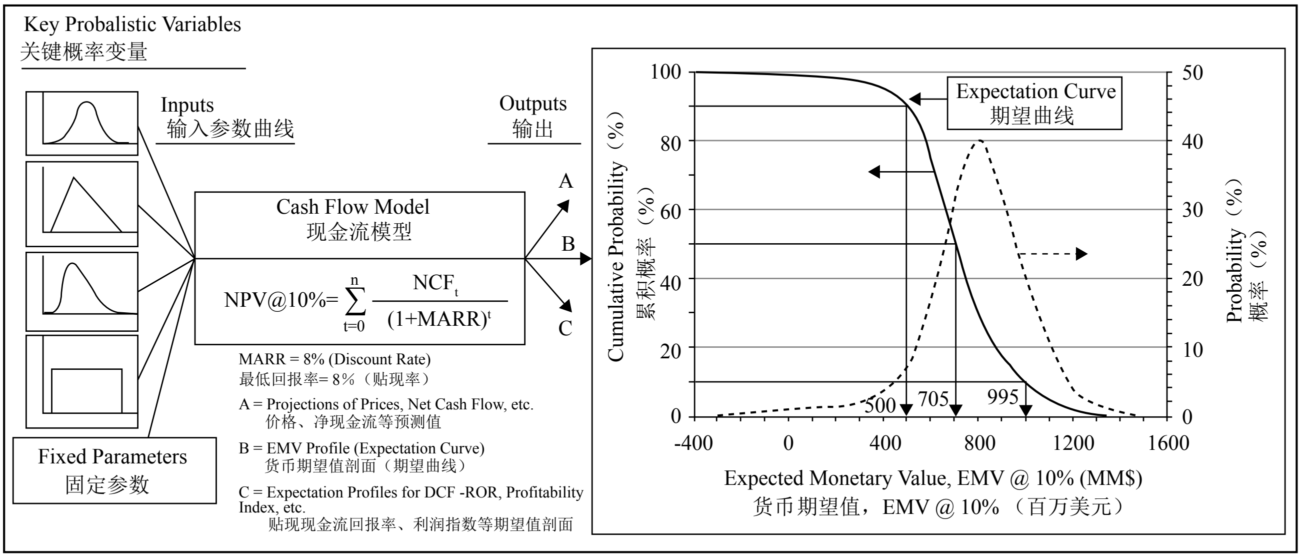

Figure 7.8　Example Evaluation: Project's EMV Profiles Generated by the MCS Technique.
图 7.8　评估案例：利用 MCS 技术构建货币期望值剖面

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第 8 章
CHAPTER 8

非常规资源的估算
Unconventional Resources Estimation

Phil Chan, John Etherington, Roberto Aguilera, C.R. Clarkson, G.J. Barker, Creties Jenkins 著

Phillip Chan、郑 舰、郭明黎、邵新军 译

8.1 Introduction

Phil Chan

Two types of petroleum resources have been defined that may require different approaches for their evaluations:

Conventional resources exist in discrete petroleum accumulations related to a localized geological structural feature and/or stratigraphic condition (typically with each accumulation bounded by a down-dip contact with an aquifer) that is significantly affected by hydrodynamic influences such as the buoyancy of petroleum in water. The petroleum is recovered through wellbores and typically requires minimal processing prior to sale.

Unconventional resources exist in hydrocarbon accumulations that are pervasive throughout a large area and that are generally not significantly affected by hydrodynamic influences (also called "continuous-type deposits"). Such accumulations require specialized extraction technology, and the raw production may require significant processing prior to sale.

The relationship of conventional to unconventional resources is illustrated by a resource triangle (Figure 8.1). Heavy oil and tight gas formations straddle the boundary; nonetheless, both present challenges in applying the assessment methods typically used for conventional accumulations.

8.1 引言

Phil Chan 著

油气资源分为两类，可分别采用不同方法进行评估：

（1）常规资源赋存在不连续的油气聚集体，与局部地质构造特征和 / 或地层条件（通常油气藏的下倾边界与含水层接触）相关，受水动力影响明显（例如石油在水中受到浮力）。这类油气资源可经钻井开采，通常销售前只需稍作处理。

（2）非常规资源赋存于大面积分布的油气聚集体（也称“连续型油气藏”），受水动力影响不明显。此类油气聚集体的开采需要专项技术，销售前可能需要对原料油气进行大规模处理。

资源三角图（图 8.1）是常规资源与非常规资源的关系示意图。重油和致密气介于两种资源类型之间，但常规油气聚集体的典型评估方法很难适用于对二者的评估。

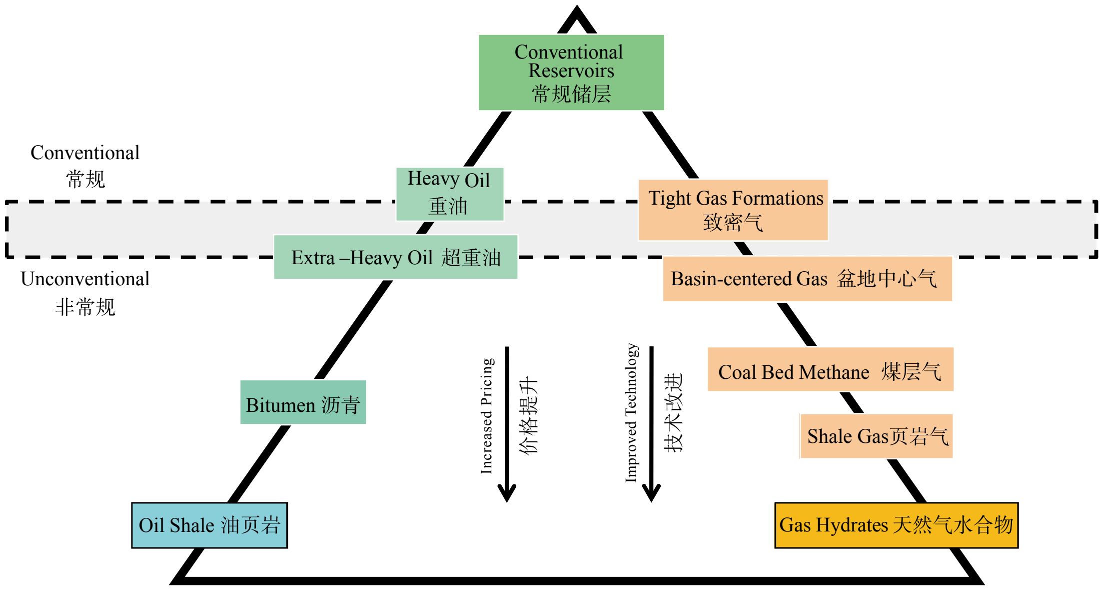

Figure 8.1 Resource triangle (Modified from Holditch, 2002)
图 8.1　资源三角图（改编自 Holditch 著作，2002）

Very large volumes of petroleum exist in unconventional reservoirs, but their commercial recovery often requires a combination of improved technology and higher product prices. Industry analysts project that unconventional liquids reservoirs (excluding oil shale) may

非常规储层赋存着大量的油气资源，但其商业开采通常需要技术改进和更高的产品价格。行业分析师预计：非常规油藏（不包括油页岩）的原始原地量可能达到 4.8 万亿桶。油页岩可能再增

contain 4.8 trillion bbl initially-in-place. Oil shales may add another 1 to 3 trillion bbl. The in-place estimates for unconventional gas accumulations range up to 30,000 Tscf (excluding gas hydrates) vs. 2,800 Tscf produced to date. Estimates for gas hydrates vary widely between 60,000 and 700,000 Tscf; however, no commercial recovery methods have yet been developed to extract these in-place volumes.

8.1.1 Assessment and Classification Issues

The Petroleum Resources Management System (PRMS) resources definitions, together with the classification system, are intended to be appropriate for all types of petroleum accumulations regardless of their in-place characteristics, the extraction method applied, or the degree of processing required. However, specialized techniques often are employed in assessing in-place quantities and evaluating development and production programs of unconventional resources.

Estimations of recoverable resource quantities must include an estimate of the associated uncertainty expressed by allocation to PRMS categories using the same low/best/high methodology as for conventional resources. Typically, the assessment process begins with estimates of original-in-place volumes. Thereafter, portions of the in-place quantities that may be potentially recovered by identified development techniques are defined. In some cases, there are no known technical methods of recovery and the in-place volumes are classified as Unrecoverable.

As in conventional accumulations, undiscovered recoverable volumes are classed as Prospective Resources and are estimated contingent on their discovery and commercial development. PRMS recognizes that the hydrocarbon type and/or the reservoir may not support a flowing well test but the accumulation may be classed as Discovered based on other evidence (e.g., sampling and/or logging).

It is not uncommon to recognize very large areas where prior drilling results have identified the presence of a Discovered resource type that, based on analogs, has production potential. Where technically feasible, recovery techniques are identified, but when economic and/or other commercial criteria are not satisfied (even under very aggressive forecasts), estimates of recoverable quantities are classified as Contingent Resources and subclassified as Development Not Viable. If the recovery processes have been confirmed as not technically feasible, the in-place volumes are classified as Discovered/Unrecoverable. As the play and technologies mature and development projects are better defined, portions of estimated volumes may be assigned to the Contingent Resources subclasses that recognize this progressive technical and commercial maturity. Typically, Reserves are only attributed after pilot programs have confirmed the technical and economic producibility and after capital is allocated for development.

In many cases, the raw production must be further processed to yield a marketable product. Integrated development/processing projects

加 1 ～ 3 万亿桶。非常规天然气的原地量预计可达 30,000 万亿立方英尺（不含天然气水合物），目前采出量为 2,800 万亿立方英尺。天然气水合物原地资源量的预测结果范围很大，在 60,000 至 70,000 万亿立方英尺之间；但尚无法商业开采。

8.1.1 评估与分类

石油资源管理系统（PRMS）对资源的定义和分类适用所有类型油气聚集体，不受地质特征、采用开采方法或所需加工处理程度的限制。但是，在评估非常规资源原地量和评价开发与生产程序时，通常需要采用专项技术。

在估算非常规可采资源量时，必须按石油资源管理系统（PRMS）的要求评估其不确定性，这与常规资源采用低估值、最佳估值、高估值方法一样。通常，评估流程是始于原始原地量的估算；随后，确定原地量中可采用现有技术开采出的部分。某些情况下，若尚无可适用的开采技术，那么原地量将被划定为不可采量。

与常规油气聚集体一样，非常规油气聚集体未发现的可采量被划定为远景资源量，并认为其发现和商业开发存在风险。PRMS 认可非常规油气聚集体可以在没有生产测试的情况下划分为“已发现”，但需要其他证据（例如取样分析和 / 或测录井）。

在尚未通过钻井确认已发现资源之前，根据类比分析核定大面积区域具有生产潜力的情形并不少见。对于技术可行，开发方式已确定，但经济和 / 或其他商业指标尚不满足（即使有乐观预期），那么预测可采量可划分为条件资源量，并细分为开发不可行。如果开采过程被确定为技术不可行，那其原地量将划分为已发现不可采。随着储层认识与技术的成熟，开发项目日趋明确，部分估算量可能因技术与商业成熟度的增加而被划至条件资源量的亚类。通常，只有先导试验已证实技术与经济可采性且开发资金已配置，才能认定储量。

多数情况下，原始产品必须进一步加工处理才能成为可销售产品。一体化开发 / 加工处理项目

include the cost of the processing and related facilities in the project economics. In other cases, the raw production is sold to a third party (at a reduced price) for further processing. In either case, development economics are highly dependent on the capital and operating costs associated with complex processing facilities.

As a result of their recent emergence as commercial ventures, the publicly available literature on the standard assessment methods and the illustrative examples for unconventional resources is limited. In addition, these accumulations are often pervasive throughout a very large area and are developed with high-density drilling; probabilistic assessment techniques may be more applicable than in conventional plays. While the authors have quoted some “rules of thumb” on drainage areas and drilling spacing unit offsets related to reserves categorization, it must be recognized that our overall goal is to assign appropriate confidence to commercial producibility; this relationship may be much more complex than in conventional reservoirs.

The following sections by different authors provide an overview of each resource type and preliminary information on evaluation approaches. It is envisioned that these sections will be updated and expanded in future editions.

8.2 Extra-Heavy Oil

John Etherington

8.2.1 Introduction

Crude oil may be divided into categories based on density and viscosity. Heavy crude oil is generally defined as having a density in the range of 10 to 23° API with a viscosity that is typically less than 1,000 cp. Although heavy crude oil is often recovered in thermal EOR projects, it is typically not a continuous accumulation and often does not require upgrading. Therefore, heavy crude is defined herein as Conventional Resources regarding assessment methods and classification under PRMS guidelines. Extra-heavy oil density is less than 10° API with a viscosity ranging from 1,000 to 10,000 cp. While mobility is limited, accumulations typically have defined oil/water contacts and exhibit normal buoyancy effects. Extra-heavy oil is herein classified as unconventional resources because it typically requires upgrading.

About 90% of the world’s known accumulations of extra-heavy oil are in the Orinoco Oil belt of the Eastern Venezuelan basin, with over 1.3 trillion bbl initially-in-place (Dusseault 2008). Depending on technology developments and associated economics, ultimate recoverable volumes are estimated at 235 billion barrels (Dusseault 2008).

8.2.2 Reservoir Characteristics—Risk and Uncertainty

Individual sand bodies in the Orinoco accumulations range in thickness up to 150 ft. The majority of oil-bearing beds are 25 to 40

的经济性包含加工及相关设施的成本。有时，原始产品是出售给第三方（以更低的价格）进一步处理。无论哪种情况，开发的经济性在很大程度上依赖于复杂处理设施的投资成本和操作费用。

由于非常规资源是新兴的商业投资项目，其标准评估方法和示例的文献资料尚十分有限。此外，由于此类油气聚集体通常大面积广泛分布，并以高密度钻井方式开采，采用概率法评估比常规油气藏更适用。虽然有的作者在划分储量类型时采用经验方法判断泄油面积和井距，但必须认识到我们的总体目标是落实商业生产性置信度，它们的关系可能比常规油气藏的情形复杂得多。

不同的作者对下文各资源类型进行了概述，并对各种评估方法进行了初步介绍。可以预见，这部分内容在将来会不断更新、扩展。

8.2 超重油

John Etherington

8.2.1 概述

原油可根据密度和黏度进行级别划分。通常，密度在10～23° API之间、黏度一般小于1000mPa•s的原油被定义为重质原油。尽管虽然重质原油一般采用热力提高采收率项目进行开采，但通常并非连续型聚集体，也不需要进行改质。因此，根据PRMS指南的评估方法与分类规则，重质原油被定义为常规资源。超重油的密度小于10° API，黏度在1000～10000mPa•s之间，其聚集体的流动性有限，一般存在确定的油/水界面，有正常浮力效应。但超重油一般需要改质，因而被划分为非常规资源。

全球已知的超重油聚集体约90%分布在委内瑞拉东部盆地的Orinoco重油带，原始原地量超过1.3万亿桶（Dusseault,2008）。依据技术研发与其经济性，预计最终可采量为2350亿桶（Dusseault,2008）。

8.2.2 储层特征——风险与不确定性

Orinoco重油带的单砂体厚度可高达150ft。

ft thick, with high porosity (27 to 32%), good permeability (up to 5 darcies), and good lateral continuity (Dusseault 2001). The major uncertainties are fault compartmentalization and water encroachment.

In the Orinoco Oil belt, cold production of extra-heavy oil is normally achieved through multilateral (horizontal) wells that are positioned in thin but relatively continuous sands, in combination with electric submersible pumps and progressing cavity pumps. Horizontal multilateral wells maximize the borehole contact with the reservoir. Extra-heavy oil mobility in the Orinoco Oil Belt reservoirs is typically greater than that of bitumen in the Alberta sands because of higher reservoir temperatures, greater reservoir permeability, higher gas/oil ratio, and the lower viscosity of extra-heavy oil. The recovery factor for an extra-heavy oil cold-production project in the Orinoco Oil belt is estimated to be approximately 12% of the in-place oil. While upside secondary recovery with thermal projects is forecast, these incremental volumes would be classed under PRMS as Contingent Resources until pilots are complete and thermal projects are sanctioned.

The majority of Orinoco production is diluted and transported to the Caribbean coast for upgrading prior to sale; thus, economics must incorporate upgrading costs either as integrated projects or through reduced pricing at the field-level custody-transfer point.

8.3 Bitumen

John Etherington

8.3.1 Introduction

Natural bitumen is the portion of petroleum that exists in the semi-solid or solid phase in natural deposits. It usually contains significant sulfur, metals, and other nonhydrocarbons. Natural bitumen generally has a density less than 10° API and a viscosity greater than 10,000 cp measured at original temperature in the deposit and at atmospheric pressure on a gas-free basis. In its natural viscous state, it is normally not recoverable at commercial rates through a well and requires the implementation of improved recovery methods such as steam injection. Near-surface deposits may be recovered using open-pit mining methods.

Bitumen accumulations are classified as unconventional because they are pervasive throughout a large area and are not currently affected by hydrodynamic influences such as the buoyancy of petroleum in water. This petroleum type requires upgrading to synthetic crude oil (SCO) or dilution with light hydrocarbons prior to marketing.

The largest known bitumen resource is in western Canada, where Cretaceous sands and underlying Devonian carbonates covering a 30,000-sq mile area contain over 1,700 billion bbl of bitumen initially-in-place (Alberta Energy Resources Conservation Board 2009). Current commercial developments are confined to the oil sands. Depending on

大部分含油砂层厚度在 25 ～ 40ft 之间，具有孔隙度高（27% ～ 32%）、渗透性好（可达 5 达西）、横向连续性良好的特征（Dusseault，2001），其主要不确定性是断层分隔和水侵。

在 Orinoco 重油带，超重油冷采作业一般通过在相对连续的薄砂层中钻多分支（水平）井，并结合使用电潜泵和螺杆泵。水平多分支井可使井眼与油藏最大化的接触。Orinoco 重油带油藏中超重油的流动性一般高于 Alberta 砂岩中沥青的流动性，因为前者的储层温度、渗透率、气 / 油比较高，同时超重油的黏度较低。Orinoco 重油带超重油冷采的采收率预计为原油原地量的 12% 左右。虽然预计可通过热采项目进行二次采油，但依照 PRMS，只有当先导试验完成、热采项目获批之后，这部分新增可采量才可划为条件资源量。

大部分 Orinoco 重油产品在销售前需要稀释，然后运输到 Caribean 海岸改质。因此其经济性评价必须考虑改质成本，通常是作为一体化项目或者降低在油田交付点的价格。

8.3 沥青

John Etherington

8.3.1 概述

天然沥青是石油的一部分，在自然沉积中处于固相或半固相，通常含有大量硫、金属和其他非烃物质。在沉积体的原始温度和大气压力脱气作用下，天然沥青的密度一般小于 10° API，黏度高于 10,000 厘泊。自然呈黏稠状态的沥青一般无法通过油井实现商业开采，需采用诸如注蒸汽等提高采收率的方法。地表附近的沥青可采用露天开采法。

由于分布面积大，并且一般不受诸如油在水中的浮力等水动力作用的影响，沥青被划定为非常规资源，这类石油需要改质为合成原油（SCO）或在销售前用轻烃稀释。

已知的最大沥青资源位于加拿大西部，这里由白垩系砂体与下层泥盆系碳酸盐岩覆盖的 30,000 平方英里的区域含有超过 1.7 万亿桶沥青原始原地量（艾伯塔能源资源保护委员会 , 2009）。目前商业开发的仅限于这部分油砂。根据设定的技术以

assumed technology developments and associated economics, estimates of technically recoverable volumes range from 170 to more than 300 billion bbl (Alberta Energy Resources Conservation Board 2009).

According to the World Energy Council (2007), outside of Canada, 359 natural bitumen deposits are reported in 21 countries. The total global volumes of discovered bitumen initially-in-place are estimated at 2,469 billion bbl.

8.3.2 Reservoir and Hydrocarbon Characteristics

Individual sand beds in the western Canada oil sands can form thick and continuous reservoirs of up to 250 ft with a net/gross ratio of over 80%. More often, there are a stacked series of 50- to 150-ft thick sands with intervening silts and clays. It is common for the sands to have high porosity (30–34%) and permeability (1–5 darcies). The sand grains are often floating in bitumen with minor clay content. Western Canadia oil sands may contain a mixture of bitumen, extra-heavy oil, and heavy oil, whose properties differ between and within reservoirs.

8.3.3 Extraction and Processing Methods

Two general processes are used to extract the western Canada bitumen: open-pit surface mining and various subsurface in-situ recovery methods.

In surface mining, the overburden is removed and the oil sands are excavated with very large “truck and shovel” operations. The oil sands are transported to a processing plant where the ore is subjected to a series of hot water froth floatation and/or solvent processes to separate the sand and bitumen. At current economics, typically about 4 tonnes of material are mined to recover 2 tonnes of oil sand ore, which yields 1.2 bbl of bitumen. While the process can recover more than 95% of the bitumen in the sand, the intermixing of clays and the mine-layout requirements combine to yield approximately an 80% recovery factor. Surface mining is typically considered where the depth to the top of the oil sands is less than 215 ft. In Canada, approximately 34 billion bbl is considered recoverable with current surface-mining technology (Alberta Energy Resources Conservation Board 2009). If all expansions and planned new projects proceed, the total production from mined bitumen could increase from 600,000 BOPD in 2009 to 1,200,000 BOPD by 2012.

Bitumen that is too deep for surface mining is typically produced using in-situ thermal recovery processes similar to those used in heavy oil projects. In general, such projects require a reservoir depth in excess of 500 ft to provide an impermeable cap to contain the required steam pressure that provides adequate reservoir energy and temperature. In cyclic steam operations, a volume of steam is injected into a well, some period of time (soak time) is allowed to pass, and then the bitumen, whose viscosity has been significantly reduced by the high-temperature steam, is produced from the same well. This process can be repeated

及经济性，预计技术可采量在 1,700 ～ 3,000 亿桶之间（艾伯塔能源资源保护委员会，2009）。

根据世界能源理事会（2007）报告，除加拿大外，另有 21 个国家报告了 359 处天然沥青矿。全球已发现沥青原始原地量约为 2.469 万亿桶。

8.3.2 储层和油气特征

加拿大西部油砂单个砂层可形成厚达 250ft 的连续储层，净毛比超过 80%。常见的是厚度为 50 ～ 150ft 的叠置砂体，夹杂着粉砂岩和泥岩。砂层的孔隙度（30% ～ 34%）和渗透率（1 ～ 5 达西）一般都较高，砂粒通常浮在含有少量黏土的沥青中。加拿大西部的油砂中可能还含有沥青、超重油和重油的混合物，其特性在油砂之间或油藏内部都各自不同。

8.3.3 开采与加工方法

加拿大西部沥青的开采通常采用两种方法：露天开采和多种地下原位开采方法。

露天开采是将覆盖层去除后，通过大型的卡车和铲车作业将油砂开采出来。油砂被运至炼厂，矿石要在炼厂进行一系列的热水浮选和 / 或溶剂加工，将砂子和沥青分离。在目前的经济性条件下，一般大约 4 吨原料可产出 2 吨油砂矿，获取 1.2 桶沥青。该工艺虽然可以采出油砂矿中 95% 以上的沥青，但受泥质夹层和矿区布局的影响，采收率为 80% 左右。油砂层顶至地表深度小于 215ft 的地区一般可以考虑采用露天开采。根据目前的露天开采技术，加拿大境内大约有 340 亿桶的可采量（艾伯塔能源资源保护委员会，2009）。如果所有项目扩建和规划的新项目全部执行，那么沥青总产量将从 2009 年的 60 万桶 / 天增加至 2012 年的 120 万桶 / 天。

埋藏深度太深而无法进行露天开采的沥青，一般采用与稠油开采相似的原地热采工艺生产。一般而言，此类项目要求储层深度超过 500ft，使上覆岩层成为一个不渗透盖层以控制注气压力，为储层提供足够的能量和温度。在蒸汽循环作业过程中，一定量的蒸汽被注入井中，经过一段时间（浸泡时间），沥青的黏度被高温蒸汽大幅降低，可从同一井眼中产出。这一流程可在同一井中重复多次，预计一般此类项目的采收率为原油原始

multiple times in the same well and the recovery efficiency in these projects is typically estimated to be 25 to 30% of the oil initially-in-place.

Most of the new in-situ projects employ a process termed steam-assisted gravity drainage (SAGD) using a pair of vertically offset horizontal wells. The upper wellbore is used for steam injection, creating an expanding steam chamber. The thermally mobilized bitumen drains into the lower wellbore from which it is produced. A typical project uses well pairs with horizontal lengths of 2,500 to 3,500 ft, and the injector is placed about 15 ft above the producer. The wells are drilled in patterns from pads consisting of 5 to 10 well pairs spaced 300 to 500 ft apart. Expected production rates are 800 to 2,000 BOPD per well. Recovery efficiencies range from 40 to 75% of oil initially-in-place (Etherington and McDonald 2004).

In Canada, the total rate from all current and planned in-situ projects is forecast at 1,500,000 BOPD. Research on improved in-situ processes continues, including use of vaporized solvent rather than steam to decrease bitumen viscosity (VAPEX), a combination of steam and solvents called ES (expanding solvent)-SAGD, and a modified fireflood technology. Firefloods are processes for extracting additional oil by injecting compressed air into the reservoir and burning some of the oil to increase the flow rate and recovery.

8.3.4 Assessment Methods—Risks and Uncertainties

Bitumen, due to its density and immobile character, may require different methods to delineate deposits and estimate in-place volumes than those used for other conventional oil assessments. Conventional production decline and material balance calculations do not apply.

For surface mine planning, a closely spaced grid of core holes is required to support a detailed volumetric assessment. The total cores are analyzed in laboratories to determine the weight percent of bitumen, which is typically 10 to 14 wt% (equivalent to 65 to 89% S_o). The Alberta Energy Resources Conservation Board (2001) has published criteria for reporting mineable resources. The Reserves classification is usually tied to the core grid spacing that defines continuity. For example, Proved Reserves may require a 1,600-ft grid (61-acre spacing) while Probable Reserves would be assigned to areas with a 3,200-ft grid (247-acre spacing). Thickness and condition of overburden, and volume allowances on the lease for mine layout and tailing ponds are examples of key factors affecting mine economics that would likely be unfamiliar to engineers focused on conventional reservoirs.

The assessment methods for in-situ bitumen-production operations require close well spacing and core analysis but are supplemented by high-resolution 3D-seismic and complete-wireline log suites. Thermal processes, such as SAGD, are sensitive to reservoirs with associated gas and/or top or bottom water zones that may act as potential thief zones.

原地量的 25% ～ 30%。

大部分原位开采新项目利用两口纵向上相互对应的水平井，通过蒸汽辅助重力泄油（SAGD）方法进行开采。上方井眼用于注入蒸汽，以形成一个扩张的蒸汽室，受热驱动的沥青泄入下方井眼，从下方井眼中产出。通常，井组的水平长度在 2500 ～ 3500ft 之间，注入井眼设置在产出井眼 15ft 高的地方；5 ～ 10 个井组组成一个井区，井间距离 300 ～ 500ft。预期产量为每口井 800 ～ 3000BOPD。采收率为原油原始原地量的 40% ～ 75%（Etherington 和 McDonald, 2004）。

在加拿大，所的原位开采项目的总产量预计为 150 万桶 / 天。提高原位开采工艺的研究仍在进行中，包括使用蒸汽溶剂代替蒸汽以降低沥青黏度（VAPEX）、蒸汽与溶剂结合的 ES—SAGD（膨胀溶剂 - 蒸汽辅助重力泄油）技术，以及改进火驱技术。火驱工艺是指向储层注入压缩空气，燃烧部分原油以增加流动速率和可采量的工艺。

8.3.4 评估方法——风险和不确定性

由于沥青的密度和不流动性，沉积体圈定和原地量估算需要使用与其他常规石油评价不同的方法。常规的产量递减法和物质平衡法不再适用。

在露天开采规划中，详细的体积评估需要密集的取心井网支持。通过实验室分析所有岩心以确定沥青的质量分数，一般为 10% ～ 14%（等于 65%～89% S_o）。艾伯塔能源资源保护委员会（2001）公布了可开采资源报告的标准。储量的分级一般与确定资源连续性的取心网格分布相关联。例如，证实储量要求 1600ft 的网格（61 英亩井距），而概算储量可能需要 3200ft 网格（247 英亩井距）。盖层的厚度和条件、矿区展布中可供租赁的体积以及尾矿池等诸多因素都是影响采矿经济性的关键，但是专注于常规油气藏开发的工程师可能并不熟悉这些。

评估原地生产沥青的方法要求密集的井眼分布和岩心分析，并辅以高分辨率的三维地震和完整的电缆测井组合。SAGD 等热采工艺对漏失层（伴生天然气和 / 或顶部或底部水层）非常敏感。水层会盗取蒸汽室内用于加热沥青的能量，造成操作成本提高、石油采收率降低。

Water zones rob the steam chamber of energy otherwise available to heat the bitumen and result in higher operating costs and poorer oil recoveries.

8.3.5 Commercial Issues

Raw bitumen is marketed at a discount to conventional petroleum at prices ranging from 25 to 85% of West Texas Intermediate (WTI) benchmark prices depending on oil quality and seasonal demand. Thus, many projects include integrated or third party upgrading to yield Synthetic Crude Oil (SCO) that is valued at prices approximating WTI crude. Bitumen operations are energy intensive and associated greenhouse gases are typically much greater than for conventional operations. As such, any legislation that taxes emissions may negatively impact the economics of bitumen projects.

8.3.6 Classification Issues

Similar to improved-recovery projects in conventional reservoirs, Reserves attribution requires “successful testing by a pilot project, or the operation of an installed program in the reservoir, that provides support for the engineering analysis on which the project or program was based.” The difference in bitumen projects is that there may be no preceding “primary” production upon which to base improved recoveries. However, as more SAGD projects have come on-stream, the performance results in adjacent analog reservoirs may be accepted to help underpin the booking of undeveloped reserves.

Under PRMS, to be classed as Reserves, owners must have committed to an approved development plan including facilities to produce, process, and transport the products to established markets. It would be difficult to apply all classical petroleum reserves criteria such as oil/water contacts and offset-well pressure response to unconventional deposits like the Canadian oil sands. The appropriate assessment methods may be a hybrid of those applied to conventional petroleum reservoirs and to mining deposits.

In Canada, the Society of Petroleum Evaluation Engineers (SPEE) has created the Canadian Oil and Gas Evaluation Handbook (COGEH 2007) that is referenced for technical guidance in Canada’s petroleum disclosure rules. COGEH Vol. 3 provides more-detailed best practices for bitumen reserves and resources assessment and classification.

8.4 Tight Gas Formations

Roberto Aguilera

8.4.1 Introduction

The US Gas Policy Act of 1978 required in-situ gas permeability to be equal to or less than 0.1 md for the reservoir to qualify as a tight gas formation (TGF) (Kazemi 1982, Aguilera and Harding 2007). For purposes of this section, the definition is expanded such that a TGF is

8.3.5 商业性问题

根据原油品质和季节需求的变化，未加工沥青的销售价格一般在常规油价格基础上进行折扣，约为西得克萨斯中质原油（WTI）基准价格的 25% 至 85%。因此，很多项目的合同者是上下游一体化运营或通过第三方对沥青原料进行改质以生产与 WTI 原油价格接近的合成原油（SCO）再进行销售。沥青开采是能源密集型作业，产生的温室气体一般要比常规作业高很多，因此，所有对排放征税的立法均可能对沥青项目的经济性产生不利影响。

8.3.6 分类问题

与常规油气藏提高采收率项目类似，储量的核定要求“先导试验成功测试，或该区已建项目能为项目或方案的工程分析提供支撑”。沥青项目与常规项目的区别在于，沥青项目不存在作为提高采收率基础的一次开采过程。但随着越来越多 SAGD 项目陆续投产，相邻类比油藏的开发效果可能会用于确定未开发储量。

根据 PRMS，要核定储量，业主须承诺已批准的开发方案，包括生产设施、加工处理以及将产品运输至已有市场。很难将所有适用于常规油气藏的经典标准（如油/水界面和邻井压力响应等）应用于非常规油气藏，例如加拿大油砂。恰当的评估方法可能是常规油气藏评估方法与采矿业评估方法的结合。

加拿大石油评估工程师学会（SPEE）已经编制了《加拿大石油和天然气评估手册》（COGEH，2007）作为加拿大油气披露规则的技术指南。COGEH 卷 3 提供了沥青储量与资源量评估和分类更详实的最佳实践。

8.4 致密气储层

Roberto Aguilera

8.4.1 概述

1978 年的《美国天然气政策法案》规定储层的原地天然气渗透率小于等于 0.1mD，才能被确定为致密气层（TGF）（Kazemi，1982；Aguilera 和 Harding，2007）。在本节中，致密气定义被扩展为

"a reservoir that cannot be produced at economic flow rates nor recover economic volumes of natural gas unless the well is stimulated by a large hydraulic fracture treatment or produced by use of a horizontal wellbore or multilateral wellbores" (Holditch 2006). The industry generally divides TGFs into (1) basin-centered gas accumulations (BCGA), also known as continuous gas accumulations (Law 2002; Schmoker 2005) and (2) gas reservoirs that occur in low-permeability, poor-quality reservoir rocks in conventional structural and stratigraphic traps (Shanley et al. 2004). Both types of accumulations can be treated within the PRMS guidelines given the following minor glossary amendment: "Unconventional TGF resources can exist in petroleum accumulations that are pervasive throughout a large area and that are generally, but not always, affected by hydrodynamic influences."

8.4.2 Resource Potential

The tight gas initially-in-place (TGIIP) in the US lower 48 states is estimated at 5,000 Tscf (Holditch 2006). The estimated recoverable resource is 350 Tscf, which represents only 7% of the TGIIP. The TGIIP in Canadian TGFs is estimated at 1,500 Tscf (Canadian Society for Unconventional Gas, Masters 1984). Application of the same recovery estimate of 7% presented above leads to a resource of 105 Tscf. The bulk of tight gas resources in Canada is stored in a BCGA in the Western Canadian Sedimentary basin (WCSB). Globally, the gas resource in TGFs is conservatively estimated at over 15,000 Tscf (Aguilera et al. 2008).

8.4.3 Reservoir and Hydrocarbon Characteristics

The primary definition used in this report assumes that TGFs, including sandstones and carbonates, are characterized by permeabilities of less than 0.1 md. The hydrocarbons in these rocks are primarily methane with some impurities, but there are also occurrences of associated gas condensate.

Permeability is not the only factor that plays a role in gas production from tight gas reservoirs. A cursory examination of the pseudo steady-state, radial flow equation illustrates that gas rate is a function of many other physical factors, including pressure, fluid properties, reservoir and surface temperatures, net pay, drainage and wellbore radius, skin, and the non-Darcy constant (Holditch 2006). Furthermore, a tight gas reservoir can be deep or shallow, high or low pressure, high or low temperature, naturally fractured, contained within a single layer or in multiple layers (Holditch 2006), continuous BCGA without a water leg (Law 2002; Schmoker 2005), or with characteristics of a conventional trap under hydrodynamic influences (Shanley et al. 2004; Aguilera et al. 2008). To succeed and improve recoveries from TGFs, it is necessary to identify the location and preferential orientation of natural fractures, to distinguish clearly between water and gas-bearing formations, to efficiently drill into and stimulate multiple zones,and to

只有经大型水力压裂或者通过水平井或分支井才能经济开采或拥有经济可采量的气藏（Holditch,2006）。石油行业通常将致密气分为：（1）盆地中心气聚集体（BCGA），也称连续型天然气聚集体（2002 年法案；Schmoker，2005）；（2）常规构造和地层圈闭中储层渗透率低、物性差的气藏（Shanley 等，2004）。上述两种气藏类型均可以按 PRMS 指南进行分类，仅需对术语略作改动：" 非常规致密气资源存在于大面积分布的油气聚集体中，通常（但不总是）受水动力的影响。"

8.4.2 资源潜力

美国本土 48 个州的致密气原始原地量（TGIIP）预计为 5,000 万亿立方英尺（Holditch，2006），可采资源量预计为 350 万亿立方英尺，仅占 TGIIP 的 7%。加拿大致密气原始原地量预计为 1,500 万亿立方英尺（加拿大非常规天然气协会，1984）。如果也按 7% 采收率估算，可采资源量约为 105 万亿立方英尺。加拿大致密气资源赋存于加拿大西部盆地（WCSB）的盆地中心聚集体（BCGA）。全球的致密气资源保守估计为 15,000 万亿立方英尺以上（Aguilera 等，2008）。

8.4.3 储层和油气特征

原始定义假定致密气储层（包括砂岩和碳酸盐岩）的特征为渗透率小于 0.1mD。这些储层中蕴藏的烃类主要是含部分杂质的甲烷，但也可能含凝析油。

渗透率并不是影响致密气储层天然气生产的唯一因素。粗略分析拟稳态的径向渗流方程可以看出：天然气的流动速率还受很多其他物理参数的作用，包括压力、流体特性、储层和地表温度、产层有效厚度、泄流半径与井眼半径、表皮系数，以及非达西常数（Holditch，2006）。此外，致密气气藏的埋深可深可浅、压力可高可低、温度可高可低，有自然裂缝，储层可能是一层或多层（Holditch，2006），可能位于无水体的连续盆地中心气聚集体（BCGA）（2002 年法案；Schmoker，2005），或位于水动力影响明显的常规圈闭（Shanley 等，2004；Auguilera 等，2008）。为成功开采致密气并提高采收率，有必要确定天然裂缝的位置和主要方向，明确区分水层和含气层，在多个层段有效钻井，

enhance the connectivity between wells and their associated drainage volumes (Kuuskra and Ammer 2004).

Continuous gas accumulations, or BCGAs, are defined (Schmoker 2005) by the US Geological Survey as “those oil or gas accumulations that have large spatial dimensions and indistinctly defined boundaries, and which exist more or less independently of the water column.” In addition, they commonly have low matrix permeabilities, are in close proximity to reservoir rocks, have low recovery factors (Schenk and Pollastro 2002), and are visualized as “a collection of gas charged cells.” All of these cells are capable of producing gas, but their production capabilities change from cell to cell, with the highest production being obtained from cells with connected natural fractures and/or higher matrix permeabilities.

There are four key elements that define a BCGA:

Abnormal pressure

Low permeability (generally ≤ 0.1 md)

Continuous gas saturation

No down-dip water leg

If any one of these elements is missing, the reservoir cannot be treated as a continuous gas accumulation. Note that lithology is not part of the four requirements listed above; the same four elements have been reported for both clastic and carbonate reservoirs.

Conventional Tight Gas Traps. An opposite view to the concept of continuous gas accumulations discussed in the previous section has been presented by Shanley et al. (2004). These authors state explicitly that “low-permeability reservoirs from the Greater Green River basin (GGRB) of southwest Wyoming are not part of a continuous-type gas accumulation or a basin-center gas system in which productivity is dependent on the development of enigmatic sweet spots. Instead, gas fields in this basin occur in low-permeability, poor-quality reservoir rocks in conventional traps.”

The model Shanley et al. use to explain their theory is called “permeability jail.” The concept was developed originally by A. Byrnes of the Kansas Geological Survey based on laboratory work conducted at room conditions and at 4,000 psi overburden stress (Shanley et al. 2004). The “permeability jail” concept indicates that a range of saturations exist, within which the relative permeabilities to gas and water are equal to zero; that is, the relative permeabilities do not cross each other as in the case of conventional reservoirs.

The controversy over whether these accumulations are basin-centered or in low-permeability conventional traps is important because the estimates of gas-in-place volumes and mobile gas are much larger in a basin that contains a BCGA instead of discrete conventional traps.

8.4.4 Assessment Methods

The integration of geoscience and engineering aspects are of

并实施增产措施，提高井间和泄气体积之间的连通性（Kuuskra 和 Ammer，2004）。

天然气连续聚集体（或 BCGA）被美国地质调查局定义为“空间规模大、边界不清，或多或少与水体无关的天然气聚集体”。此外，通常此类气藏的基质渗透率较低，紧邻储集层，采收率低（Schenk 和 Pollastro，2002），被形象地视为是含气单元的集合。所有这些单元都能产气，但各个单元的产能不同，天然裂缝相连和 / 或基质渗透率高的单元产量最高。

盆地中心气（BCGA）的 4 个关键要素为：

（1）压力异常；

（2）渗透率低（一般≤ 0.1mD）；

（3）含气饱和度连续；

（4）无下倾水体。

缺少任何一个要素，都不能被认为是连续型天然气聚集体。请注意：岩性并不是上述 4 项要素之一；此 4 要素对碎屑岩和碳酸盐岩均适用。

常规致密气圈闭。Shanley 等（2004）提出一种与上文讨论的连续型天然气聚集体概念相反的观点。这些著者明确指出：“怀俄明州西南部 Greater Green River 盆地（GGRB）的低渗透率储层既不属于连续型气藏，也不属于其产量依赖于‘甜点’的盆地中心天然气系统，该盆地内的气田形成于常规圈闭中渗透率低、质量差的储集层中。”

Shanley 等用来解释其理论的模型被称作“渗透率禁锢”模型。该理论最初是由堪萨斯地质调查局的 A.Byrnes 根据在室内条件以 4000psi 上覆压力开展的实验室研究建立的（Shanley 等，2004）。“渗透率禁锢”理论显示饱和度存在一定的范围，在其范围内，气相和水相的相对渗透率等于零；也就是说，相对渗透不再像常规储层那样相互交叉。

关于致密气聚集体是盆地中心气还是低渗透常规圈闭的争论十分重要，因为在含 BCGA 的盆地中，天然气原地量和可流动量要比离散常规圈闭的多很多。

8.4.4 评估方法

综合利用地球科学和工程手段对致密气进行勘探与评价至关重要。褶皱、断层、天然裂缝、地应力、多层系统、矿物和岩石学、连通性与连续性、不渗透夹层、煤隔层和页岩隔层仅仅是致

paramount importance in exploring for and assessing TGFs. Folding, faulting, natural fracturing, in-situ stresses, multilayer systems, mineralogy and petrology, connectivity and continuity, permeability barriers, and interbedded coals and shales are just some of the aspects that must be taken into account when evaluating TGFs (Aguilera et al. 2008). These are affected by the dominating tectonics, which in the case of the Rocky Mountain basins are wrench/extensional, while in the Western Canadian Sedimentary basin they are compressional (Zaitlin and Moslow 2006).

Exploration methods focus on how to locate swarms of natural fractures, positive closures, and "sweet spots" of higher matrix permeability. Once these are located and natural fracture orientations are determined, wells are drilled in a way that intercepts the natural fractures. Inducing formation damage must be avoided as much as possible, which generally implies the use of underbalanced drilling. However, even if the reservoir is not damaged, stimulation(s) of the TGF will likely be required to establish commercial production. To be Commercial under PRMS guidelines, in addition to technical development feasibility, the project must include economic, legal, environmental, social and governmental viability.

Seismic velocity reductions can indicate zones of high porosity, while variations in seismic velocity with direction (azimuthal anisotropy) can be related to fractures in the rocks. Wide azimuth seismic acquisition and processing techniques allow the detection of natural fractures, which appear as wavy or sinusoidal reflectors on the seismic data. The recognition of fractures, slots (Byrnes et al. 2006a and 2006b), and the best porosities allows optimum positioning of drilling targets and, consequently, a reduction in capital and operating costs (Aguilera and Harding 2007; BP 2008).

This 3D-seismic approach has been used in a large-scale survey in the Wamsutter gas field in Wyoming (USA), which covers an area of around 4,000 km^2. The reservoir section has a thickness of approximately 600 m and is made up of thousands of very thin gas pay zones. It is also being used for evaluation of tight gas sands in the In Amenas and In Salah fields in Algeria and in the Khazzan and Makarem gas fields in Oman (BP 2008).

Ant tracking (Pedersen et al. 2002) is another approach that offers hope for locating fracture swarms. The technique has been found to be useful for automatic determination of fault surfaces from conditioned fault-enhancing attributes. In those instances where the fractures are fault related, the method can provide indirect indications of where the fractures are located.

An integrated approach using shear wave splitting, P-wave azimuthal velocity anomalies, cores, image logs, and geomechanical methods (Billingsley and Kuuskraa 2006) has proven useful for locating

密气评估时必须考虑的部分内容（Aguilera 等，2008）。这些因素受主控地质构造的影响，例如 Rocky Mountain 盆地为扭转 / 拉伸构造，而加拿大西部沉积盆地属于挤压构造（Zaitlin 和 Moslow，2006）。

勘探方法重点关注如何定位天然裂缝群、闭合度和具有较高基质渗透率的“甜点”。一旦确定了这些位置和天然裂缝方向，便可以采用与天然裂缝交叉的方式钻井。要尽可能避免储层伤害，因此一般需要采用欠平衡钻井。但是，即便储层未被破坏，为实现商业生产，仍需对致密气采取增产措施。为实现 PRMS 指南中的经济性，除技术开发可行性外，项目还必须具有经济、法律、环境、社会和政府方面的可行性。

地震波速度的降低可能指示高孔隙度区域，地震波速度方向性的变化（方位角各向异性）与岩石中的裂缝相关。通过宽方位角地震波采集和处理技术可检测天然裂缝，天然裂缝的地震数据显示为波状或正弦反射。识别裂缝、缝隙（Byrnes 等，2006a，2006b）和“甜点”，可以有助于实现钻探目标的最佳定位，随之降低资金投入和操作成本（Aguilera 和 Harding，2007；BP，2008）。

美国怀俄明州 Wamsutter 气田已使用三维地震方法进行大型勘测，覆盖面积 4000km^2。总厚度约为 600m 左右的气田储层由数千个非常薄的天然气产层组成。阿尔及利亚 In Amens 和 In Salah 气田、阿曼 Khazzan 和 Makarem 气田的致密气砂层评估也使用了该方法（BP，2008）。

蚂蚁跟踪法（Pedersen 等，2002）也可用于裂缝群的定位。目前已证明，该技术在断层增强属性条件约束下可有效地自动追踪断层界面。如果裂缝与断层相关，那么该方法能够间接指示裂缝的位置。

一种综合应用横波分裂、纵波方位角速度异常、岩心、成像测井和地质力学的方法（Billingsley 和 Kuuskraa，2006），已在美国 3 个不同沉积环境的致密气盆地成功定位天然裂缝，包括落基山脉的 Piceance 盆地和 Wind River 盆地以及俄克拉何马州西部的 Anadarko 盆地。在有利条件下，该技术还能够对裂缝密度和孔径进行估计。据报道，该技术已将 Piceance 盆地 Rulison 油田的透镜状气藏

natural fractures in three distinct geologic settings and tight gas basins in the US: the Piceance and Wind River basins in the Rocky Mountains, and the Anadarko basin in western Oklahoma. Under favorable conditions, this technology allows fracture density and apertures to be estimated. This technology has been reported to improve ultimate recoveries significantly in lenticular gas plays of the Rulison field in the Piceance basin from 0.9 Bcf/well in 1956–1972 to 2.0 Bcf/well more recently. The number of dry holes has also dropped from 45% to a low percentage (Billingsley and Kuuskraa 2006).

Hydrodynamic studies must be conducted to determine if the TGF is over- or underpressured, whether it has a down-dip water leg, if it is continuously gas saturated, and what the approximate size of the TGF is. This work is useful in determining whether the TGF is a continuous accumulation (BCGA) or a conventional structural or stratigraphic low-permeability trap. This work is also very important in planning the development strategy of the reservoir. If the TGF is a continuous gas accumulation, large problems with water production probably will not be an issue. However, if the hydrodynamic study shows the presence of a down-dip water leg, it is reasonable to anticipate that eventually there will be water production problems.

Although porosities are lower in TGFs, this does not necessarily translate into lower calculated gas saturations. The reason for this is that there are lower values of the Archie cementation exponent, m, in TGFs resulting from the presence of fractures and slot pores (Aguilera 2008). The recovery efficiency, however, would be lower than in a conventional gas reservoir due to the low matrix permeabilities.

An excellent and valuable compilation of rock properties for the Mesaverde Group has been published by Byrnes et al. (2006a, 2006b) for the Green River, Piceance, Powder River, Sand Wash, Uinta, Washakie and Wind River basins in the Rocky Mountains region of the US. Included in their work are routine in-situ porosity, permeability, and grain-density measurements, along with special core analyses, including cementation and saturation exponents, cation exchange capacities, mercury injection capillary pressures, drainage critical gas saturations, thin sections, and core descriptions. Ideally, the same type of information should be collected for all TGFs, along with the most recent generation of well logs, including image logs and nuclear magnetic resonance (NMR) logs.

The work of Byrnes et al. (2006a, 2006b) also shows that the value of m becomes smaller as porosity decreases. They relate the low values of m to the presence of slot pores in TGFs, and state that “this pore architecture is similar to a simple fracture that exhibits cementation exponents near m = 1.” The slot porosity can be visualized as grain bounding fractures that result from uplifting and cooling (Billingsley and Kuuskra 2006).

的估算最终可采量从 1956 至 1972 年的单井 9 亿立方英尺大幅提高至近期的单井 20 亿立方英尺。干井数量也从 45% 降至了较低比例（Billingsley 和 Kuuskraa，2006）。

必须进行流体动力学研究以确定致密气层的压力是否过高或过低，是否存在下倾水体、是否为连续气体饱和状态，以及气层分布的大致范围。这项研究对确定致密气层是否是连续型气藏（BCGA）或常规构造或地层低渗透率圈闭非常有用，同时这对规划气藏开发战略也非常重要。如果致密气是连续型气藏，那么伴随产水出现的大量问题可能就不会出现。但是，如果水动力学研究显示地层有下倾含水区，那么有理由预期地层最终将出现产水问题。

虽然致密气层的孔隙度低，但不能因此得出其天然气饱和度较低。这是因为裂缝和缝隙的存在导致致密气中阿尔奇（Archie）胶结指数 m 值较低。但由于基质渗透率低，致密气层的采收率低于常规天然气气藏。

Byrnes 等（2006a，2006b）合作出版了一本关于美国落基山地区 Green River 盆地、Piceance 盆地、Powder River 盆地、Sand Wash 盆地，Uinta 盆地、Washhakie 盆地和 Wind River 盆地 Mesaverde 组岩石性质的书，极有价值。该书汇编了他们的部分工作，包括常规原地孔隙度、渗透率、颗粒密度测量，以及特殊岩心分析结果，包括胶结与饱和指数、阳离子交换能力、压汞毛管压力、排驱临界含气饱和度、薄片和岩心描述。理想情况是收集所有致密气层的信息和最新的测井信息，包括成像测井和核磁共振（NMR）测井。

Byrnes 等（2006a，2006b）的工作还表明：m 值随着孔隙度的降低而变小。著者将 m 值的降低与致密气层中存在的缝隙相关联，并指出“这种孔隙结构类似于胶结指数接近于 1 的单一裂缝”。缝隙可被视为由抬升和冷却导致的颗粒边界小裂缝（Billingsley 和 Kuuskraa，2006）。

由于致密气层的渗透率非常低，所以测井、规划和分析要求采用特殊的专业方法。单孔隙度储层法（Lee，1987）和双孔隙度储层法（Shahamat 和 Aguilera，2008）可供采用。可利用

Well testing, planning, and analysis require specialized methods because of the very low permeabilities of TGFs. Methods for single- (Lee 1987) and dual-porosity reservoirs (Shahamat and Aguilera 2008) are available for this purpose. The special signature of gas production decline can be analyzed with specialized techniques (Arevalo-Villagran et al. 2006; Palacio and Blasingame 1993) that under favorable circumstances permit estimating permeability and volumes of gas-in-place with a flowing-gas material balance (Rahman et al. 2006). Specific-purpose type curves can be developed in some instances based on the tight gas production-decline history of TGFs. Given that well spacing is smaller in tight gas reservoirs than in conventional reservoirs, single-well simulators can provide reasonable results.

Decline-curve analysis using normalized gas rates can provide good results for estimating performance, if wells have been producing for several years. If normalization is not possible because of the lack of pressure data, hyperbolic declines can be used with generally reasonable results. In this case, it is important to constrain the forecasted production time so that estimates of ultimate recovery are not skewed by very long production periods (a guideline is to consider a maximum of 30 years).

The TGF can act in some cases as a gas storage facility, while in other cases (e.g., in a conglomerate) it can act as the commercial delivery medium to the wellbore. This happens sometimes in the WCSB of Canada, with the Cadomin conglomerate feeding the wellbore. As the Cadomin pressures drop, the Nikanassin tight sandstone starts feeding gas into the higher permeability conglomerate (Zaitlin and Moslow 2006).

8.4.5 Drilling, Completion, and Stimulation Issues

Intercepting natural fractures requires knowledge of fracture(s) strike and dip. The accepted concept in TGFs is that the well must be drilled perpendicular to the open fractures. If more than one set of open fractures is present, a properly designed slanted, horizontal, or multilateral wellbore can maximize gas production and recovery by intersecting as many fracture sets as economically possible.

In conventional drilling, the mud weight is chosen to exceed the reservoir pressure to avoid potential blowouts. In TGFs, however, mud invasion can result in large values of skin factor because these formations are highly susceptible to damage. The problem is exacerbated because of the complex geology of TGFs, which includes natural fracturing (causing fluid leakoff and potential sand screenouts), folding and faulting (resulting in high stresses that could make initiation of the hydraulic fractures difficult or impossible), and channel sands and interbedded coals and shales (resulting in leakoff into cleats or unexpected fracture-propagation paths).

As a result, underbalanced drilling appears as a reasonable approach for drilling TGFs. In underbalanced drilling, the usual mud is

专业技术（Arevalo-Villagram 等，2006；Palacio 和 Blasingame，1993）分析天然气产量递减的这一特征，即在有利环境下可使用气体流动物质平衡法（Rahman 等，2006）评估渗透率和天然气原地量。某些情况下，可根据致密气产量递减的历史数据绘制用于特定用途的曲线。假设致密气气藏的井距小于常规气藏的井距，单井模拟器可以得出合理的结果。

如果气井已经生产几年，那么用归一化气产量进行递减分析就可以对动态进行合理预测。如果缺少压力数据而无法进行归一化，那么可采用双曲线递减，通常也可得到合理结果。在这种情况下，重要的一点是限定预测时间，避免最终采收率的预测因生产期过长而受影响（指南建议最长考虑 30 年）。

有时，致密气储层可作为天然气储气库；而有些情况下（例如砾岩），可成为连通井筒的商业输送介质。在加拿大的西部盆地，有时就会出现这种情况：随着 Cadomin 地层压力的下降，Nikanassin 致密砂岩中的天然气开始运移到渗透率更高的砾岩中（Zaitlin 和 Moslow，2006），并通过 Cadomin 砾岩流入井筒。

8.4.5 钻井、完井与增产措施

截取天然裂缝，需要知道裂缝的走向和倾角。一个已经被业界认可的致密气开发概念是：钻井须垂直开启裂缝。如果开启裂缝超过一组，那么采用精心设计的斜井、水平井或分支井在经济可行条件下与尽可能多穿插裂缝组，可使天然气产量和可采量最大化。

在常规钻井中，为避免发生潜在的井喷，选择的泥浆比重需超过储层压力。但在致密气层中，因为这些地层非常容易受到伤害，泥浆入侵可导致较大的表皮系数值。这一问题由于致密气层复杂的地质条件而更加严重，这些复杂情况包含天然裂缝（造成钻井液漏失和潜在的脱砂）、褶皱和断层（导致高应力，使水力压裂启动困难或无法实现）、河道砂以及煤和页岩夹层（导致向夹层的漏失或预料之外的裂缝延伸路径）。

因此，欠平衡钻井成为钻探致密气的一种合理方法。在欠平衡钻进中，常用的泥浆被特殊钻井

replaced by fluids, such as inert gases and foams, to make the hydrostatic pressure exerted on the reservoir smaller than the reservoir pressure. This eliminates fluid invasion through the fractures and, consequently, minimizes damage to the tight gas formation. Downhole sensors near the drill bit gather and send information to the surface, which permits the bit to be steered through the best portions of the reservoir, improving the probability of success (Bennion et al. 1996).

Unfortunately, underbalanced drilling is not a panacea in TGFs because it can sometimes induce severe nonanticipated damage. Some of the potential problems include (Craig et al. 2002) fluid retention, adverse rock/fluid and fluid/fluid interactions, countercurrent imbibition effects, glazing and mashing, condensate dropout, and entrainment from rich gases, fines mobilization, and solids precipitation.

Hydraulic fracturing jobs (single or multistage) are necessary in most cases in TGFs, even when drilling slanted or horizontal wells. However, water retention is a big problem in some TGFs. As a result, many potential fracturing solutions have been attempted in the past, including fluids such as pure oil, CO_2 energized oil, and cross-linked water-based poly-emulsion and water-based foam (Rahman et al. 2006; Craig et al. 2002).

8.4.6 Processing and Marketing

A general observation based on experience is that where there is “conventional gas,” there is also “tight gas” (Aguilera et al. 2008). Furthermore, “tight-sand accumulations should occur in all or nearly all petroleum provinces of the world” (Salvador 2005). As a result, the processing and marketing of tight gas could proceed hand in hand with that of conventional gas. Stranded gas, both from conventional and unconventional reservoirs (including TGFs), requires special handling and economic considerations due to the very large investments required. In all cases the PRMS guidelines would still apply.

8.4.7 Commercial Issues

Economic considerations have to take into account special drilling, stimulation, and completion practices; and long transient-flow periods that can last for several years and even decades in some cases prior to finding any reservoir boundary or discovering the production effect of an offset well. A larger number of wells per unit area are always required in TGFs compared to conventional reservoirs. In order to move some of the huge tight gas resources into reserves, efforts need to focus on many technological improvements that have the potential to reduce costs and increase gas production rates. The handling of liquids, even in continuous accumulations without down-dip water, is an important consideration that must be taken into account when producing TGFs in order to optimize production.

液所替代，例如惰性气体和泡沫钻井液，使施加在储层的水力静压小于储层压力，避免钻井液通过裂缝入侵，从而对致密气层的伤害最小化。钻头附近的井下感应器收集并向地表发送信息，这样可操纵钻头朝着储层的最佳位置钻进，提高成功的可能性（Bennion 等，1996）。

不幸的是，欠平衡钻井对致密气的开采并非总是万能，有时会引发意料之外的严重伤害。潜在的问题（Craig 等，2002）包括液体滞留、岩石 / 流体之间以及流体 / 流体之间的不利相互作用、逆流吸入效应、板结和破碎、凝析液析出、富气夹带、细颗粒移动、固体沉淀等。

既使采用斜井或水平井，绝大部分致密气开采都必须进行水力压裂作业（一段或多段）。当然，水的滞留对一些致密气藏而言是个大问题。所以，已开展了多种压裂溶剂的试验，包括纯油、CO_2 增能油、水基交联聚乳液和水基泡沫（Rahman 等，2006；Craig 等，2002）。

8.4.6 加工处理和市场销售

根据经验可观察到：有常规天然气的地方一般也有致密气（Aguilera 等，2008）。此外，世界所有油气区或其附近区域均有致密砂岩聚集体（Salvador，2005）。所以，致密气的加工与销售可以与常规天然气联合进行。常规气藏和非常规气藏（包括致密气藏）的开采由于需要巨额投资，所以需特别运作并考虑其经济性。任何情形均适用石油资源管理系统（PRMS）的应用指南。

8.4.7 商业性问题

致密气项目的经济性须考虑特殊的钻井工艺、增产措施和完井作业；有时，在确定气藏的边界或邻井的生产影响之前，不稳定流阶段可能会持续几年甚至几十年。与常规气藏相比，致密气藏单位面积部署的井数更多。为了使庞大致密气资源的一部分转化为储量，应重点关注可降低成本和提升产量的技术进展。即使是无下倾水层的连续型气藏，为了优化生产，液烃的处理也是致密气层开发必须考虑的重要因素。

8.4.8 Classification and Reporting Issues

The PRMS (classification, categorization, and definitions) is generally applicable to TGFs, but given the characteristics of TGFs discussed previously, there are some differences with respect to conventional reservoirs that should be highlighted, including the following:

In spite of low porosities, the volume of gas initially-in-place (GIIP) is generally much larger in tight gas reservoirs located in BCGAs compared with conventional reservoirs. In fact, the continuity of BCGAs suggests that the volume of gas they contain is very large. To avoid being overly optimistic (Schmoker 2005), the "assessment scope needs to be constrained from that of crustal abundance to resources that might be recoverable in the foreseeable future." The gas volume of a BCGA would initially be classified as total PIIP in the PRMS guidelines. At a smaller scale it could be divided between Discovered PIIP and Undiscovered PIIP. Although there would be little doubt about the existence of the TGF, the uncertainties associated with the presence of natural fractures, higher matrix permeability, low values of water saturation, and the size of individual well drainage areas will all affect whether the accumulation can progress from Prospective Resources to Contingent Resources and Reserves.

The gas recovery efficiency, as a percentage of the total GIIP in the entire BCGA without a water leg, is generally much lower (less than 10%) than in a conventional reservoir. However, the gas recovery efficiency from a given property (lease or license area or study area) located in a sweet spot within the continuous accumulation can reach 50% or more. The bulk of the resources are categorized initially as Contingent Resources but can move very rapidly to Reserves, if the project's commercial threshold is met. For a given property, it is also important to remember that generally a small percentage of the wells will contribute to the bulk of the gas production. This is sometimes known as the "20-80 rule," whereby 20% of the wells produce 80% of the gas.

With detailed geoscience, engineering, and economic data, this estimate could be classified into Reserves (category 1P, 2P, and/or 3P) and Contingent Resources (category 1C, 2C, and/or 3C). The undiscovered gas can be classified as Prospective Resources (category low, best, and/or high).

Once a project satisfies the required commercial risk criteria, if the foreseeable future is within the suggested guideline of maximum 5 years, the associated Contingent Resources can be classified as Reserves.

Well spacing is smaller in TGFs, compared with conventional reservoirs. Generally, the smaller spacing is the result of infill drilling when commercial production has been established in offset wells but there are no indications of well-interference. A good example is the

8.4.8 分类和报告

石油资源管理体系（PRMS）的分类、分级与定义对致密气储层普遍适用，但由于致密气具有前面所讨论的特征，需要强调其与常规气藏的以下区别：

（1）虽然孔隙度低，但与常规气藏相比，BCGA 中致密气藏的天然气原始原地量（GIIP）通常大得多。事实上，BCGA 的连续性意味着其中的天然气量非常大。为避免过于乐观，研究人员（Schmoker，2005）指出：“评价范围应限定为地壳中可预见的未来可能开采的资源。”按 PRMS 指南，BCGA 的天然气总原始原地量（PIIP），可进一步划分为已发现 PIIP 或未发现 PIIP。虽然对致密气的存在异议不大，但天然裂缝、高基质渗透率区域、低含水饱和度区域以及单井泄气面积大小的不确定性，都将对天然气聚集体是否能从远景资源量提升为条件资源量和储量产生影响。

（2）通常，无含水区 BCGA 的天然气采收率占全部 GIIP 的百分比（小于 10%）远远低于常规气藏。但位于连续型气藏甜点区指定资产（租用、租赁区或研究区）的天然气采收率可达到 50% 或更高。大部分此类资源最初被归类为条件资源量，但只要其满足项目的商业开发条件，很快就可以作为储量。对于指定资产而言，有一点非常重要：大部分天然气产量通常产自一小部分井。有时这也被称为“二八原则”，即 20% 的井产出了 80% 的天然气。

（3）根据详细的地球科学数据、工程数据和经济数据，可将这种估算归类为两大类：储量（分为 1P、2P 和 / 或 3P）和条件资源量（分为 1C、2C 和 / 或 3C）。未发现的天然气可被归类为远景资源量（分级为低估值、最佳估值和 / 或高估值）。

（4）一旦项目满足对商业风险的条件要求，“可预见的未来”是指南建议的“最多 5 年”范围以内，那么对应的条件资源量可划为储量。

（5）与常规气藏相比，致密气藏的开发井距较小。通常，较小井距是在邻井实现商业生产、但无井间干扰信号时进行加密钻井的结果。怀俄明州 Jonah 气田就是一个典型示例，该气田的初始井距为 160 英亩，现在已经减少至不到 10 英亩。

Jonah field in Wyoming that started at a 160-acre well spacing and is now down to less than 10 acres per well. The infill wells are an incremental project (or projects) that adds GIIP and reserves with time. By contrast, in conventional reservoirs, GIIP remains relatively constant with time and the 1P, 2P and 3P reserves tend to converge, with the 2P remaining approximately constant, the 3P decreasing, and the 1P increasing with time.

8.5 Coalbed Methane

C.R. Clarkson and G.J. Barker

8.5.1 Introduction

Coal is defined as a “readily combustible rock containing more than 50% by weight and more than 70% by volume of carbonaceous material formed from compaction and induration of variously altered plant remains similar to those in peaty deposits” (Schopf, 1956). Coalbed methane (CBM), variously referred to as natural gas from coal (NGC, Canada) or coalseam gas (CSG, Australia), is generated either from methanogenic bacteria or thermal cracking of the coal. Since much of the gas generated in coal can remain in the coal, primarily because of sorption of gas in the coal matrix, coal acts as both the source rock and the reservoir for its gas. Exploration for and exploitation of CBM resources requires knowledge of the unique coal-fluid storage and transport processes as well as special processes (well completions and operations) required to extract commercial quantities of gas.

8.5.2 Global Potential

CBM resources worldwide are immense, with estimates exceeding 9,000 Tscf (Jenkins and Boyer 2008). The primary producing countries include the US, Canada, and Australia. More than 40 countries have evaluated the potential of CBM. The US has the most mature production, with commercial production starting in the 1980s. US production of CBM in 2009 was approximately 1.9 Tscf.

8.5.3 CBM Characteristics

CBM reservoirs are generally naturally-fractured, and the majority of gas storage is by way of sorption because of the immense internal surface area provided by organic matter within the coal matrix. The transport of natural gas and water to the wellbore is dictated primarily by the natural-fracture system. The coal matrix has a very low permeability, and the mechanism of gas transport is generally considered to be due to diffusion (concentration-driven flow). Gas diffuses from the coal matrix into the natural fractures and moves under Darcy flow to the wellbore. The production profiles of CBM reservoirs are unique and are a function of a variety of reservoir and operational factors.

The primary mechanisms for gas storage in CBM reservoirs are: (1) adsorption upon internal surface area, primarily associated with

加密井是能够使 GIIP 和各级储量随时间增加的增产项目（或项目）。与此相反，常规气藏的 GIIP 随时间流逝保持相对恒定，而 1P、2P 和 3P 储量逐渐趋同，其中 2P 基本保持恒定，3P 递减，1P 增加。

8.5 煤层气

C.R.Clarkson 和 G.J.Barker 著

8.5.1 概述

煤的定义为：一种易燃岩石（富碳物质的质量比例大于 50%、体积比例大于 70%），由各种高等植物经压实和成岩作用形成的类似泥炭的沉积物。（Schopf, 1956）。煤层气（CBM），也称煤层天然气（NGC，加拿大；或 CSG，澳大利亚），是由产甲基菌的生物化学作用生成或由煤热裂解产生。因为生成的大部分气体在煤中主要由基质吸附，所以煤既是气体的源岩也是其储层。煤层气资源的勘探与开采要求开发者需掌握独特的煤—液赋存机制、集输以及特殊工艺（完井和作业）以实现气藏的商业开发。

8.5.2 全球潜力

全球 CBM 资源数量庞大，预计超过 9,000 万亿立方英尺（Jenkins 和 Boyer，2008）。主要生产国包括美国、加拿大以及澳大利亚。40 多个国家已经对 CBM 潜力进行了评估。美国的生产最为成熟，其商业生产始于 20 世纪 80 年代。美国 2009 年的 CBM 产量接近 1.9 万亿立方英尺。

8.5.3 CBM 的特点

CBM 储层一般具有天然裂缝，储集的大部分气体吸附在煤基质中有机质的巨大内表面。气体和水向井眼的运动主要通过天然裂缝系统实现。煤基质的渗透率非常低，天然气的输送机制为扩散（浓度驱动的流动）。天然气从基质扩散进入天然裂缝，以达西渗流向井眼移动。CBM 储层的生产情况特殊，受各种储层及作业因素的影响。

CBM 储层中天然气的主要赋存机理：（1）储层内表面（主要是有机质）的吸附气；（2）天然裂缝中的游离气；(3) 基质孔隙中的游离气；(4) 沥青和地层水中的溶解气。请注意术语“ 吸附 ”，

organic matter, (2) conventional (free-gas) storage in natural fractures, (3) conventional storage in matrix porosity, and (4) solution in bitumen and formation water. Note that the term "sorption" is used here to encompass adsorption of gas on the internal surface area of coal and solvation of gas by liquid/solids in the coal matrix—when sorption isotherms are measured in the laboratory for establishing gas content, these mechanisms of storage are typically not distinguished. Generally, free-gas is negligible compared to sorbed gas storage and is usually ignored in CBM reservoirs because of low fracture-pore volumes and high water saturations. The exception is for some dry CBM reservoirs, in which free-gas storage may be more significant (Bustin and Clarkson, 1999; Bustin and Bustin, 2009). Solution gas is also usually ignored.

Sorbed gas storage is by far the most important storage mechanism in most CBM reservoirs. High-rank coals have surface areas on the order of 100 to 300 m^2/g, whereas conventional reservoirs typically have surface areas < 1 m^2/g. Most of the gas-accessible surface area of the coal matrix is associated with organic matter whose pore structure is generally dominated by microporosity, which are pores that are < 2 nanometers in diameter (Sing et al. 1985). The controls on CBM-matrix pore structure include thermal maturity (rank), organic matter content, and coal composition (Bustin and Clarkson 1998). The immense ratio of surface area to volume in the coal matrix means that a large surface area is exposed to attract gas molecules through molecular forces (dispersion and electrostatic) that in turn cause adsorption to occur.

The adsorption of CBM-reservoir gases is thought to be primarily physical vs. chemical, meaning that molecular interaction is weak and reversible. Gas is stored in a near-liquid-like state, with a higher density than compressed gas at typical reservoir temperatures and pressures. The controls upon sorption, in addition to the organic matter pore structure, include: pressure, temperature (Levy et al. 1997), moisture (Joubert et al. 1973), thermal maturity (rank) (Levy et al. 1997), mineral matter content (grade) (Mavor 1996), organic matter composition (Clarkson and Bustin 1999), and gas composition (Hall et al. 1994). Sorption on coal is a nonlinear function of pressure and has been modeled using a variety of empirical and theoretical equations. By far the most commonly applied single-component and multicomponent gas adsorption model for coal is the Langmuir isotherm (Mavor 1996). The Langmuir equation can be used to estimate coal-gas content if the coalseams are saturated (i.e., the in-situ gas content is equal to the in-situ storage capacity), the reservoir pressure and gas composition are accurately known, the free-gas and solution-gas storage are negligible, and the average coal composition of the reservoir is known.

The primary mechanisms governing gas flow in coals include pressure-driven flow (modeled with some form of Darcy's law) through the fractures and concentration-driven flow (modeled with some form of

这里包括煤层内部表面的吸附气体和煤基质中液体 / 固体中的溶解气—实验室可通过测量等温吸附线来测算含气量，这些赋存机理通常没什么区别。与吸附气体相比，因为裂缝孔隙体积较小，而含水饱和度较高，CBM 气区的游离气一般微不足道，通常可以忽略。但一些 CBM 干气藏例外，其游离气的赋存量可能更为可观（Bustin 和 Clarkson, 1999; Bustin 和 Bustin 2009）。溶解气通常也被忽略。

截至目前，吸附气存储是大多数 CBM 储层最重要的赋存机制。高阶煤的表面积约为 100 ～ 300m^2/g，而常规储层表面积一般小于 1m^2/g。天然气可接触的大部分煤基质的表面积都与有机质有关，其孔隙结构通常主要为微孔隙，即直径小于 2nm 的孔隙（Sing 等，1985）。CBM 基质孔隙结构的决定因素包括热成熟度（等级）、有机质含量以及煤组分（Bustin 和 Clarkson，1998）。煤基质的表面积与体积的巨大比值意味着大量暴露的表面积通过分子力（分散和静电）吸引气体分子，使气体发生吸附。

CBM 储层气体的吸附主要通过物理方式进行，而不是化学方式，即分子的相互作用很弱且可逆。天然气以类似液体的状态存储，密度高于典型储层温度和压力下压缩气体的密度。除有机质的孔隙结构外，吸附的决定因素还包括：压力、温度（Levy 等，1997）、湿度（Joubert 等，1973）、热成熟度（等级）（Levy 等，1997）、矿物质含量（品位）（Mavor，1996）、有机质组分（Clarkson 和 Bustin，1999），以及气体组分（Hall 等，1994）。煤的吸附能力与压力成非线性关系，各种经验和理论方程已经对此进行模拟。到目前为止，对于煤储层最常使用的单组分和多组分气体吸附模型当属 Langmuir 等温线（Mavor，1996）。Langmuir 等温吸附方程可用于在下列条件下估计煤层气含量：煤层饱和（例如，煤层气原始含量等于原始存储能力）；已知准确的储层压力和气体组分数据，游离气和溶解气可以忽略不计；已知储层中煤的平均组分。

煤层中气体流动方式主要包括：裂缝中的压力驱动流动（基于达西定律模拟）和煤基质中的浓度驱动流动（基于菲克定律模拟）。天然气和

Fick's law) through the coal matrix. Gas and water flow to the wellbore through a well-defined natural-fracture system called "cleats." Cleats generally exist as an orthogonal set; that is, they are perpendicular to each other and also perpendicular (or nearly so) to the bedding planes. The "face" cleat is better developed and more continuous than the "butt" cleat, which terminates into the face cleat. Other, subordinate ("tertiary") fractures may also occur (Mavor 1996).

Flow in the fractures is often modeled using some form of Darcy's law, modified in some instances to account for two-phase flow (gas + water) and non-Darcy flow effects. Note that if coals are undersaturated (i.e., the in-situ gas content is less than the in-situ storage capacity), they will need to be dewatered before gas saturation develops in the fractures. In this case, single-phase flow of water will occur through the fractures until the critical desorption pressure is reached. If the coals are saturated (in-situ gas content = sorbed gas content), then two-phase flow of gas will occur from the start of production. Absolute permeability in coal is highly dependent upon the existence, frequency, orientation (relative to current in-situ stresses), height, and degree of mineral infilling in the natural-fracture set (Laubach et al. 1998). A common model for describing cleat porosity and permeability in coal is the matchstick model (Seidle 1992). The permeability is extremely sensitive to fracture aperture, with which it has a cubic relationship. Any process acting to modify the cleat aperture will have a strong effect on absolute permeability.

In coal reservoirs, two physical processes will act to change the physical dimension of the fracture apertures: (1) changes in effective stress and (2) matrix shrinkage. Note that fines migration may also act to reduce fracture apertures. With Process 1, because the fracture pore volume is highly compressible with pore volume compressibilities typically on the order of 10^{-4} psi^{-1}, increases in effective stress because of pore-pressure depletion can cause the fracture apertures to decrease in width, which in turn causes a reduction in absolute permeability. In some coal reservoirs, Process 2 will cause the absolute permeability to increase with depletion, because the coal matrix will shrink during desorption, causing an increase in fracture apertures.

Several analytical models (Palmer 2009) have been developed that predict permeability changes as a function of (1) effective stress and (2) matrix shrinkage/swelling. Other important controls on fluid flow through the fracture system include relative permeability effects (changes in effective permeability to gas and water during dewatering), reservoir pressure, pressure drawdown, and fluid properties. For some CBM reservoirs, gas properties will change during depletion not only because of changes in reservoir pressure, but also as a result of gas composition changes caused by adsorption behavior. For example, in the Fruitland coal fairway of the San Juan basin, the initial gas composition contained a significant amount of CO_2 (10 mol% or more in some areas), which has increased during reservoir depletion to greater than 20%. This occurs

水通过查明的天然裂缝系统（“割理”）向井眼的流动。割理通常作为一组正交集合存在；也就是说，割理相互垂直，并与层理面垂直或几乎垂直。面割理比端割理发育好，也更连续，端割理在面割理处终结。此外还可能存在次级（第三级）裂缝（Mavor，1996）。

一般使用达西定律对裂缝中的流动进行模拟，有时用两相流（天然气＋水）和非达西流动效应进行修正。请注意：如果煤层欠饱和（即煤层气原始含量小于原始存储能力），那么在裂缝达到气体饱和之前需要对煤先排水。在这种情况下，裂缝中发生水的单相流动，直至达到临界解吸压力。如果煤层饱和（煤层气原始含量等于吸附气含量），那么生产开始时即发生气体两相流动。煤层的绝对渗透率与天然裂缝组中矿物充填的存在、频率、方向（当前地应力）、高度以及程度密切相关（Laubach 等，1998）。火柴模型（Seidle，1992）是描述割理孔隙度和煤层渗透率的通用模型。渗透率对孔隙开度非常敏感，与其成立方关系。任何改变割理开度的过程都将对绝对渗透率产生巨大影响。

在煤层中，两个物理过程可以改变裂缝开度的物理尺寸：（1）有效应力的改变；（2）基质收缩。请留意，微粒的移动也可能减小裂缝开度。在过程（1）：因为裂缝孔隙容积可大幅压缩（孔隙体积压缩率一般为 10^{-4} psi^{-1}），孔隙压力衰减导致的有效应力增加可使裂缝开度的宽度降低，从而造成绝对渗透率降低。在某些煤储层中，过程（2）可以使绝对渗透率随压力衰减而增大，因为煤基质在解吸过程中收缩，使裂缝开度增加。

已研发出多个分析模型（Palmer，2009），用于预测基于有效应力和基质收缩/膨胀作用的渗透率变化。影响液体在裂缝系统流动的其他关键因素包括相对渗透率作用（排水过程中气相和水相有效渗透率的变化）、储层压力、压力下降以及流体性质。某些 CBM 储层的天然气性质在压力衰减过程中会发生变化，原因不仅包括储层压力的变化，还因为吸附作用使气体组分发生变化。例如，San Juan 盆地 Fruitland 煤区的气体原始组分包括大量 CO_2（摩尔分数 10%，某些区域甚至更高），

because coal has a greater affinity for CO_2 than methane, so it gives up CO_2 in greater amounts as the reservoir is depleted.

The coal matrix provides a source of gas to the fractures. If the fracture density is great enough, and/or the diffusion coefficient is large enough, the matrix may be assumed to be in equilibrium with the fractures and desorption may be modeled as an instantaneous release of gas to the fractures. Also, assuming that the pressure in the fracture system dictates the sorbed gas content in the matrix, an equilibrium sorption isotherm equation, such as the Langmuir equation, can be used to model the matrix desorption.

In cases where the fractures are more widely spaced and/or the diffusion coefficient is small, then desorption from the matrix to the fractures is not instantaneous, and may need to be modeled using either a pseudo steady-state formulation (using an average gas concentration in the coal matrix that is not equal to that at the fracture face) or a nonsteady-state formulation, in which concentration gradients in the matrix are modeled. In either case, some form of Fick's law for concentration-driven flow (diffusion) is used to model matrix transport.

Because of the unique storage and transport mechanisms associated with CBM reservoirs, CBM wells can exhibit unusual gas-production profiles. The production characteristics of a CBM well exhibiting two-phase flow are illustrated using an example from the San Juan basin (Figure 8.2).

随着储层的开采，CO_2含量增加至20%以上。这是因为煤对CO_2的吸附性比甲烷强。所以随着气藏开发，会释放更多CO_2。

煤基质可为裂缝系统提供气源。如果裂缝密度足够大，且/或者扩散系数足够大，那么可以假定基质与裂缝实现平衡，解吸作用按瞬间（向裂缝）释放气体来模拟。另外，假定裂缝系统的压力决定基质吸附的气体量，可利用平衡吸附等温方程（例如Langmuir方程）模拟基质解吸。

如果裂缝间距大，并且/或者扩散系数小，那么从基质向裂缝的解吸就不是瞬时的，需要利用拟稳态流公式（使用煤基质中的平均气体浓度，其与裂缝表面浓度不同）或非稳定状态公式建模，模拟基质内气体的浓度梯度。不论哪种情况，浓度驱动流动（扩散）的菲克定律的某些形式可用于模拟气体在基质中的渗流。

由于CBM气藏特殊的赋存和渗流机制，CBM井的生产剖面非常特别。San Juan盆地CBM井两相流的生产特征参见图8.2。

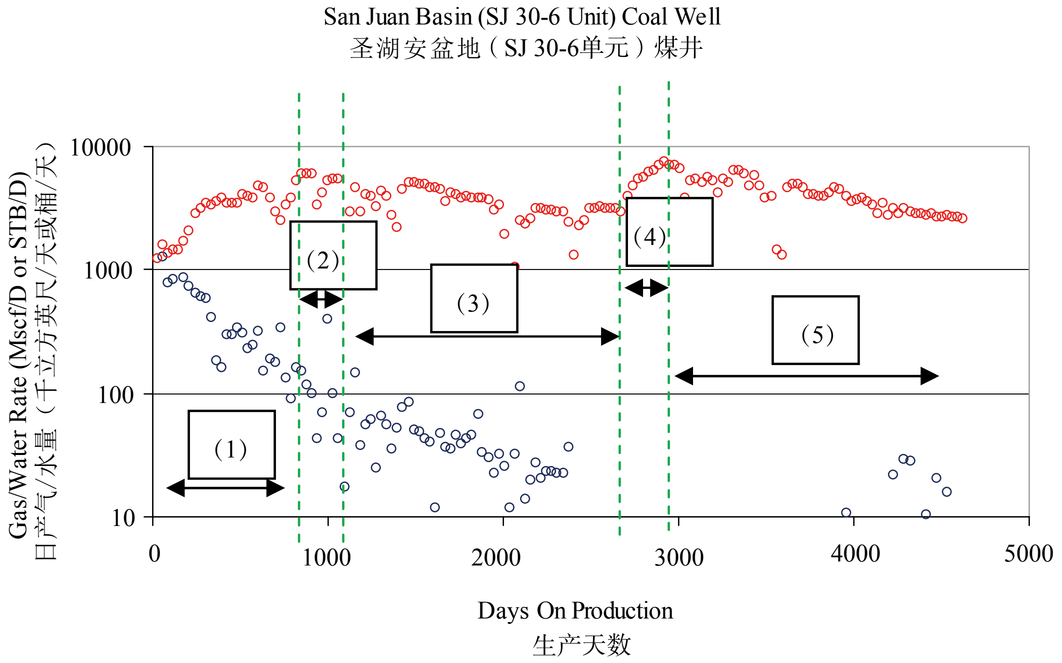

Figure 8.2　Production profile for CBM well (Fruitland coal) in the San Juan basin. Red markers indicate gas production, blue markers represent water production.
图8.2 San Juan盆地Fruitland煤层气井产量剖面
红色为产气量，蓝色为产水量

In this example, during the early dewatering period (1), gas production inclines primarily as the result of an increase in the effective permeability to gas. Flowing pressures are also rapidly decreasing during this period, which is referred to as the "negative decline" period. Once the well has contacted no-flow boundaries (in this case, probably created by offsetting wells), the well reaches a peak rate (2) and starts to exhibit a normal decline (3). Note that conventional decline curves cannot be fit to this dataset until several months after peak production is reached (> 1,000 days after first production). A disturbance in the well-production profile occurs at around 2,700 days because of a rapid lowering of backpressure associated with the installation of compression (possibly coupled with restimulation). This rapid backpressure decrease causes an additional change in effective permeability to gas caused by an alteration of near-wellbore water saturation and, possibly, absolute permeability (caused by matrix-shrinkage effects). These changes result in a short negative-decline period (4). Lastly, a terminal-decline period occurs (5) when, once again, a decline curve may be fit to the data.

Some dry coal wells, such as those in the Horseshoe Canyon play in Alberta, exhibit a more conventional decline profile, analogous to shallow gas wells. In the Fruitland coal of the San Juan basin, wells only a few miles from each other may exhibit production characteristics that are drastically different. Care must, therefore, be taken in the selection of analog reservoirs and wells for reserves estimation.

8.5.4 Exploration and Development Considerations

Play- and prospect-analysis tools developed for conventional reservoirs are not directly applicable to CBM or shale reservoirs (Haskett and Brown 2005; Clarkson and McGovern 2005). The variability of key CBM-reservoir properties from basin-to-basin and even field-to-field necessitates a more stochastic approach to CBM exploration. Failure to reach commercial CBM production is often related to lack of permeability, resulting in subeconomic rates. Sweet spots can occur in CBM plays due to enhanced natural fracturing and 3D-seismic techniques are currently being adapted to identify these enhanced permeability areas (Hyland et al. 2010).

For CBM exploration and appraisal, a key step is the design of the pilot program (Roadifer, 2009). Uncertainties associated with production forecasting include relative permeability, absolute permeability, and the effect of stress and desorption on permeability during depletion, permeability anisotropy, and multilayer effects. It is for these reasons that pilots are needed particularly for undersaturated

在该例中，在排水初期（阶段 1），天然气产量曲线上的斜坡主要是因为气相的有效渗透率增大。流动压力在这个阶段也快速下降，该阶段被称为“负递减”阶段。一旦煤井接触不渗透边界（这种边界一般由邻井形成），产量达到峰值（阶段 2）并开始正常递减（阶段 3）。请注意：常规递减曲线直至产量达到峰值的数月之后（投产 1000 天之后）才适用。从井生产剖面上看，在第 2700 天左右出现扰动，这是因为压缩机启用而引起的回压快速降低（可能伴有重复增产措施），由于井眼附近含水饱和度变化，回压快速降低引起近井地带含水饱和度改变，造成气相有效渗透率进一步变化，并且绝对渗透率也可能改变（由基质收缩效应导致）。这些变化导致短暂的负递减阶段（阶段 4）。最后，最终递减期出现（阶段 5），递减曲线可能再次与数据响应。

某些无水煤井（例如艾伯塔 Horseshoe 峡谷的煤井）展示出了与浅层气井相似的更类似常规递减剖面。在 San Juan 盆地 Fruitland 煤田中，相互距离仅几英里，井的生产特征却可能极为不同。因此在储量评估时，须谨慎选择类比气藏和类比井。

8.5.4 勘探与开发

针对常规气藏所研发的勘探目标评价软件不能直接应用 CBM 和页岩气藏（Haskett 和 Brown，2005；Clarkson 和 McGovern，2005）。盆地之间乃至气田之间，主要储层物性的多变性使得 CBM 的勘探有必要采用随机方法。CBM 不能商业开采通常是由于渗透率低，导致单井产量不经济。天然裂缝系统经后期改造，可能在 CBM 储层形成甜点区；现在可采用三维地震技术来识别这些渗透率改善的区域（Hyland 等，2010）。

对于煤层气的勘探与评价来说，先导试验设计是一个关键步骤（Roadifer，2009）。与产量预测相关的不确定性包括相对渗透率、绝对渗透率、衰竭开采过程中应力与解吸对渗透率的影响、渗透率各向异性和多层层间干扰等。正是由于这些原因，对于非饱和煤层气藏特别需要进行先导试验，在那些气藏中心井的周边部署外围井，加快

coal reservoirs, where interior wells are bounded by exterior wells to accelerate dewatering. The interior wells need to achieve significant (commercial) gas rates, and effective permeability to gas must be established before reserves bookings can be contemplated. The pilots need to be designed to reduce the uncertainty in key reservoir parameters and to test various completion/drilling technologies to determine which are most cost-effective.

The unique CBM properties also impact later-stage development planning. The two-phase flow nature of most CBM plays means that well spacing, well geometry and well orientation should be designed to accelerate dewatering, which will, in turn, increase effective permeability to gas, initiate gas production, and reduce the time to peak gas production. Care must be taken, however, not to overdrill or overdevelop, leading to pure acceleration with infill drilling. Critical data gathered during the exploration phase, such as gas contents, isotherm data, pressures (flowing and shut-in) and effective/absolute permeability data must continue to be collected during early and sometimes mature stages of development because of the heterogeneity (vertical and lateral) of CBM plays. Collection of these key data is necessary to informed development and business decisions.

Surface operations must also be planned carefully to account for production behavior. Facilities must be designed to dewater coal wells (artificial lift) and to gather, transport (trucking or water-gathering system), and treat (subsurface or surface disposal) large amounts of water, particularly in the early life of a field. Compression must be considered to assist with early dewatering and to optimize well performance. Additionally, because of the potential for evolving gas compositions during depletion, facilities may be needed to scrub nonhydrocarbon gases (such as carbon dioxide) to meet market specifications.

8.5.5 Commercial Issues

A primary consideration for commerciality is the resource size, related to the thickness and gas content of the coals. Depth of the coal is an important factor affecting both gas content (through pressure and temperature) and absolute permeability, which generally decreases with depth due to the stress-sensitivity of the coal fracture apertures. Commercial production of CBM is generally limited to depths < 4,000 ft for this reason. Factors affecting the timing of first significant gas production (above the economic limit rate in order to pay out operating costs)—such as degree of undersaturation—will impact commerciality. Commerciality will also be affected by factors controlling time to peak production and peak gas rate, such as effective permeability to gas, which changes with saturation and reservoir pressure.

排水。中心井要获得高的（商业）产量，必须形成有效的气体渗透率才可能登记储量。在先导试验的设计里，需要减少气藏主要参数的不确定性，测试各种完井、钻井技术，以确定哪些是最符合成本效益的。

CBM 的独特属性也影响其后期的开发方案。大多数 CBM 开采中的两相流性质表明设计必须考虑井距、井身结构和方向以加速排水，反过来，这又会增加气相的有效渗透率、最初天然气产量，减少达到天然气峰值产量的时间。但必须注意不要过度打井或过度开发，避免导致单纯增加加密井。由于 CBM 区块的（水平和垂直）非均质性，在勘探阶段即需要开始收集关键数据，例如天然气含量、等温线数据、压力（流动和关井压力）以及有效 / 绝对渗透率数据，在开发初期甚至成熟阶段还应继续收集。这些数据对于开发和商业决策来说很有必要。

地面作业也必须谨慎规划，需考虑开采动态。必须对作业设施进行合理设计，以便进行煤层气井排水（人工举升）、收集、输送（卡车或集水系统）和处理大量产出水（尤其是在气田开发初期）。为促进初期排水，并优化井的性能，必须考虑压缩机配置。此外，由于开采过程中气体组分可能变化，可能还需要分离非烃气体（例如二氧化碳）的设施，以满足市场要求。

8.5.5 商业性

商业性的一个主要考量是资源规模，其与煤层厚度和气体含量有关。煤层的深度是一项既可以影响气体含量（通过压力和温度），又能影响绝对渗透率的重要因素；由于煤层裂缝开度的应力敏感性，绝对渗透率一般随深度的增加而降低。因此，CBM 的商业生产一般只限于深度不超过 4000ft 的煤层。影响天然气实现大量生产（产量高于可支付操作成本的经济极限）时间的因素（例如欠饱和度）也影响商业性。其商业性还受影响总产量达到峰值和天然气产量达到峰值时间的因素影响（例如气相有效渗透率），这些因素随饱和度和气藏压力而变化。

In CBM projects, it is important that (1) infrastructure is sufficient to gather and dispose of high initial-water volumes; (2) sufficient compression is installed to improve CBM recovery and assist with well dewatering; (3) artificial lift is planned for and included in operating costs; (4) facilities are designed to scrub nonhydrocarbon gas from produced gas to meet market specification (where applicable); and (5) regulatory concerns are addressed.

8.5.6 Unique Assessment Methods/Issues

Methods for the assessment of CBM resource/reserves have been adapted largely from techniques developed for conventional reservoirs. Four general methods are applied:

(1)Volumetric
(2)Material balance
(3)Production data analysis (PDA)
(4)Reservoir simulation

The appropriate application of these methods depends on the phase of development of the CBM reservoir. Although both volumetric and simulation methods can be applied at all stages of development, their accuracy will improve with increased data availability. Material balance, decline curve, and PDA methods can only be applied after a significant amount of production, flowing pressure, and shut-in pressure data become available.

Volumetrics. Volumetric estimates of CBM reserves is the simplest method, as well as the most potentially error prone, because of the uncertainty in basic parameters such as recovery efficiency and parameters in the total gas initially-in-place (TGIIP) calculation [such as bulk volume of the reservoir (Ah), and in-situ gas content]. Estimated ultimate recovery (EUR) may be obtained from TGIIP simply by multiplying TGIIP by recovery efficiency (Rf). The most commonly used form of the GIIP equation for coal is (Zuber 1996)

$$G_i=Ah\left(\frac{43560\phi_f(1-S_{wi})}{B_{gi}}+1.3597\bar{\rho}_c\bar{G}_c\right) \tag{8.1}$$

where

G_i = GIIP, Mscf
A = reservoir area, acres
h = reservoir thickness, ft
ϕ_f= natural-fracture porosity, dimensionless, fraction
S_{wi} = initial water saturation in the natural fractures, dimensionless, fraction
B_{gi} = initial gas formation volume factor, Rcf/Mscf
1.3597 = conversion factor
$\bar{\rho}_c$= average in-situ coal-bulk density corresponding to the

对CBM项目而言，以下几个方面很重要：(1) 基础设施足以收集和处理大量初期产水；（2）安装了充足的压缩设备，以提高CBM采收率并协助煤层气井排水；（3）设计了人工举升并包括在操作成本中；（4）为满足市场要求（如果适用），设计了煤层气的非烃气体分离设施；（5）考虑了监管问题。

8.5.6 特殊的评估方法 / 问题

CBM资源 / 储量的评估方法主要来源于常规气藏评价技术。常用的四种方法是：

（1）容积法；
（2）物质平衡法；
（3）生产数据分析（PDA）法；
（4）气藏模拟法。

需基于CBM气藏的开发阶段合理应用这些方法。虽然容积法和气藏模拟法在开发的所有阶段均可应用，但准确性随着可用数据的增加而提高。物质平衡法、递减曲线和PDA法只能在获得大量产量、流动压力数据和关井压力数据后才能使用。

8.5.6.1 容积法

容积法是估算CBM储量最简单的方法，也是最可能出错的方法，因为采收率和计算总天然气原始原地量（TGIIP）的参数[例如储层的总体积（Ah）和原始天然气含量等基本参数]存在不确定性。估算最终可采储量（EUR）可通过TGIIP乘以采收率（Rf）而获得。最常用的煤层气原始原地量（GIIP）的计算公式（Zuber，1996）如下：

$$G_i=Ah\left(\frac{43560\phi_f(1-S_{wi})}{B_{gi}}+1.3597\bar{\rho}_c\bar{G}_c\right) \tag{8.1}$$

式中 G_i—GIIP，Mscf；
A— 储层面积，英亩；
h— 储层厚度，ft；
ϕ_f— 天然裂缝孔隙度，无量纲，分数；
S_{wi}— 天然裂缝中的原始含水饱和度，无量纲，分数；
B_{gi}— 原始地层天然气体积系数，Rcf/Mscf；
1.3597—换算系数；
$\bar{\rho}_c$— 煤层原地平均组分对应的原地平均总密

average in-situ coal composition, g/cm^3

$\overline{G}_c$= average in-situ coal-gas content corresponding to the average in-situ coal composition, scf/ton.

The primary modification to the conventional GIIP equation has been the inclusion of adsorbed gas content, which requires specialized field- and lab-based techniques to ascertain. Adsorbed gas cannot be directly detected in-situ using current petrophysical methods. Recently (Lamarre and Pope 2007), however, a downhole technique based upon Raman spectroscopy was introduced that may hold promise for gas-in-place determination, if certain rigid conditions are met. Raman spectroscopy can be used to measure gas in solution (produced water) from which the partial pressure of methane is obtained. If it can be assumed that the partial pressure of methane in the coal is equivalent to gas in solution, and if a representative coal isotherm is available, the gas content of the coal can be determined (Lamarre and Pope 2007). Carlson (2006) introduced a technique to establish the critical desorption pressure (CDP) of undersaturated coals through estimation of bubble point pressure of the water, which they demonstrate to be equal to CDP.

In the derivation of Eq. 8.1, it is assumed that only gas sorbed in the coal matrix and free-gas stored in the natural-fracture system are contributing to the gas-in-place. In general, the sorbed gas content within the coal matrix is the dominant contribution to gas-in-place, and free-gas storage in both the matrix and the fractures is generally considered to be negligible.

It is very difficult to obtain an accurate value for coal-gas content ($\overline{G}_c$), mainly because of the heterogeneity of the coal and the difficulty in the use of well-logging to infer gas content. Fortunately, the Gas Research Institute (GRI) has published excellent guidelines (e.g., McLennan et al. 1995) on the proper assessment of in-situ gas content. Recent advances have been discussed by Clarkson and Bustin (2010).

Both inorganic and organic fractions of coal affect coal density ($\overline{G}_c$). Coal seam bulk densities are related to the volume fraction of each of these components. Because coal contains more than 70 vol% (50 wt%) of organic matter by definition, it is easy to detect coals using openhole density logs. Historically, an upper limit of 1.75 g/cm^3 has been used as a cutoff in the identification of coal on the density log, believed to be in part related to the above definition of coal. However, as pointed out by Mavor and Nelson (1997), using this definition may exclude the contribution of other organic-rich materials (i.e., carbonaceous shales) from the total gross-thickness calculation. One approach to include them is to establish the coal bulk-density

度，g/cm^3；

$\overline{G}_c$— 煤层原地平均组分对应的原地平均煤层气含量，scf/t。

与常规 GIIP 方程式相比，最主要的改动即引入了吸附的天然气含量，其数值需要根据专业的现场和实验室技术确定。使用目前的岩石物理方法无法直接探测出吸附天然气。但近期（Lamarre 和 Pope，2007）行业引入的一项以拉曼光谱为基础的井下技术，为确定天然气原地量带来了可能（只需满足某些特定条件）。拉曼光谱可用于测量溶解于产出水中的煤层气，从中得出甲烷的分压。如果可以假定煤层气的分压等于溶解气分压，并且有一条代表性的煤等温线可供采用，那么煤层中的气体含量即可以确定（Lamarre 和 Pope，2007）。Carlson 等（2006）介绍了一种方法，即通过估算水层泡点压力建立欠饱和煤层的临界解吸压力（CDP），他们表示两者是相同的。

在式（8.1）的推导中，假定只有煤基质吸附的气体和天然裂缝体系中保存的游离气构成煤层气的原始原地量。通常，煤基质中吸附的气体量是煤层气原始原地量的主要组成部分，基质和裂缝中存储的游离气一般可以忽略。

很难准确计算煤层气含量（$\overline{G}_c$），主要原因是煤层的非均质性以及通过测井很难确定气体含量。幸运的是，天然气研究所（GRI）已出版了一本非常优秀的关于正确评估煤层气原地含量的指南（McLennan 等，1995）。Clarkson 和 Bustin（2010）对研究进展进行了探讨。

煤的无机和有机组分都会影响煤的密度（$\overline{G}_c$）。煤的总密度与各组分的体积比相关联。根据煤的定义，煤有机质的体积分数超过 70%（质量分数超过 50%），所以很容易通过裸眼密度测井探测煤层。基于历史经验，密度测井识别煤层的上限截止值为 1.75g/cm^3，相信此数值的选取与煤的定义有关。但是，Mavor 和 Nelson（1997）指出：使用这一定义可能使其他富含有机质（例如碳质页岩）的地层被排除在总厚度的计算之外。将其他含有机质地层计算在内的一种方法是在零吸附气含量下设置煤总密度上限值。使用这种方法的 Fruitland 煤层得出的密度上限与 Mavor 和 Nelson upper limit at zero adsorbed gas content. Using this approach for Fruitland coal samples, the upper density limit obtained was consistent with those cited by Mavor and Nelson (1997) (2.1 to 2.5 g/cm^3).

The reservoir thickness (h) is intended to be coal thickness, after a density cutoff has been applied. For each coal reservoir, this may be best estimated using a density cutoff corresponding to zero adsorbed gas content. In the absence of quality density log data, other wireline logs may be used to estimate coal thickness. Neutron-porosity logs, which can be run in cased hole, may be used because coals generally have neutron porosities of > 40%. Gamma ray logs must be used in parallel with other logs, because although gamma ray responses in coal are generally low, this depends on the uranium content of the coal.

The reservoir area (A) may correspond to artificial or natural boundaries at the well, field, play, or basin scale. Artificial boundaries include ownership, survey limits, or well interference (Mavor 1996). Natural boundaries include coal pinchouts, faults, permeability changes, lateral facies changes, and other geologic variability. Individual coal seams are so thin, it is often difficult to resolve them and identify their boundaries with 3D seismic. Well-production-data analysis, material-balance calculations, and simulation history matching may be used to infer drainage volumes, which, when combined with volumetric information, can be used to estimate drainage areas.

In Eq. 8.1, the porosity term refers to natural fracture porosity (ϕ_f), which is difficult to determine quantitatively from core analysis as discussed by Mavor (1996). Initial water saturation in the fracture system (S_{wi}) is similarly difficult to ascertain from core techniques and is commonly assumed to be 100%. In most commercial CBM reservoirs, fracture porosity (generally < 1%) tends to contribute little to the total gas storage, and some error in the estimate will, therefore, not have a material impact on estimates of GIIP. However, given that this porosity is initially filled with water, the practical aspect of having 2% fracture porosity instead of 1% fracture porosity is that twice as much water will have to be moved to dewater the reservoir.

There are several approaches to estimating R_f (Zuber 1996):

(1)Adsorbed gas content calculated at initial (desorption pressure) and abandonment conditions using the adsorption isotherm

(2)Analogy

(3) Reservoir simulation

Material Balance. A number of material-balance equations have been developed that include adsorbed gas storage (King 1993; Jenson

引用的一致（2.1 ～ 2.5g/cm^3）。

储层厚度 (h) 指考虑密度截止值的煤层厚度。对各煤层而言，使用与零吸附气含量对应的密度截止值可能是厚度预测的最佳方法。如果缺少高质量的密度测井数据，那么可使用其他电缆测井结果预测煤层厚度。因为煤的中子孔隙度一般大于 40%，所以可使用中子孔隙度测井（可在已下入套管井中进行）。伽马射线测井必须跟其他测井结合使用，因为虽然伽马射线在煤层中的响应一般较低，但也与煤层中铀的含量有关。

储层面积（A）与井眼、气田、区块或盆地规模的人工 / 天然边界对应。人工边界包括所有权边界、勘测边线或井间干扰边界（Mavor，1996）。天然边界包括煤层尖灭边界、断层边界、渗透率变化边界、横向相变边界以及其他地质变化边界。由于单个煤层非常薄，通常很难用 3D 地震确定和识别煤层边界。单井的生产数据分析、物质平衡计算和数值模拟的历史拟合可用于推算泄气量，之后可利用泄气量和体积测定信息预测泄气面积。

在方程式 8.1 中，孔隙度一词指天然裂缝孔隙度（ϕ_f），正如 Mavor（1996）所述，很难根据岩心分析定量确定。裂缝系统中原始含水饱和度（S_{wi}）情况类似，也很难根据岩心分析技术确定，通常被假定为 100%。大部分具有商业价值的 CBM 储层的裂缝孔隙度（通常 <1%）对天然气总量的贡献很小，因此，其预测的某些错误对 GIIP 预测不会产生实质性影响。但是，如果这类孔隙最初填充了水，那么因为实际裂缝孔隙有 2% 而不是 1% 的裂缝孔隙度，所以储层排水需去除两倍的水量。

预测 R_f 的方法包括如下几种（Zuber，1996）：

（1）原始（解吸压力）和废弃条件下，使用吸附等温线计算吸附天然气含量；

（2）类比；

（3）气藏模拟。

8.5.6.2 物质平衡法

已研发了多种包含吸附气储集的物质平衡方程式（King,1993；Jenson 和 Smith,1997；

and Smith 1997; Seidle 1999; Clarkson and McGovern 2001; Ahmed et al. 2006), but the degree of complexity of the equations increases as free-gas (or compressed-gas) storage, water and pore volume compressibility, and water production and encroachment are accounted for. The method developed by King (1993) remains the most rigorous, although the equations may be difficult to apply in practice because of the need for iterative calculations. Since 1997, starting with Jensen and Smith's (1997) work, approximations have been developed that ease the use of material balance for CBM reservoirs, without necessarily sacrificing significant accuracy.

Production Data Analysis. The most abundant data collected for CBM reservoirs is gas- and/or water-production data, so it is logical to maximize the use of these data for reserves estimates. Advanced production-data-analysis methods (i.e., production type curves and flowing material balance) have similarly been adapted to include adsorbed gas storage, and very recently have been modified to include more-complex CBM-reservoir behavior, such as two-phase flow (gas + water), nonstatic absolute permeability (caused by effective stress changes or matrix shrinkage), and multilayer effects (Clarkson et al. 2007; Clarkson et al. 2008; Clarkson 2009; Clarkson et al. 2009). Maturing CBM fields and recent simulation studies have provided some guidelines for the appropriate use of empirical production-analysis techniques such as Arps decline curves for dewatered or dry CBM reservoirs. A comprehensive study by Rushing et al. (2008) used constant flowing pressure numerical simulation to investigate the impact of many CBM reservoir properties on decline characteristics.

Reservoir Simulation. Reservoir simulation includes the use of analytical and numerical flow models that are "calibrated" by history-matching, well production, and flowing and static (shut-in) pressures, and are then used to forecast single or multiwell production under a variety of operational and development scenarios. A variety of commercial simulators now exist for analyzing CBM-reservoir behavior, including many aspects of the storage and transport mechanisms unique to CBM. Reservoir simulation may be performed at the single- or multiwell level. In either case, for reserves-booking purposes, reservoir simulators must be properly calibrated to existing well performance using proper constraints on static and dynamic data.

8.5.7 Classification and Reporting Issues (Barker 2008)

The current practices to classify CBM resources often use an incremental approach to delineation and development, similar to that used in the mining industry and the "well spacing" concepts traditionally applied in the petroleum sector. The basis for this

Seidle,1999；Clarkson 和 McGovern, 2001；Ahmed 等 ,2006），但方程的复杂程度随着考虑游离气（或压缩气）含量、水和孔隙体积压缩性，以及钻遇出水和侵蚀情况而加大。King（1993）制订的方法是其中最严谨的，但因为该方法需要进行迭代计算，所以实际应用会困难些。自 1997 年 Jensen 和 Smith（1997）的论著出版之后，近似法得到了发展，既简化了 CBM 气藏物质平衡预测法的使用，又不会对准确性产生较大影响。

8.5.6.3 生产数据分析法

收集到的 CBM 气藏数据最丰富的就是气 / 水产量数据，所以应充分利用这些数据进行储量评价。先进的生产数据分析方法（例如，生产类型曲线和流动物质平衡）均进行了类似调整，引入了吸附气含量，近期的改进还引入了更复杂的 CBM 气藏动态，例如两相流（气 + 水）、非静态绝对渗透率（由有效应力变化或基质收缩导致），以及多层效应（Clarkson 等，2007；Clarkson 等，2008；Clarkson，2009；Clarkson 等，2009）。CBM 气田的日趋成熟及近期的增产研究为合理使用生产数据分析技术（例如 Arps 递减曲线在排水开采 CBM 气藏或 CBM 干气藏的应用）提供了一些指导。Rushing 等（2008）进行的一项综合研究使用了恒定流动压力数值模拟来研究 CBM 气藏各种属性对递减特征的影响。

8.5.6.4 气藏模拟

气藏模拟过程包括根据单井产量、流动和静态（关井）压力的历史拟合来标定解析与数值流动模型，然后预测各种不同的作业与开发情景下单井或多井的产量。现有很多商业模拟软件可分析 CBM 气藏的生产动态，包括 CBM 气藏的独特存储与渗流机制。气藏的模拟可针对单井或多井。无论单井还是多井，为了核定储量，气藏模型必须使用适当的静态和动态数据，合理地拟合已有气井生产动态。

8.5.7 分类与报告（Barker，2008）

目前实践中通常是使用增量法（与采矿业方法以及传统上在石油行业中应用的井距概念相类似）进行煤层气资源分类的实践做法。该方法基

approach is that uncertainty increases as the distance to known well control increases resulting in a progression from Proved to Probable to Possible Reserves. Under these concepts, all the Developed reserves are Proved and Undeveloped reserves may be Proved, Probable or Possible. However, there may be no explicit evaluation of the range of uncertainty in recovery efficiency for a project. Consequently, CBM projects often see large reserves growth provided that the overall area is prospective and there is a tendency to grow reserves toward a 3P value.

This approach can result in a significantly different reserves maturation profile over time than that experienced in the conventional petroleum industry where the reserves are based on uncertainty in recovery for the applied project and are expected to trend towards the 2P value. Moreover, it is important that a direct link between the applied project and the resource estimate is maintained to ensure compliance with the project-based principles of the PRMS. The following summarizes the current practices in defining the resource areas:

Contingent Resources. Demonstrated by drilling, testing, sampling and/or logging hydrocarbon gas content (e.g., coal sample or gas flow) and coal thickness sufficient to establish the existence of a significant quantity of potentially moveable hydrocarbons (i.e., there should be data indicating sufficient permeability for flow within the coal seam). Gas rates may be undemonstrated or uneconomic, gas composition may or may not support marketability, significant distance from existing well locations that have demonstrated commercial potential, outside coal fairway or acceptable depth limits (typically 200 to 1000 m) may require as yet unproven well technology, (e.g., untried stimulation techniques or horizontal/multilateral wells), outside areas that can be accessed legally (e.g., protected land), development plan immature or subeconomic, market not assured, lack of approvals.

Reserves. Demonstrated commercial production potential (pilot test), marketable gas composition and commercial gas content and thickness (coal sample, gas sample), depth within accepted economic limits within coal fairway (e.g., 200 to 1000 m depending on the area), development plan feasible, economically viable, market exists, firm commitment to develop within a reasonable time frame, approvals existing or imminent.

Proved Developed. Applies to the nominal drainage area for producing or nonproducing wells that are proven to have commercial quantities of recoverable gas. Well spacings will vary depending on the region. Typical drainage areas per well are reported to be 80 to 320 acres (Jenkins and Boyer 2008) and up to 550 acres in the Fairview/

本特点是随着离成熟控制区的距离增加，证实储量、概算储量、可能储量的不确定性逐级增加。根据这些概念，所有已开发储量都是证实的，未开发储量可以是证实、概算或可能储量，而项目采收率的不确定性范围并没有明确的评价。因此，如果整个区域都有开发前景，煤层气项目经常会有大幅度的储量增长，趋近 3P 估值。

该方法得到的储量成熟度随时间关系剖面可能会与传统石油行业的经验明显不同。通常，储量的评估是基于已实施项目的可采量不确定性，预期趋近 2P 值。此外，遵循 PRMS 基于项目的原则，保持已实施项目和资源评估之间的直接关联关系非常重要。以下是目前资源划分的做法。

8.5.7.1 条件资源量

已经钻井、测试、取样分析和/或测录井证实烃类气体含量（如煤样或气样分析），有足够的煤层厚度支撑大量流动烃类的存在（即应该有数据表明煤层内部有足够的渗透率）。产气量可能未经证实或不经济，气体组分可能符合或不符合市场需求，离已证明具有潜在商业价值的现有井位较远，在煤层甜点区域外，或在可接受深度限制（通常为 200～1000m）范围外，可能还需尚未证实的作业技术（例如未经实验的增产技术或水平/多分支井技术），在合法作业区域之外（如保护区），开发方案不成熟或不经济，市场不确定，或尚未批准等风险因素仍存在。

8.5.7.2 储量

已证实商业生产前景（先导试验），达到可销售的气体组分以及商业含气量和厚度（煤样、气样），在煤层气甜点区经济极限深度范围（200～1000m）内，开发方案可行，经济上可行，有市场存在，公司承诺按合理时间表开发，已批准或即将批准。

8.5.7.3 证实已开发储量

适用于生产井泄气面积或已证实有商业数量的可采气的未生产井泄气面积。井间距随地区变化。通常单井泄气面积在 80～320 英亩 之间（Jenkins 和 Boyer，2008），最高是澳大利亚 Bowen 盆地的 Fairview/Spring Gully 气田，达到了 550 英亩（King,2008）。

Spring Gully fields, Bowen Basin, Australia (King, June 2008).

Proved Undeveloped. Well spacing rules—distance from Proved Developed location (typically 1 spacing, in some instances this may be increased to 2 well spacings if the permeability is high and regional experience justifies good lateral continuity of the coals).

Probable. Well spacing rules—distance from Proved location (typically 2 well spacings, but this may be extended to greater distances between Proved areas if coal geology, coal quality, and local experience permits).

Possible. Well spacing rules—distance from Probable location (typically 2 well spacings, may be extended to greater distances if coal geology, coal quality, and local experience permits or constrained by geological/geographical limits).

The current conventions are also illustrated diagrammatically in Figure 8.3. The 200 m and 1000 m depth contours are shown, which for this example are intended to represent the vertical limits of anticipated commercial production. These rules of thumb may be modified by experience or additional data (e.g., pressure data from observation wells, which supports continuity over distances and larger well drainage areas).

8.5.7.4 证实未开发储量

井距规则——与证实已开发井位的距离通常为 1 个井距；若渗透率高，且有区域经验证明煤层横向连续性好，则可增加到 2 个井距。

8.5.7.5 概算储量

井距规则——与证实井位的距离通常为 2 个井距；但如果煤层地质、煤层质量和地方性经验允许，在证实区域之间的距离可扩展到更大。

8.5.7.6 可能储量

井距规则——与概算井位的距离通常为 2 个井距；如果煤层地质、煤层质量和地方性经验允许，距离可扩展到更大。

图 8.3 展示了目前的惯例做法。图上所示的 200m 和 1000m 等深线是本例的预期商业生产的垂向深度界限。这些经验法则可以根据经验或更多的数据（如观察井的压力数据，其反映更远距离和更大泄气面积的连通性）来改进。

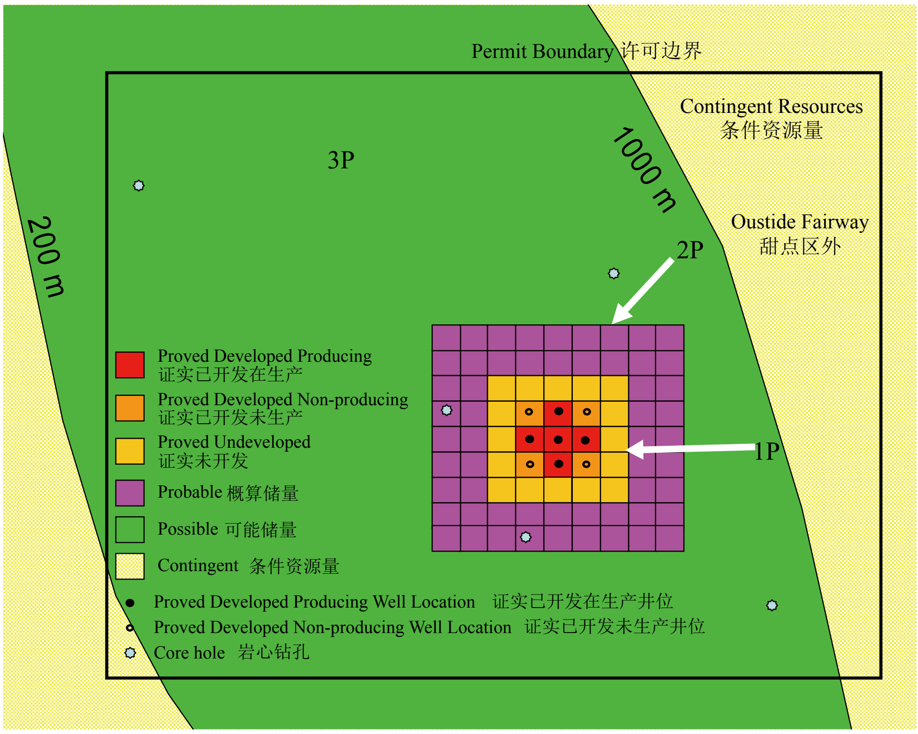

Figure 8.3　Conceptual 1P 2P and 3P Areas used in the CBM Industry (Barker 2008).
图 8.3　煤层气行业 1P、2P 和 3P 区域概念示意图（据 Barker，2008）

Comments on Current Practice. The current practices have several implications. In the initial period of appraisal or development, substantial 2P reserves growth is often seen because the full resource potential may not have been captured and/or disclosed. This is understandable since coal properties can vary substantially over short distances and sufficient data needs to be gathered to develop confidence in the recovery estimates away from known data. Area is used as the main variable in recoverable volume uncertainty. The rate of conversion to 1P reserves implies that what is termed 2P and 3P must have much higher confidence levels than one would expect compared to conventional reserves estimates. Some practitioners will have sufficient confidence in the geological and engineering data to“ bracket ” areas together and so accelerate this conversion.

In the absence of any further modifying information, using the typical well spacing conventions, each Proved Developed well can “ prove up ” a further 8 Proved Undeveloped and 40 Probable locations ⑧ . The full area can be categorized as 2P reserves if 1/49 (approximately 2%) of the total planned wells were to be successfully drilled and placed on production at commercial rates. This is premised on establishing that this well group is located in the coal fairway in terms of laterally continuous coal thickness and sufficient gas content and permeability.

The full area can be categorized as 1P Reserves after drilling 1/9 (i.e., 11%) of the planned development wells assuming an even spacing. At this point, all the original Probable and Possible Reserves have been converted into Proved Reserves. This implies that there is very little uncertainty in the estimate of recovery, which given the nature of CBM, is unlikely for projects of any reasonable scale. As a result, the reserves tend to approach the 3P estimate over time and as wells get drilled. It is also not unusual to see growth in the 3P component as Contingent and Prospective Resources are converted to Reserves.

The booking of CBM reserves based on the traditional incremental “ well spacing ” approach has advantages in that it is a predictable rules-based system, but the following issues should be considered in its application:

(1)It is typically based on a “ best estimate ” outcome for wells

8.5.7.7 生产实践评价

目前的生产实践有几点要注意。在评价或开发初期阶段，因为整个气藏资源潜力可能还没有完全发掘和 / 或披露，2P 储量经常大幅增长。这也可以理解，因为在很小距离内煤层的性质就可能有很大的差别，需要获取足够的数据来增加对可采量评估的信心。面积是影响可采量不确定性的主要变量。1P 储量的转化速率意味着 2P 和 3P 必须具有比常规储量估算更高的置信度。有些开发者充分相信地质和工程数据，将一些区域“ 串连 ”起来，加速这一转化过程。

在没有任何进一步调整信息的情况下，使用常规的井距规则，每个证实已开发井位可以进一步证实 8 个证实未开发井位和 40 个概算储量井位⑧。如果 1/49（约 2%）的计划井可以成功完钻并以商业产量投产，整个区域可划分为 2P 储量。这一结果实现的前提是该井组位于煤层厚度、充足含气量和渗透率在横向连续性上均发育的有利区。

完钻 1/9（即 11%）的计划开发井（假设双倍井距）后，整个区域可以划分为 1P 储量。这时，原来所有的概算和可能储量都转化为了证实储量。这意味着，可采量评估的不确定性将很小；根据煤层气的性质，这对任何合理规模的煤层气项目都是不可能的。因此，随着时间和钻井的进展，储量趋近于 3P 评估值。同样，在条件资源量和远景资源量转化为储量时也通常趋近 3P 估值。

基于传统井距增量法的煤层气储量核算的优点是可预见、有规则，但在应用中应注意以下几个问题。

（1）通常所有的储量级别都是基于井的最

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⑧ A practice called “ bracketing ” or ”rubber-banding ” is also used with this method that enables areas larger than that associated with the well spacing conventions to be categorised in a higher confidence resource class and/or category. For example, Probable areas located adjacent to or between Proved areas may be deemed Proved if, based on the judgment of the evaluator, there is sufficient certainty in reservoir continuity and coal properties. Similarly, Possible areas located adjacent to or between Probable areas may be deemed Probable, and the same principles can apply to Contingent Resource areas.
所谓“ 串连 ”或“ 橡皮带式 ”的做法也在该方法中使用，使得比井距规则所确定的更大的区域能被划归为置信度更高的资源级别和 / 或类别。例如，如果足够确信气藏的连续性和煤层质量（根据评估者的判断），相邻于证实区域或在证实区域之间的概算区域可被认为是证实区域。同样，相邻于证实区域或在证实区域之间的可能区域可被认为是证实区域。条件资源量区也可以应用相同的规则。

in all reserves category and relies primarily on area to provide a range of uncertainty in the outcome.

(2)The defined project applied will need to include development and appraisal of the Probable and Possible areas to define the ultimate project limits for Reserves to be claimed over these areas. The definition of the project required to develop the 1P, 2P, or 3P scenario may have a vastly different scale of investment and market requirements, which has implications for project approvals and the potential exists for noncompliance with the project-based principles within PRMS. If Reserves are claimed, they must have the necessary degree of operator commitment.

(3)The approach may not clearly separate risk (i.e., the likelihood of commercial production being realized from a given project) and uncertainty (i.e., the uncertainty in the amounts that will actually be recovered from the applied project).

Application of the PRMS using an uncertainty-based cumulative approach could provide a better indication of the risks associated with successive expansion projects proceeding and the uncertainty associated with the recovery of each project. Another advantage of approaching the problem in this fashion is that the uncertainty analysis lends itself to probabilistic assessment should this be required, which may yield additional insight.

Each project will have special circumstances and data availability with regards to technical merits of the project, maturity of the management approvals, marketing certainty, etc., that will guide the classifications and volume assignments.

8.6 Shale Gas

Creties Jenkins

8.6.1 Introduction

Shale gas is produced from organic-rich mudrocks, which serve as a source, trap, and reservoir for the gas. Shales have very low matrix permeabilities (hundreds of nanodarcies), requiring either natural fractures and/or hydraulic-fracture stimulation to produce the gas at economic rates. Shales have diverse reservoir properties, and a wide array of drilling, completion, and development practices are being applied to exploit them. As a result, the process of estimating resources and reserves in shales needs to consider many different factors and remain flexible as our understanding evolves.

8.6.2 Resource Potential

The Potential Shale Gas Committee (Potential Gas Agency 2008) estimates that there are 616 Tscf of technically recoverable shale gas resources in the US. An estimate by the INGAA Foundation (Vidas and Hugman 2008) places recoverable shale gas resources at 385 Tscf for

佳估算结果，面积对结果不确定性的影响最大。

（2）对具体项目评估时，要包括概算和可能地区的开发和评价，以确定项目在这些区域最终可获得的储量的界限。项目需要 1P、2P 或 3P 情景来确定，其对应的投资规模和市场要求有极大的不同，这会影响项目的审批并可能退出，因此不符合 PRMS 基于项目的原则。如果申报了储量，作业者必须有一定程度的承诺。

（3）该方法不会明确区分风险（即，给定项目实现商业生产的可能性）和不确定性（即，已实施项目实际开采出的数量的不确定性）。

用不确定性累积分析法来应用 PRMS，可以更好地说明持续扩建系列项目在进展中的风险和与每个项目可采量相关的不确定性。用这种方法解决问题的另一个优点是不确定性分析促进了概率法评估的发展，可进行更多分析。

每个项目的适用技术、管理审批的进程、市场因素的确定性等都有其具体情形和可用数据，这将为资源分类与（体积）数量核定提供依据。

8.6 页岩气

Creties Jenkins 著

8.6.1 引言

页岩气产自富含有机质的泥岩，这些泥岩是页岩气的源岩、圈闭和储层。页岩的基质渗透率非常低（数百纳达西），需要发育有天然裂缝和 / 或通过水力压裂措施方能获得经济产气量。页岩的储层特征具有多样性，人们通过大量钻探、完井和开发实践来对其进行开采。因此，页岩气的资源量和储量的评估需考虑很多因素，并随着我们的认知程度的提升而变化。

8.6.2 资源潜力

页岩气委员会（Potential Shale Gas Committee）［天然气署 2008 年报告（Potential Gas Agency，2008）］预测美国页岩气技术可采资源量为 616 万亿立方英尺。INGAA 基金会预测（Vidas 和 Hugman，2008）美国页岩气可采资源

the US and 131 Tscf for Canada. A study in 2001 (Kawata and Fujita 2001) estimated that the total initially-in-place shale gas resource base for the world is 16,103 Tscf. Shale gas currently represents nearly 10% of total US gas production and has been growing rapidly over the past few years. This has fueled work to find and develop similar reservoirs around the world.

8.6.3 Reservoir Characteristics

Shales are complex rocks that exhibit submillimeter-scale changes in mineralogy, grain size, pore structure, and fracturing. In thermogenic shale gas reservoirs (like the Barnett shale), the organic matter has been sufficiently cooked to generate gas, which is held in the pore space and sorbed to the organic matter. In biogenic shale gas reservoirs (like the Antrim shale) the organic matter has not been buried deep enough to generate hydrocarbons. Instead, bacteria that has been carried into the rock by water has generated biogenic gas that is sorbed to the organics. TOC (Total Organic Content) values are high in biogenic shales (often > 10 wt%), but relatively low (> 2 wt%) in thermogenic shales where most of the TOC has been converted to hydrocarbons.

A common feature of productive thermogenic shale gas plays is brittle reservoir rock containing significant amounts of silica or carbonate and “ healed ” natural fractures. Relative to more clay-rich rock, the brittle rock shatters when hydraulically fracture stimulated, which maximizes the contact area. Thermogenic shales are often referred to as “ fracturable ” shales instead of “ fractured ” shales. In contrast, biogenic shales are commonly less brittle and rely on the existence of open natural fractures to provide conduits for water and gas production. A comprehensive suite of data are needed to fully characterize shale gas reservoirs in terms of their geochemistry, geology, geomechanics, fluid properties, fracture characteristics, and well performance. Table 8.1 summarizes these data.

8.6.4 Well Performance

Wells have produced gas from shales since the 1820s, and many studies have been carried out over the past 30 years to understand and predict their performance. Thermogenic shale gas reservoirs exhibit steep initial declines of 30 to 80% or more in the first year, followed by a flattening characterized by a decline exponent (*b*-factor) greater than 1.0. This decline behavior is evidence that wells are in transient flow. This may persist for many years depending upon well spacing and permeability. Because the permeability is so low in these reservoirs, it may be tens of years before pressures begin to decrease substantially away from hydraulic fractures. As a result, even though up to half the gas initially-in-place in thermogenic shale gas reservoirs may be sorbed gas, only a small fraction of this gas will be produced over the life of the well.

量为 385 万亿立方英尺、加拿大为 131 万亿立方英尺。一项研究（Kawata 和 Fujita，2001）预测全球页岩气资源总原始原地量为 16,103 万亿立方英尺。目前美国页岩气产量占全国天然气总产量近 10%，且近几年增长迅速，这激发了全球勘探和开发类似资源的热情。

8.6.3 储层特点

页岩结构复杂，其矿物成分、颗粒大小、孔隙结构和裂缝呈亚毫米级变化。热成因的页岩气藏（例如 Barnett 页岩）中，有机质经充分热演化生成气体，然后存储在孔隙空间并被有机质吸附。在生物成因的页岩气藏（例如 Antrim 页岩）中，有机质埋藏浅，热成熟度不足以生烃；但岩石中由水体带来的细菌可经生物化学作用生成生物气，并吸附在有机质上。生物成因页岩 TOC 值（总有机碳含量）较高（通常重量百分比大于 10%），但热成因页岩的大部分 TOC 已转化为烃类物质，其 TOC 值相对较低（重量百分比大于 2%）。

具有生产能力的热成因页岩气区块的一个共同特征是，脆性储层岩石中含有大量硅质或碳酸盐和弥合的天然裂缝。相对于富含黏土的岩石来说，经过水力压裂，脆性岩石碎裂后可使接触面积最大化。热成因页岩通常被称为可压裂的页岩，而不是“ 开裂的 ”页岩。与此情况不同，生物成因页岩脆性不高，由开启的天然裂缝为水和气提供渗流通道。描述页岩气储层特性的数据涉及地球化学、地质学、地质力学、流体性质、裂缝特点，以及井的动态，汇于表 8.1。

8.6.4 页岩气井的动态特征

自 19 世纪 20 年代，就有井生产页岩气的历史，在近 30 年来开展了许多研究以了解和预测页岩气井的生产动态。热成因页岩气气藏生产的第一年的初始递减为 30% ～ 80% 甚至更多，之后趋于平缓，其特征是递减指数（b 因子）大于 1.0。这种递减特征是气井处于不稳定流阶段的依据。根据井距和渗透率的不同，该状态可能持续多年。因为渗透率很低，需要几十年的时间，远离水压裂缝的地方压力才开始下降。因此，尽管热成因页岩气储层的天然气原始原地量近一半为吸附气，但仅一小部分可在井的生命期内产出。

Table 8.1 Data Needed to Fully Characterize Shale Gas Reservoirs
表 8.1 页岩气储层表征全参数列表

Data 数据	Usage 用途
TOC 总有机碳含量	Provides an indication of source-rock richness and sorption capacity. 反映源岩丰度和吸附能力的一项指标。
Gas content 天然气含量	Includes the volumes of desorbed, lost, and residual gas obtained from the desorption of core. It is an indicator of the in-situ sorbed gas content. 包括岩心解吸过程获得的天然气解吸量、损失量和残留量，是计算吸附气原地量的一项指标。
Sorption isotherm 等温吸附线	A relationship, at constant temperature, describing the volume of gas that can be sorbed to a shale as a function of pressure. 恒温条件下，页岩吸附天然气体积随压力的变化关系。
Gas composition 气体组分	Used to quantify the percentage of methane, carbon dioxide, nitrogen, ethane, etc. in the desorbed gas. Used to build composite sorption isotherms. 定量表述吸附气中甲烷、二氧化碳、氮气、乙烷等组分的百分比含量。可用于构建复合吸附等温线。
Rock-eval pyrolysis 岩石热解分析	Assesses the petroleum-generative potential and thermal maturity of organic matter in a shale sample. 评估页岩样本的生油潜力和有机质成熟度。
Mineralogical analyses 矿物学分析	Determines bulk and clay mineralogy using petrography, X-ray diffraction, scanning electron microscopy, and similar techniques. 利用光谱、X 射线衍射、扫描中心显微镜观察和类似技术，确定体积和黏土矿物。
Vitrinite reflectance 镜质体反射率	A value indicating the amount of incident light reflected by the vitrinite maceral. It is a fast and inexpensive means of determining thermal matunity. 指示镜质组显微组分反射的入射光量的数值。是一种快速且经济的热成熟度确定方法。
Core description 岩心描述	Visually captures lithology, bedding, fracturing, grain size variations, etc. 对岩性、层理、裂缝、粒度变化等的直观描述。
3D Seismic 三维地震	Used to determine interwell shale properties including lateral extent, thickness, faulting, and those areas with higher gas saturation and brittleness. 用来确定井间的页岩属性，包括横向分布、厚度、断裂，以及天然气饱和度与岩石脆度高的区域。
Kerogen types 干酪根类型	Used to assess whether rocks are Type I（oil-prone）, II（mixed）, or III（coal）. 用来评估岩石是否属于 I 类（亲油）、II 类（混合）或 III 类（煤质）。
Routine core analysis 常规岩心分析	Includes total porosity, fluid saturations, bulk density, and matrix permeability（via pressure pulse testing on crushed samples）. 包括总孔隙度、流体饱和度、总密度以及基质渗透率（通过岩样压力脉冲测试）。
Conventional logs 常规测井	SP, GR, resistivity, microlog, caliper, density, neutron, sonic, and temperature logs are run to provide thickness, porosity, matrix, and sorbed gas saturations. 进行 SP、GR、电阻率测井、微电极测井、井径测井、中子测井、声波测井、温度测井，以提供厚度、孔隙度、基质以及天然气吸附饱和度等数据。

Data 数据	Usage 用途
Special logs 特殊测井	May include image logs（fractures）, NMR logs（free water, bound water, gas saturation), pulsed neutron and geochemical tools（mineralogy), dipole sonic（geomechanical properties), spectral GR（clay types), etc. 可包括成像测井（裂缝）、NMR 测井（游离水、结合水、天然气饱和度）、脉冲中子和地球化学测井（矿物性）、偶极声波（地球化学属性）、自然伽马能谱测井（黏土类型）等。
Pressure-transient tests 瞬变压力测试	Pressure buildup or injection fall-off tests to determine static reservoir pressure, permeability, skin factor, and to detect fractured-reservoir behavior. 压力恢复或注入压降测试，以确定储层的静态压力、渗透率、表皮系数，并检测裂缝性储层的动态。
Geomechanical properties 地质力学属性	Young's modulus and Poisson's ratio for determining shale brittleness, stress orientations and magnitudes to predict fracture growth. 用杨氏模量和泊松比确定页岩的脆性、应力的方向与大小，以预测裂缝的延伸情况。
Microseismic 微地震	Used to assess hydraulic fracture geometries and stimulated reservoir volumes. 用来评估水压裂缝的几何形状和压裂体积。
Fracture diagnostics 裂缝诊断	Treating pressures, closure stress, pumped volumes, flowback volumes, etc. to determine the quality of a fracture stimulation. 处理压力、闭合应力、泵出量、回流量等，以确定压裂增产措施的效果。
Gas, water rates 产气量和产水量	Captured daily（preferably）to assess individual well behavior. 最好按天采集，以评估单井生产动态。
Bottomhole pressures 井底压力	Preferably recorded in closely-spaced increments（every 10 min）early in well life; can also use surface pressures with wellbore-fluid gradients. 最好在单井生命期的早期密集采样（每 10 分钟）；也可使用地面压力和井筒压力梯度。
Tracer surveys 示踪剂检测	Chemical or radioactive tracers to assess which fracture stages are contributing. 化学或放射性示踪剂，以评估对产量有贡献的压裂段。
Facilities 设施	Variations in line pressure, etc., that affect producing well rates. 管线压力的变化等，将影响井的产量。
Rate-transient analysis 瞬变速率分析	Decline analysis tool that analyzes production rates and pressures using various methods to assess EUR, GIP, drainage area, etc. 可分析产量与压力的关系的递减分析工具，通过各种方法评估 EUR、GIP 和泄气面积等。
Numerical modeling 数值模拟	Helpful in understanding reservoir mechanisms, predicting early well behavior, and estimating EURs and recovery factors. 有助于理解储层的开发机理，预测井的早期开发动态，估算 EUR 和采收率。
Decline-curve analysis 递减曲线分析	Traditionally used to forecast well performance. More reliable later in well life （after a few years）due to uncertainties regarding b-factor values. 通常用于生产井动态预测。由于 b 因子存在不确定性，在井生命期的后期（几年之后）预测更加可靠。
Analogs 类比	May be useful to estimate EURs and recovery factors if a strong correlation exists between key reservoir parameters of subject and analog reservoir. 如果目标储层与类比储层的关键参数之间存在高关联性，则有助于 EUR 和采收率的评估。

Thermogenic shale gas reservoirs are generally found at depths greater than 3,000 ft, and production is dominated by dry gas held in the pores of the shales. Initial gas rates for fracture-stimulated horizontal wells are typically greater than 1 MMcf/d with corresponding EURs of more than 1 Bcf. Shales that are thermally immature (in the oil or wet-gas window) generally have lower IPs and EURs due to relative permeability effects and the difficulties related to moving liquids through the very small pore throats. Biogenic shale gas reservoirs tend to have significantly lower production rates and EURs than thermogenic shales because of their shallow depths, lower gas initially-in-place, and the need to dewater the fractures before producing the sorbed gas.

8.6.5 Drilling and Development

The most important factor behind the rapid expansion in shale gas development has been advances in drilling and completions technology. Most notable among these are the use of (1) horizontal drilling, (2) light-sand slickwater fracs, and (3) microseismic. The impact of these techniques on gas production has been dramatic. Fracture-stimulated horizontal wells in the Barnett are expected to produce about 3.8 times as much gas over their lifetime as fracture-stimulated vertical wells, based on a comparison of median well EURs (Frantz et al. 2005).

These drilling and completion techniques have been adapted and applied to multiple shale gas developments including Fayetteville, Woodford, Marcellus, and Haynesville. Lateral well lengths have increased along with the number of stimulation stages that are pumped. It is now common for laterals to be 5,000 ft long and contain 15 to 20 fracture stages, which substantially increases the contacted reservoir volume and accelerates drainage. Microseimic is used to monitor the stimulations to understand fracture geometries and estimate the stimulated reservoir volume.

Laterals are drilled parallel to each other and oriented perpendicular to the maximum compressive stress. Typical patterns in a section (640 acres) range from 4 wells (160-acre spacing) to 8 wells (80-acre spacing) with some pilot projects containing wells spaced at 40 acres. The choice of well spacing depends on multiple factors including gas-in-place, permeability, and the volume of rock contacted by hydraulic fractures. Laterals are commonly landed in the most brittle intervals of the shale to more easily initiate fractures and more intensely fracture-stimulate the rock. Care is taken to avoid structural complexities including faults with significant displacement and vertically adjacent water-productive units.

热成因页岩气气藏的埋深一般超过 3000ft，主要产量来自页岩孔隙中的干气。压裂增产的水平井初期产气量一般大约为 1 MMcf/d，对应的估算最终可采储量（EUR）超过 1 Bcf。由于相对渗透率作用以及液体难以在微小孔喉中渗流，处于油窗或湿气窗的热演化未成熟页岩的 IP 和 EUR 一般较低。生物成因页岩气藏的埋深浅、天然气原始原地量小，开采吸附气之前需要进行裂缝排水，所以生物成因页岩气藏的产量和 EUR 比热成因页岩低得多。

8.6.5 钻井和开发

页岩气开发迅速扩张背后的最主要因素是钻井和完井技术的进步。其中最值得一提的，一是水平井钻井，二是低砂含量减阻水力压裂，三是微地震的应用。这些技术对天然气产量的影响巨大。基于中等井的 EUR，Barnett 页岩压裂水平井生命期的天然气产量预计是压裂直井的 3.8 倍（Frantz 等，2005）。

这些钻井和完井技术经改进后已经应用于多处页岩气开发，包括 Fayetteville 页岩、Woodford 页岩、Marcellus 页岩和 Haynesville 页岩。分支井段的长度随着压裂级数的增加而增加。目前，裂缝长度 5000ft、压裂段 15 ～ 20 个的分支井段十分常见，这大幅增加了储层动用体积并加快了开采。微地震被用来监测增产效果，以掌握裂缝的几何形状和预测储层压裂体积。

分支井彼此平行钻探，方向与最大压应力垂直。典型模式是 1 个区段（640 英亩）4 口井（井距 160 英亩）至 8 口井（80 英亩间距），还有一些试点项目井距为 40 英亩。井距需根据多个因素决定，包括天然气原始原地量、渗透率，以及水力压裂的岩石体积。分支井一般位于页岩的脆性区层段，以便更容易实现压裂并使岩石压裂增产效果更显著。应注意避开复杂构造带，包括有大位移的断层和与垂向上出水单元紧邻的区域。

8.6.6 Commercial Issues

The greatest successes in shale gas development are realized by companies that acquire large acreage positions at low cost in locations that eventually become the core area of a shale gas play. Work begins by assessing the available data and establishing a lease position in a prospective area. This is followed by the drilling of numerous appraisal wells and pilot projects, at a total cost that often exceeds USD 100 million, to assess whether shale gas development will be commercial. Once this is demonstrated, a viable play requires billions of additional dollars to drill and complete hundreds of development wells. The cost for these can range from USD 2 to 3 million for a well in the Barnett shale to more than USD 8 million for a well in the Haynesville shale.

Because the development of any new shale gas play requires climbing up the learning curve, it is likely that the earliest wells will deliver some of the poorest results. As a result, well economics may be marginal until technological innovation, increases in operational efficiency, and economies-of-scale increase production rates and drive down costs. Gas prices also play a critical role because low prices not only reduce revenue but also reduce available capital, which slows the pace of development and further diminishes the present value of the project.

Wells in thermogenic shale gas reservoirs produce at very high initial rates and decline rapidly. This is due to multiple factors, including a reduction in reservoir pressure near the wellbore, a reduction in permeability as pore pressure decreases, and reductions in fracture conductivity resulting from proppant crushing, proppant embedment, and fines migration. Because many wells produce more than half of their total gas within the first two years, drilling must expand continuously to increase the field gas rate. In shale gas reservoirs dominated by sorbed gas, such as the Antrim shale, production may be delayed because of dewatering and more closely-spaced wells may be needed to accelerate this process.

In the early years of development it may not be possible to gather sufficient data to understand well spacing, drainage areas, and interference issues because wells are drilled at a wide spacing (often one well per section) just to hold acreage. As infill drilling proceeds, these issues can be addressed, and it may be advisable to restimulate or redrill early wells using what has been learned during the initial phase of development.

Initial gas rates and EURs for shale gas wells are highly variable and difficult to predict, with values often varying by one to two orders-of-magnitude across any given area. Because of the log-normal distribution of individual well EURs, the top 5% of wells drilled are

8.6.6 商业性

页岩气开发最成功的公司是以低成本获得大面积开采区，并最终建成页岩气生产核心区。他们的工作通常始于可用数据评估和在目标区域建立租赁区。然后，钻探众多评价井进行先导试验（总费用通常为 1 亿美元以上），以评估页岩气开发是否具有商业价值。一旦商业价值得以证实，页岩气储层的开发还需数十亿美元钻数百口开发井。Barnett 页岩 1 口井的钻完井成本为 200 万至 300 万美元，而 Haynesville 页岩 1 口井的钻完井成本超过 800 万美元。

因为任何新页岩区的开发都需要学习的过程，所以最初的井可能出现极差的结果。因此，在技术创新、作业效率提高，规模效益等增加单井产量、降低成本之前，井的经济性很差。天然气价格也起着关键作用，因为低价不仅会减少收入，而且还会减少可用资金，从而减缓开发进程、进一步降低项目的当前价值。

热成因页岩气气藏的井初始产量非常高，之后快速递减。这是多种因素作用的结果，包括井眼附近储层压力降低、孔隙压力减小导致渗透率降低，以及支撑剂压碎、支撑剂嵌入和微粒运移造成裂缝传导性降低。因为大部分井全部生命期的总产量的一半以上会在最初的两年产出，所以为增加气田天然气产量，需持续钻井。至于由吸附气体占主导的页岩气气藏，例如 Antrim 页岩，生产可能因排水而延迟，可能需要更小井距以加速生产。

开发的最初几年可能无法收集到足以确定井距、泄气面积以及干扰等问题的数据，这是因为最初的井距很大（通常每个区段 1 口井），目的仅是占地。这些问题可以通过钻加密井解决，也可以根据开发初期获得的信息重新实施增产措施或重钻早期完钻的井。

页岩气井的天然气初始产量和 EUR 变化很大，在同一区域内通常相差 1 至 2 个数量级，难以预测。由于单井 EUR 呈对数正态分布，所以

critical to the overall economic success of any project. The goal is to understand what makes these wells so successful and to replicate this in succeeding wells.

8.6.7 Classification of Prospective and Contingent Resources

Shale gas resources may be estimated deterministically or probabilistically, with best practice being to use both methods. Prior to discovery, these techniques can be used to generate low, best, and high estimates of prospective gas resources, which are commonly risked by a chance of discovery (P_g) and a chance of commerciality (P_c). The difference between the low and high estimates will likely be very large, reflecting the uncertainty in both gas-in-place volumes and recovery factors. Data available for this task could include 2D seismic data and information such as logs, cuttings, mudlogs, and/or cores from wells that passed through the shale on the way to deeper horizons.

Prospective Resources can become Contingent Resources once a well is drilled and a discovery is made. According to PRMS, a discovery requires that the collected data establish the existence of a significant quantity of potentially moveable hydrocarbons. This definition reflects the expansive nature of PRMS, whereby accumulations such as tar sands may be discovered without flowing oil to the surface. For shales, there are several criteria that should be considered before an accumulation is declared to be “discovered.” The first is a well test, which may require fracture stimulation that produces enough gas to the surface to be of commercial interest. The second is core and log data that provide convincing evidence of a significant volume of moveable hydrocarbons. The third is identification of a commercially-productive analog with sufficient similarity to the subject reservoir to conclude that it should be able to produce gas at comparable rates and recoveries. It is the combined weight of these three criteria that is important, which means, for example, if the gas flow rate is thousands of cubic feet per day, then the evidence from core, logs, and analogs needs to be more compelling than if the gas flow rate is millions of cubic feet per day.

Once the discovery is made, the next decision is whether a project can be defined using existing technology or technology under development (see Section 2.3). If not, then the accumulation should be classified as Discovered Unrecoverable Resources. Initially, Contingent Resources may be placed in the “economic status undetermined” category while wells are being drilled to evaluate the commercial potential of the play. Contingent Resources should only be assigned to this category while an ongoing evaluation is taking place. During this time, contingencies that impede production (such as poor reservoir properties or completions) and/or contingencies that impede

产量排名前5%的井对项目总体经济性至关重要。目的是认识这些井成功的经验，以便在今后的钻井中应用。

8.6.7 页岩气远景资源量和条件资源量的划分

对于页岩气资源量可以采用确定法或概率法评估，但根据实践，最好两种方法都采用。发现之前可使用这些技术，根据发现几率（P_g）和商业几率（P_c）估算天然气远景资源量的低估值、最佳估值和高估值。低估值和高估值之间的差异可能很大，反映了天然气原地量和采收率的不确定性。此项工作可用的数据包括二维地震数据和下列信息：测井、岩屑、泥浆录井，和 / 或页岩至更深层段的岩心。

一旦钻井有所发现，远景资源量就可以成为条件资源量。根据 PRMS，一个“ 发现 ”需要所采集的数据证实有大量潜在可动烃的存在。该定义反映了 PRMS 的广泛性，其中诸如沥青砂等聚集体可能不需要油流到表面就能被发现。对页岩来说，由聚集体到发现需要几个限定条件。首先是单井测试，可能需要压裂措施保证产出足够多的气体达到商业需要。第二是岩心和测井数据证明有足够体积的可动烃。第三是通过类比识别商业性生产，即通过类比分析证明目标气藏应该具备一定的单井产量和可采量。这三个方面的综合分析非常重要，这也就意味着，例如 1 口井每天产量为几千立方英尺，那么从岩心、测井分析和类比法得到的证据必须要比单井产量每天百万立方英尺的更可靠。

一旦有了发现，下一步是确定是否可以运用现有技术和正开发的技术实施项目（参见第 2.3 节），如果不可以，那么该聚集体应该定义为已发现不可采资源。在钻评价井评估开发区经济潜力期间，条件资源量最初可能被划为“ 经济状态未确定 ”。只有在评估期间，条件资源量才能划归经济未确定。在此期间，可能发现有阻碍生产（例如储层质量差或完井效果不佳）和 / 或阻碍开发（例如天然气价格较低或资金不足）的情况

development (such as low gas prices or insufficient capital) may be recognized. If it is clear that these cannot be overcome, the resources need to be assigned to the Unrecoverable or Not Viable subclass.

After a sufficient number of wells have been drilled to demonstrate that the project is technically feasible and a development plan has been generated, economics can be run to determine whether the project should be placed in the marginal or submarginal Contingent Resources category. Because projects at this stage have a chance of failure, evaluators can express the degree of commercial risk by describing the specific contingencies, quantifying the chance of commerciality, and/or assigning an appropriate Project Maturity subclass (see Section 2.5). Once the gas has been shown to be commercially recoverable under defined conditions for a given project, and there is a commitment to proceed with development, shale gas Contingent Resources can be classified as Reserves.

Since shale gas plays extend beyond the limits of conventional traps, the decision regarding how far away from existing well control Contingent Resources should be assigned can be difficult. Two guidelines that should be applied in this work are (1) information from seismic data showing that the shale is a continuous accumulation of similar character extending away from well control and is not cut by a sealing fault, and (2) indications that reservoir properties from wells that bound the Contingent Resources area are sufficiently similar to those of the discovery well that their well performance is expected to be similar.

8.6.8 Classification of Shale Gas Reserves

The most common way to assign Proved Reserves and Developed Producing Reserves in shale gas reservoirs is through the use of decline-curve analysis. Horizontal wells start out with a steep initial decline that eventually flattens, often after a year or more of production. This flattening continues until some terminal decline rate is attained (commonly greater than 5 to less than 10%), which is extrapolated to the economic limit. The shape of the decline curve often is based on comparisons of the subject well to similar wells either in the same shale gas reservoir or in analogous shale gas reservoirs.

A key drawback in the use of decline curves is the uncertainty associated with projecting well performance in early time. For example, in the Haynesville shale, a well that initially produces at a rate of 18 MMcf/d may decline to less than 3 MMcf/d after a year of production. Depending on how much the decline curve is projected to flatten beyond this first year, the b-factor can range from 0 (exponential) to 1.5 (super-harmonic), and the associated reserves can vary by a factor of two. In these circumstances, it may be reasonable to use a conservative decline to assign Proved Reserves, and less conservative declines to assign Developed Probable and Possible Reserves.

发生。如果这些障碍无法解决，那么资源将划归为“不可采”或“开发不可行”亚类。

钻井数量足以证明项目技术可行，且开发计划制订完成后，可评估经济性，以确定项目应被划至边际或次边际条件资源量。因为处于这一阶段的项目仍可能失败，评估人员需通过描述具体意外事件，量化商业几率，和/或划分项目成熟度亚类来描述商业风险（参见第2.5节）。一旦某项目的天然气被证明在特定条件下具有商业可采性，并且继续开发的相关承诺已作出，那么页岩气条件资源量即可被划为储量。

由于页岩气的储层分布超出了传统圈闭的范围，难以确定离已钻井多远可以核定条件资源量。这时应遵循以下两个指导性意见：(1) 有地震数据支撑井控范围的页岩为物性相似的连续聚集体，没有封堵断层切割；(2) 有依据表明条件资源量区域钻井获得的储层性质与发现井的储层性质相似，预期这些井的开发动态也相似。

8.6.8 页岩气储量划分

页岩气气藏的证实储量和已开发正生产储量最常用的核定方法是递减曲线分析。水平井在生产初期递减大，通常在生产1年或更长时间之后递减曲线才趋于平缓，直到达到最小递减率（一般大于5%至小于10%），然后外推至经济极限。递减曲线的形状通常可对比相同页岩气储层或类比储层的相似井来获得。

使用递减曲线的主要缺点是预测单井初期动态具有不确定性。例如，Haynesville页岩气的1口井初始产量为18MMcf/d，生产1年之后可能会低于3MMcf/d。依据第1年后不同的递减趋势，b因子的范围可能在0（指数递减）至1.5（超调和递减）之间变化，相应储量的变化可能是2倍。在这种情况下，使用保守的递减曲线确定证实储量是合理的，不保守的部分可以定为已开发概算和可能储量。

为降低初期预测的不确定性，可采用瞬变速

To help reduce the uncertainty associated with these early forecasts, rate-transient analysis and numerical modeling techniques can be applied. Both of these approaches require high-frequency rate and bottomhole-pressure data from producing wells, and detailed information about the hydraulic fracture stimulation. Other techniques, such as material balance, do not work very well because the permeability is so low that it is not possible to obtain accurate static reservoir pressures. No matter which forecasting technique is used, it is good practice to compare the resulting EURs to the original gas in place volumes to ensure that the resulting recovery factors are reasonable.

The assignment of Proved Undeveloped Reserves to offset well locations requires reasonable certainty that these locations will be economically productive and that the reservoir is laterally continuous with the drilled Proved locations. Lateral continuity is generally not a problem, unless the shale is cut by a fault, but the large variability in individual well IPs and EURs can make the assignment of PUDs problematic at distances beyond one development spacing unit from a producing well. In general, if there is consistency in the initial rates and estimated ultimate recoveries of producing wells, then it seems reasonable to assign PUDs at a distance of two or perhaps three development spacings from these wells as long as these PUD locations are bounded by other PDP wells. If there are a large number of PDP wells (at least 50 to 100), then it may be possible to apply the statistical techniques described in SPEE Monograph 3 (2010) to assign PUDs to a much larger area between PDP wells.

Undeveloped Probable and Possible Reserves may be assigned to well locations beyond PUDs using type curves derived from producing wells. The choice of which type curve to use depends on a number of factors including area, permeability-thickness, lateral length, and completion effectiveness. In practice, it seems reasonable to assign Probable Reserves to 2 to 3 drilling locations beyond PUDs, and Possible Reserves to 2 to 3 drilling locations beyond the Probable Reserves area. However, in making these assignments, a number of factors need to be considered including (1) the amount of well control, (2) whether reserves are being assigned between existing wells or beyond existing wells, (3) whether the geological and petrophysical data indicate that reservoir properties are similar in the Proved, Probable, and Possible areas, and (4) whether discontinuities such as potentially sealing faults are present. For reporting purposes, according to PRMS, shale gas reserves can be statistically aggregated up to the field, property, or project level. Beyond this level, PRMS recommends using arithmetic summation by reserves category, which may result in very conservative Proved Reserves estimates and very optimistic 3P reserves estimates due to the portfolio effect. Operators should also be

率分析和数值模拟技术。这两种方法均要求生产井提供高频产量数据和井底压力数据，以及水力压裂增产的详细信息。物质平衡法等其他技术的效果不是很好，因为渗透率太低而无法获得准确的储层静压数据。无论采用哪种技术，都应将得到的 EUR 与天然气原始原地量进行比较，以保证采收率的合理性。

核定邻井证实未开发储量时，要求邻井经济上可生产、储层与已证实井的储层有横向连续性。横向连续性一般不是问题（除非页岩被断层切断），但单井 IP 和 EUR 之间的巨大差异会使确定超过生产井 1 个井距的 PUD 值变得困难。一般说来，如果生产井的初始产量和估算最终可采量具有一致性，那么确定这些生产井周围两个甚至 3 个井距外的区域为证实未开发储量看似都是合理的（只要这些 PUD 区域被其它 PDP 井包围）。SPEE 专著 3（2010）认为在钻取大量的 PDP 生产井（至少 50 ～ 100 口），才可以应用统计技术，确定较大 PDP 井间距范围为 PUD 区域。

利用生产井的典型曲线，可以划分 PUD 以外的未开发部分为概算和可能储量。典型曲线的选择需取决于多个因素，诸如面积、渗透率—厚度、水平长度，以及完井的有效性。实际上，将 PUD 以外 2 ～ 3 个井距划为概算储量，概算储量以外 2 ～ 3 个井距为可能储量似乎是合理的。然而在划分储量时需要考虑多个因素，包括（1）井控数量；（2）已钻井之间或之外是否有储量；（3）地质和岩石物理数据是否显示在证实、概算和可能区域的储层性质相似；（4）是否存在诸如潜在封闭断层的不连续性。根据 PRMS，页岩气储量可以通过统计学汇并成油田、资产或项目级别。此外，PRMS 还推荐根据储量分级进行算术求和，这样根据组合效应可以得出最保守的证实储量和非常乐观的 3P 储量。如果作业者仅依赖于典型曲线预测单井可采量，那么采用汇并数据时应谨

cautious in relying on aggregations if they are supported only by type curve approaches to forecasting individual wells.

8.7 Oil Shale

John Etherington

8.7.1 Introduction

Oil shales are fine-grained sedimentary rocks (shale, siltstone, and marl) containing relatively large amounts of organic matter (known as "kerogen") from which significant amounts of shale oil and combustible gas can be extracted by destructive distillation.

The organic matter in oil shale is composed chiefly of carbon, hydrogen, oxygen, and small amounts of sulfur and nitrogen. It forms a complex macromolecular structure that is insoluble in common organic solvents (versus bitumen that is soluble). Because of its insolubility, the kerogen must be retorted at temperatures of about 500°C to convert it into oil and gas. Oil shale differs from coal in that the organic matter in coal has a lower atomic H:C ratio and the organic matter to mineral matter ratio of coal is much greater.

Global oil shale in-place resources are conservatively estimated at 2.8 trillion bbl. The largest known deposit is the Green River oil shale in the western US, with an estimated 1.5 trillion bbl of oil originally-in-place. Other important deposits include those of Australia, Brazil, China, Estonia, Jordan, and Morocco (World Energy Council 2007).

8.7.2 Production Methods and Assessment Issues

All current commercial extraction projects use surface mining techniques. Oil shales of Estonia are used directly as fuel for power generation and in cement plants. China and Brazil also have significant oil shale production. Brazil has developed the world's largest surface oil shale pyrolysis retort and 2009 production was about 3,600 BOPD.

Despite very significant research investments in the Colorado Piceance basin deposits since the 1970s, there is no current commercial production. Initial pilots were based on surface mining and associated retort facilities. Typical yields were < 1 bbl of hydrocarbon liquids per tonne of shale. Environmental issues include the disposal of large amounts of processed shale with associated contaminants and the potential contamination of groundwater.

Recent research has focused on the potential for in-situ conversion process using various methods to concentrate heat in the reservoir. The assessment techniques are similar to the mapping of facies and organic content as employed in shale gas assessments.

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8.7 油页岩

John Etherington 著

8.7.1 概述

油页岩是含有较高有机质（被称为“干酪根”）的细粒沉积岩（页岩、粉砂岩、泥灰岩），经蒸馏降解其有机质可生产大量页岩油和可燃气体。

油页岩中的有机质主要由碳、氢、氧和少量硫和氮构成。它复杂的大分子结构不溶于普通有机溶剂（而沥青可溶于普通有机溶剂）。由于它的不可溶性，干酪根必须在500℃左右的温度下才能够转化成油和气。油页岩与煤的不同在于煤的有机质中H:C原子比率低，但煤的有机质：矿物质比率高很多。

全球油页岩原地资源量保守估计为2.8万亿桶。已知的最大矿藏是美国西部的Green River油页岩，其石油原始原地资源量估计为1.5万亿桶。其他重要矿藏分布在澳大利亚、巴西、中国、爱沙尼亚、约旦、摩洛哥等（世界能源理事会，2007）。

8.7.2 生产方式与评估的问题

目前所有商业的开采项目均采用露天开采技术。爱沙尼亚的油页岩被直接用作发电和水泥厂的燃料。中国和巴西也已实现了油页岩的规模生产。巴西已经开发了世界最大的油页岩热解蒸馏项目，2009年的产油量约为3,600桶/天。

尽管从20世纪70年代起就对科罗拉多Piceance盆地矿体的研究投入了大量研究，但仍未实现商业生产。最初的先导项目以露天开采和相关蒸馏设施为基础。一般每吨页岩的烃类液体产出量小于1桶。环境问题包括处置页岩加工后的大量污染物和对地下水的潜在污染问题。

近期的研究重点是用各种方法对储层集中加热以实现原地转化的潜力。其评估技术与页岩气评估中采用的的沉积相和有机质含量成图技术类似。假如根据近期产品的预测价格，目前的生产

Assuming that the current production/processing costs do not support economic projects under near-term product price forecasts, estimated recoverable volumes for identified deposits would be classified as Contingent Resources—Development Not Viable.

8.8 Gas Hydrates

John Etherington

8.8.1 Introduction

Gas hydrates are naturally occurring crystalline substances composed of water and gas, in which a solid water lattice accommodates gas molecules in a cagelike structure, or “clathrate.” At conditions of standard temperature and pressure (STP), one volume of saturated methane hydrate will contain as much as 164 volumes of methane gas. Gas hydrates form when gases, mainly biogenic methane produced by microbial breakdown of organic matter, combine with water at low temperature and high pressure.

8.8.2 Resource Potential

Because of its large gas-storage capacity, gas hydrates are thought to represent an important future source of natural gas. They bind immense amounts of methane within seafloor and Arctic sediments. The worldwide amount of methane in gas hydrates is considered to exceed 10,000 gigatonnes of carbon. This is about twice the amount of carbon held in all fossil fuels on earth. Other estimates are quoted as 700,000 Tscf (Collett et al. 1971) in-place. The Mackenzie River delta in northern Canada contains some of the most concentrated deposits. A number of other countries such as Russia, the US, India, Japan, and China also have substantial marine gas-hydrate deposits.

8.8.3 Production Methods and Assessment Issues

Theoretical production methods involve either depressurization or downhole heating, but the technology to support commercial production has yet to be developed. Research projects are underway using exploration seismic techniques, petrophysical assessment methods, and experimental production. Selected areas have mapped significant gas hydrate accumulations penetrated while targeting deeper conventional reservoirs. Such accumulations may be classified as Contingent Resources—Development Not Viable, or as Currently Unrecoverable in-place volumes.

/ 加工成本使项目开发没有经济性，目前预测的可采量可以划定为条件资源量中的——开发不可行亚类。

8.8 天然气水合物

John Etherington 著

8.8.1 概述

天然气水合物是由天然气与水自然形成的结晶物，其中，结晶水的晶格呈笼状结构或络合物包裹气体分子。在标准温度与压力状况下（STP），1 体积的饱和甲烷水合物可包含 164 体积的甲烷气。在低温和高压条件下，当有机质被微生物降解生成的生物甲烷气与水结合，就生成了天然气水合物。

8.8.2 资源潜力

由于储集天然气的能力大，天然气水合物被认为是一种未来重要的天然气资源。在海底和极地沉积中的天然气水合物捕集了大量的甲烷。全球天然气水合物的甲烷碳含量估计超过 10 万亿吨，约是地球所有化石燃料碳含量的两倍。有人预测天然气水合物原始原地资源量高达 700,000 万亿立方英尺 (Collett 等 , 1971)。加拿大北部的麦肯兹河三角洲发育的天然气水合物浓度最高。其他许多国家（例如俄罗斯、美国、印度、日本、中国）也拥有可观的海上天然气水合物资源。

8.8.3 开发生产方法与评估问题

理论开采方法包括降压法或井底加热法，但尚未研发出可支撑商业生产的开采技术。应用勘探地震技术、岩石物理评估方法和试采技术的研究正在进行中。在选定区域钻探更深部位的常规气藏时已钻遇了大量天然气水合物。此类天然气水合物沉积可划分为条件资源量——开发不可行亚类，或当前暂划归为不可采原地量。

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第 9 章
CHAPTER 9

产量的计量与处理
Production Measurement and Operational Issues

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9.1 Introduction

An underlying principle within PRMS (SPE 2007) is that reserves and resource quantities will be reported in terms of the sales products in their condition as delivered from the applied development project at the custody transfer point. This is defined as the “reference point.” The objective is to provide a clear linkage between estimates of subsurface quantities, measurements of the raw production, sales quantities, and the product price received. PRMS provides a series of guidelines to promote a consistent approach in all types of projects.

9.2 Background

The following discussion provides context for application of PRMS guidelines regarding the linkage of production measurement to resource estimates in both conventional and unconventional resource projects.

Figure 9.1 illustrates typical oil and gas production with local or lease processing; the SPE historical guidance on measurement points was built around such a model with roots in small-scale onshore gas operations.

9.1 引言

按 PRMS（SPE,2007）的基本原则，储量和资源量的报告数量是开发项目在交付点条件下所提交的销售产品量。该交付点定义为“参照点”。这样考虑的目标，是为了在地下资源估算量、井口计量产量、销售量以及产品价格之间建立清晰的关联关系。为促进各类项目（针对油气数量）采用一致的处理方法，PRMS 提供了一系列指引。

9.2 背景

下面探讨如何在常规和非常规项目中，应用 PRMS 指南将产量计量与资源评估相关联。

图 9.1 是典型的本地（或合同区）加工处理油气生产作业流程示意图；SPE 以前有关计量点的指南就是基于这种小型陆上天然气生产作业模型建立的。

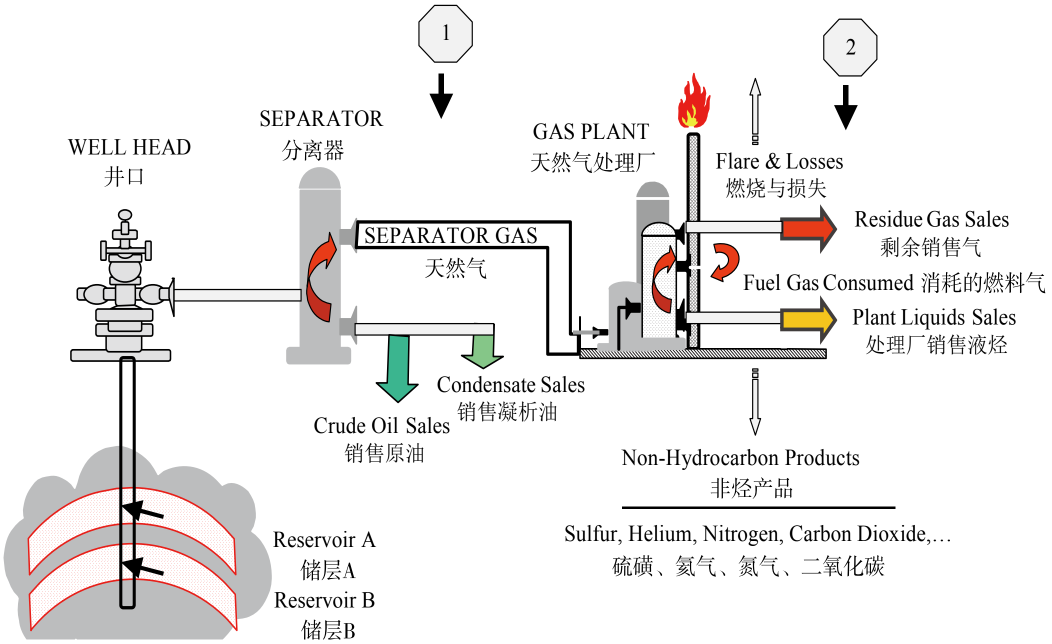

Figure 9.1 Reference points in a typical oil and gas operation

图 9.1 典型油气生产作业链中的参照点

A measurement reference point must be clearly defined for each project. It is typically the sales point or where custody transfer of the product occurs. For conventional oil and gas operations, the measurement point can vary. In many operations, it is at the exit valve of the lease separator (Point 1 in Figure 9.1). Where gas plants are involved as part of an integrated project, the measurement point is typically at the plant outlet (Point 2 in Figure 9.1).

每个项目都必须明确界定一个计量参照点。通常，为销售点或是产品交付点。对于常规油气作业，计量点可以变化。在多数生产作业链中，其位于油田分离器的出口阀处（图 9.1 的点 1）。当天然气处理厂是一体化项目组成部分时，通常计量点为处理厂的出口处（图 9.1 的点 2）。

Volumes of oil, gas, and condensate are adjusted to a standard temperature and pressure defined in government regulations and/or in product sales contracts. Liquid sales products may be measured as volumes (e.g., barrels of oil with associated density) or in terms of their mass (e.g., tonnes of oil). Natural gas is measured in volumes (e.g., cubic feet or cubic meters) and typically sold on a heating-value basis (e.g., Btu). Products are further specified by their quality and composition (e.g., sweet light crude, less than *X*% sulfur).

There is a wide range of complexity in processing facilities. "Local plants" may range from a simple dehydration unit to a sulfur-recovery plant to a liquefied natural gas (LNG) complex or a bitumen upgrader. The "plant" may be physically located on the producing property or may be a considerable distance away connected by a pipeline.

The following levels of processing are recognized:

(1)Level 1: Volumes undergoing purification and physical separation (e.g., separation of condensate and natural gas liquids (NGLs) and removal of sulfur from sour gas with subsequent sale of residual dry gas).

(2)Level 2: Volumes requiring more extensive treatment (e.g., upgrading by coking), where chemical changes are induced but no nonreservoir quantities are added. Inert gas and contaminants are also removed in the process.

(3)Level 3: Volumes undergoing significant chemical change or where nonreservoir quantities are added (e.g., hydrotreating that adds hydrogen using catalysts to rechain the hydrocarbon molecule). Inert gas and contaminants are also removed in the process.

In Level 1 projects, the processing is primarily physical separation, and outlet quantities are portions of the original reservoir petroleum; thus, resource measurements should be given in terms of the outlet products (Point 2 in Figure 9.1). If natural gas is sold before extraction of liquids (wet gas), resource estimates are given in terms of that volume. Any further processing beyond this reference point, including additional liquid recoveries (e.g., in "straddle plants") are not to be reflected in resource quantities.

Typically, a product sales contract (or pipeline constraints) sets maximum limits on the nonhydrocarbon "contaminants" content on natural gas deliveries. The volume sold may include some small fraction of nonhydrocarbons (H_2S, CO_2) as long as that fraction does not exceed specifications. Then the resource volumes captured in PRMS categories and classifications would be estimated including the same nonhydrocarbon content as in the sales gas.

In the case of LNG plants, while significant purification and associated fuel-use shrinkage is involved, there is no intent to chemically alter the gas but only to change its physical state for transportation. Inert gases and contaminants that must be removed

根据政府和 / 或产品销售合同规定，原油、天然气和凝析油的体积需要转换为指定标准温度与压力下的体积。液态销售产品可以按体积（例如原油桶数，标注密度）或质量（例如原油吨数）进行计量。天然气则按体积进行计量（例如立方英尺或立方米）和通常按热值（例如 Btu）进行销售。产品可根据其质量与组分进一步细分（例如，含硫量低于 *X*% 的低含硫轻质原油）。

关于油气加工处理设施，其复杂程度差异很大。“本地处理厂”的范围，可以从 1 套简单的脱水装置、1 个硫磺回收厂、1 个液化天然气（LNG）综合设施，或是 1 套沥青改质设施。处理厂的地理位置可在生产现场，也可在有管线连通的较远区域。

油气加工处理可以分级为：

（1）一级：产品提纯与物理分离（例如凝析油与天然气凝析液的分离，干气在销售前的脱硫处理等）。

（2）二级：产品进一步加工处理（如焦化改质），该过程会导致化学变化，但不会添加非储层产物。在此加工处理过程中，惰性气体以及杂质也会被去除。

（3）三级：产品经重要化学变化或加入非储层产物（例如加氢处理，即加入氢气并利用催化剂使烃分子链发生改变）。该加工处理过程也可去除惰性气体及杂质。

一级加工处理作业，主要是进行物理分离，出口处的油气数量是原始储层油气蕴藏量的一部分。因此，应依据出口（图 9.1 的点 2）处计量的产品数量来进行资源测算。如果天然气（湿气）在未提取液烃之前就已销售，那应按照其销售的数量进行资源估算。参照点之后的任何加工处理，包括额外的液烃回收 (例如，“第三方处理厂”的液烃回收)，均不反映在资源数量之中。

通常，一份产品销售合同（或管输条约）对交付天然气的非烃“杂质”含量设有上限。只要不超出规定限制，销售气可含有少量非烃组分（H_2S，CO_2）。相应地，PRMS 分类分级所核定的资源数量也应包括这部分非烃物质。

对于液化天然气（LNG）处理厂，尽管有大规模天然气提纯作业和伴生自用燃料导致的数量收缩，但加工处理的目的只是改变天然气的物理状态（便于输送），而非发生化学变化。加工处

during processing are part of shrinkage. If condensate or NGLs are extracted during processing and reported, the gas volume should be adjusted accordingly. Volumes must be adjusted downward for plant fuel consumption. While output is measured in tons of LNG, associated reservoir estimates are stated in terms of equivalent purified/shrunk volume of gas.

Levels 2 and 3 may both be considered upstream manufacturing processes. The actual custody transfer point in integrated upstream projects depends on the legal structure and contract terms. Where the same corporate entity shares in both the upstream and downstream operations, it may be necessary to establish the custody transfer point arbitrarily. Production streams should be physically measured at the plant inlet, or quantities may be estimated from the outlet products to account for shrinkage (including fuel usage) and additives. For example, in bitumen-upgrading operations, whereas the coking process involves significant shrinkage, the addition of hydrogen results in a volume gain. The synthetic oil delivered at the plant outlet is the final upstream sales product. Where the custody transfer is deemed to be at the upgrader inlet, a virtual inlet price may be derived through a netback calculation.

This technical analysis must be combined with royalty treatment, regulatory guidance, and accounting to ascertain the logical measurement point for stating resource quantities. In cases of fully integrated extraction and processing operations, transfer prices should be calculated to value quantities correctly at the designated measurement point.

A further issue is the treatment of the nonhydrocarbons; that is, whether they are contaminants (with disposal costs and/or no net sales value) or byproducts (e.g., sulfur or helium) that can be sold to produce additional income. There is general industry agreement that these nonhydrocarbons in excess of sales specifications are not included in resources quantity estimates; however, income generated by their sale can be used to offset expenses to extract and process the associated hydrocarbons (subject to applicable regulatory guidance) when determining economic producibility for PRMS classifications.

Some disclosure jurisdiction may require separate reporting of heavy oil from light/medium crude. It is not intended to prescribe here granularity of reporting by the oil and gas industry.

9.3 Reference Point

Reference point is a defined location in the production chain where the produced quantities are measured. It is typically the point of sale, and where custody transfer takes place between the buyer and seller. Quantitative transfer across the reference point over a fixed period of time defines sales production volumes.

理过程须去除惰性气体或杂质，这也是数量缩减原因之一。若处理过程中提取了凝析油或天然气液，并进行报告，天然气体积应作相应调整。若有燃料消耗，产品体积也须下调。当产品以液化天然气形态按“吨”计量时，相应的气藏估算量可按净化 / 收缩后的天然气当量体积表述。

二级和三级加工处理均可视为是上游生产加工过程。对于一体化上游项目而言，实际产品交付点是根据法律架构和合同条款确定的。当同一公司实体同时参与上、下游作业时，有必要指定交付点。产品流应在处理厂入口处进行物理计量，或者根据出口处的产品量核定缩减量（包括燃料用量）与增添量。例如，在沥青改质中，尽管焦化处理会造成体积明显缩减，但氢的加入又会导致体积增加；输送至处理厂出口的合成油是上游最终销售产品；炼制设施的入口认定为交付点，可通过净回价计算获得入口处的虚拟价格。

技术评价分析必须与矿税处理、监管规章制度以及财会规则相结合，厘清支撑资源核定的逻辑计量点。对于开采与处理完全一体化的运营作业，油气交付价格的确定应与计量参照点匹配，正确反映产品价值。

另一个问题，是非烃物质的处理，即杂质（有处理成本，有 / 或无净销售价值）或是可销售获取额外收入的副产品（如硫磺或氦气）。行业普遍认同，销售规定之外的非烃物质不纳入资源的数量核算；但在 PRMS 分类确定经济性，非烃销售收益可用于补偿（按适用规定）油气开采与处理成本。

一些信息监管规定可能要求将重油与轻 / 中质油分开，单独披露。这里就不再详细罗列业界有关信息披露的具体细节。

9.3 参照点

参照点是在油气生产作业链中计量产量的指定位置。通常位于销售点，也就是买方与卖方的交付地点。规定时间段内通过参照点的产品数量为产品的销售数量。

The reference point may be defined by relevant accounting regulations to ensure that the reference point is the same for both the measurement of reported sales quantities and for the accounting treatment of sales revenues. This ensures that sales quantities are stated according to their delivery specifications at a defined price. In integrated projects, the appropriate price at the reference point may need to be determined using a netback calculation.

Sales quantities are equal to raw production less nonsales quantities, being those quantities produced at the wellhead but not available for sales at the reference point. Nonsales quantities include hydrocarbons consumed as fuel, flared, or lost in processing plus nonhydrocarbons that must be removed before sale. Each of these may be allocated using separate reference points, but when combined with sales, they should sum to raw production. Sales quantities may need to be adjusted to exclude components added in processing but not derived from raw production. Raw production measurements are necessary and form the basis of engineering calculations (e.g., production performance analysis) based on total reservoir voidage.

9.4 Lease Fuel

In hydrocarbon production operations, in-field produced natural gas is often used for plant operation, mostly for power generation. Substantial savings can be achieved to the operating cost of a project by avoiding the purchase of alternative supplies of gas or refined fuels such as diesel.

Data records of consumption for fuel, flare, and other operational requirements need to be kept for operational and reservoir monitoring purposes. These data may also be required by regulatory bodies.

Internationally, the gas (or crude oil) consumed in lease operations is usually treated as shrinkage and is excluded from sales quantities; thus under PRMS, it would normally not be included in reserves and resource estimates.

Some jurisdictions allow gas volumes consumed in operations (CiO) to be included in production and reserves because they replace alternative sources of fuel that would be required to be purchased in their absence. The value of the fuel used is considered to offset the revenue and operating costs and hence does not fall into either category. Incidental flared gas is not included in production or reserves. Gas that is used in operations and has been purchased off the lease is treated as a purchase and is not included in production or reserves. If gas consumed in operations is included in production or reserves, it is recommended that a footnote be used to indicate that the volume of gas CiO is included.

Third-party gas obtained under a long-term purchase, supply, or similar agreement for whatever purpose is excluded from reserves.

参照点也可能根据有关财会规则来确定，确保报告销售量计量与销售收入会计核算的参照点一致，也确保交付规定的销售数量与价格一致。在上下游一体化项目中，参照点价格可能需要通过净回价计算来获取。

销售量等于井口原料产量减去非销售量——即从井口产出但未参与参照点销售的数量。非销售量包括自用燃料、火炬燃放或处理损失的油气数量，以及销售前须去除的非烃数量。这些非销售量可以在不同参照点进行数量核定，但与销售量汇并时，其总量应等于井口原料产量。销售量可能也需扣减处理过程加入的非原料组分。井口原料产量的计量十分必要，它是油藏工程基于储层地下亏空的各种分析计算（例如生产动态分析）的基础。

9.4 合同区自用燃料

在油气生产作业中，油气田生产的天然气经常会用作处理厂运行的燃料，最常见的是用于发电。这样就可避免购买其他来源的天然气或炼制燃料（如柴油），从而大幅节省项目运行成本。

为了开展作业与油气藏监测，需要保存自用燃料、火炬燃放和其他运行要求的消耗记录。监管机构也可能要求提供这些数据。

国际上，油气田作业区消耗的天然气（或原油）通常被视为损耗，从销售量中扣除；因此，PRMS 通常不将其纳入储量与资源量的估算。

有一些监管规定允许将作业消耗的天然气量纳入产量与储量核算，因为其替代了本应购买的燃料。但通常认为，自用燃料的价值是收入与操作成本的补偿，其数量不计入任何资源级别。火炬燃放的天然气也不计入产量或储量。从油气区外购入的作业消耗气量，按购买量处理，不纳入产量或储量。若产量或储量包含作业消耗的自用燃料气，建议注明所计入的自用燃料气数量。

通过长期购买、供应或类似协议从第三方获取的天然气数量，无论何种目的，均不计入储量。

9.5 Associated Nonhydrocarbon Components

If nonhydrocarbon gases are present, the reported volumes should reflect the condition of the gas at the point of sale. Correspondingly, the accounts will reflect the value of the gas product at the point of sale. Hence, if gas as produced includes a proportion of CO_2, the pipeline may accept sales gas with a limited CO_2 content. For example, if produced gas has 4% CO_2 and the pipeline will accept up to 2% CO_2, then it is acceptable to design facilities to deliver sales gas to that specification. Thus, the sales gas volume would include 2% CO_2 and reserves dedicated to that pipeline would be estimated including 2% CO_2. In the case where CO_2 must be extracted before sale, and the sales gas contains only hydrocarbon gases, then all categories of reserves should reflect only the hydrocarbon gases that will be sold.

The treatment of gas and crude oil containing H_2S is generally handled in a similar fashion. For gas containing small quantities of H_2S, this may be included in the reserves where the gas is sold (e.g., for power generation) and the levels are low enough not to require treatment. Whereas for LNG and processes involving compression where the dangers following stress-cracking-embrittlement are important, the H_2S must always be totally removed and therefore should be excluded from reserves.

For high concentrations of H_2S (concentrations as high as 90% have been known), the H_2S gas may be separated and converted to sulfur, which can then be sold. In such cases, the natural gas reserves exclude the H_2S volumes, and the sulfur volume may be quoted separately. At times, prices for sulfur can be low, and stockpiling for future sale is not uncommon.

Under PRMS, the volumes of nonhydrocarbon byproducts cannot be included in any reserves or resources classification, but the revenue generated by the sale of the nonhydrocarbon byproducts may be used to offset project operation expenses, potentially allowing for the recognition of additional reserves resulting from a lower economic limit. In some cases, revenue from byproducts such as helium or sulfur can be very significant.

9.6 Natural Gas Reinjection

Gas can be injected into a reservoir for a number of reasons and under a variety of conditions. Gas may be reinjected into reservoirs at the original location for recycling, pressure maintenance, miscible injection, or other enhanced oil recovery processes and be included as reserves. Gas is routinely processed in commingled facilities and redistributed for reinjection, but to retain its reserves status, these volumes should not have moved past the field's reference point as described in 9.3. If reinjected gas volumes are to be included in the

9.5 伴生非烃组分

若存在非烃气体组分，披露的天然气数量应反映其在销售点的状态。相应地，销售账目也应反映该天然气产品在销售点的价值。若生产的天然气含有 CO_2，输送管线可能会对销售气 CO_2 含量有所限制。例如，若产出气含有 4%CO_2，管线允许的 CO_2 含量上限为 2%，那么可通过设计处理设施，使销售气达到这一规定要求。因此，销售气量可包含 2%CO_2，该管线关联的储量也应包含 2%CO_2。若 CO_2 必须在销售之前进行分离，销售气仅含烃类气体，那么各级储量应只反映待销售的烃类气体。

通常，含 H_2S 天然气与原油的处理方式类似。对于含少量 H_2S 的天然气，当其 H_2S 含量无需处理即可销售（如供发电），储量中可计入 H_2S 量。但对于液化天然气（LNG）和含压缩设施的加工处理而言，由于 H_2S 在应力裂解—脆化过程中造成危害的风险很大，必须完全去除，因此其含量应从储量中扣除。

对于含高浓度 H_2S（已知含量高达 90%）的天然气，可将 H_2S 气分离出来，转化为硫磺作为副产品销售。这种情形下，天然气储量中不计入 H_2S，硫磺数量单独登记。硫磺因价低储存、待价而沽的情况并不少见。

根据 PRMS 规定，非烃副产品的数量不计入任何储量或资源量，但其销售的收益可用于补偿项目的作业费用，从而可能降低经济极限，获得储量增量。在某些情况下，副产品的收益（如氦气或硫磺）是非常可观的。

9.6 天然气回注

在多种原因和条件下，可将天然气注入储层。产出天然气原位回注到油气藏可实现循环利用、压力维持、混相注入或其他提高采收率目的，并计入储量。天然气经混合设施常规处理之后，重新分配、回注，但若要保留其储量状态，则不能穿越油田参照点（如第 9.3 节所述）。回注天然

reserves, they must meet the normal criteria laid down in the definitions. In particular, they need to be demonstrably economic to produce once available for production; the proximity of a gas pipeline distribution system or other export option should be in evidence; and production and sale of these gas reserves should be part of the established development plan for the field. In the case of miscible injection or other enhanced recovery processes, due allowance needs to be made for any gas not available for eventual recovery as a result of losses associated with the efficiencies inherent in the corresponding process. Normally, these volumes are not included in any PRMS reserves category. In some cases, the objective of gas injection in a reservoir can be efficient disposal of the gas; in such cases, no gas reserves should be allocated to reserves.

Third parties may also purchase gas to be used in a reservoir different from where it is produced for recycling, pressure maintenance, miscible injection, or other enhanced oil recovery processes. In such cases, for the originator of the gas, gas reserves, production, and sales are reported in the normal way; for the recipient, however, even if the gas eventually will be sold, the gas normally would be a purchase of gas, presumably under a long-term purchase agreement, and such a gas purchase would not be considered as reserves. It should be accounted for as inventory. When produced, the gas would not contribute toward field production or sales. Typically, under such circumstances, the field would then contain gas that is part of the original in-place volumes as well as injected gas held in inventory. On commencing gas production from the field, the last-in/first-out principle is recommended; hence, the inventory gas would be produced first and not count toward field production. Once the inventory gas has been re-produced, further gas production would be drawn against the reserves and recorded as production. The above methodology ensures that the uncertainty with respect to the original field volumes remains with the gas reserves and not the inventory. An exception to this could occur if the gas is acquired through a production payment. In this situation, the volumes acquired could be considered as reserves.

9.7 Underground Natural Gas Storage

Natural gas may be produced from a field and transported through pipelines and injected into an underground storage (UGS) reservoir for production at a later date. UGS can be used to meet fluctuations in gas demand profile, which is subject to the seasonal cycle. UGS may also reduce flaring by storing the gas for later use rather than burning off the evolved gas from the produced crude stream. The revenue stream from the produced volumes sold should account for the molecules produced and then stored in another reservoir according to the contracts in place between the various owners.

气量若要计入储量，须满足定义标准。尤其需证明其开采经济性，邻近有天然气集输和外输条件，以及其生产与销售是油田开发方案的一部分等。对于混相注入或其他提高采收率措施，需考虑到相关过程存在必然损耗，以致回注气最终不能采出。通常，这部分天然气量不纳入 PRMS 储量的任何级别。有时，将天然气注入储层的目的是为了有效处理废气；这种情况下，不应计入天然气储量。

第三方也可能从异地购买天然气，用于储层循环注气、保持压力、混相注入或其他提高采收率措施。在这种情形下，天然气气源拥有者正常上报天然气储量、产量与销售量；但气源接受者，即使最终天然气将被售出，这些天然气通常划归为购入天然气（假定为长期购买协议），而此类购入不视作储量，应视为库存量。一旦开采，不应算作油气田的产量或销售量。通常，这种情况下，地下油气田中储藏了原始油气藏的部分气量以及作为库存的注入气量。当气田投入生产，推荐采用后进、先出原则；因此，库存气应最先产出。一旦库存气再次产出，应从天然气产量中扣除，不计入储量和产量。上述方法确保了气田的不确定性仍与天然气储量相关而非库存气。有一种可能出现的例外情形，如果天然气是以产量支付方式购入，那么这部分购入天然气量可视为储量。

9.7 地下储气库

天然气从气田采出后，可经管线输送，注入一个地下储气库（UGS），以备将来开采。地下储气库可用于应对受季节周期影响的天然气需求波动。地下储气库也可通过存储天然气以备后期使用，避免直接燃烧生产中采出的天然气，从而减少火炬燃放量。产量销售收入应标明产量的组份分子量，并可根据不同业主之间签署的协议而存储于另一个储气库内。

9.8 Production Balancing

9.8.1 Production Imbalances (Overlift/Underlift)

Production overlift or underlift can occur in annual records because of the necessity for companies to lift their entitlement in parcel sizes to suit the available shipping schedules as agreed among the parties. At any given financial year-end, a company will be in an overlift or an underlift situation. Based on the production-matching of the company's accounts, production should be reported in accord with and equal to the liftings actually made by the company during the year, and not on the production entitlement for the year.

For companies with small equity interests, where liftings occur at infrequent intervals (perhaps greater than 1 year), the option remains to record production as entitlement on an accrual basis.

9.8.2 Gas Balancing

In gas-production operations involving multiple working interest owners, an imbalance in gas deliveries can occur that must be accounted for. Such imbalances result from the owners having different operating or marketing arrangements that prevent the gas volumes sold from being equal to the ownership share. One or more parties then become over/underproduced. For example, one owner may be selling gas to a different purchaser from the others and may be waiting on a gas contract or pipeline installation. That owner will become underproduced, while the other owners sell their gas and become overproduced. These imbalances must be monitored over time and eventually balanced in accordance with accepted accounting procedures.

Some points to consider in gas-balancing arrangements:

(1) In gas swaps, early production from one field may be traded with later production from another field.

(2) Take or pay gas means that the production has to be paid for even if it is not "taken" (i.e., produced).

There are two methods of recording revenue to the owners' accounts. The "entitlement" basis of accounting credits each owner with a working interest share of the total production rather than the actual sales. An account is maintained of the revenue due the owner from the overproduced owners. The "sales" basis of accounting credits each owner with actual gas sales, and an account is maintained of the over- and underproduced volumes (relative to the actual ownership). The production volumes recorded by the owners will be different in the two cases. The reserves estimator must consider the method of accounting used, the current imbalances, and

9.8 产量平衡

9.8.1 产量分配失衡（超提 / 欠提）

产量的超提或欠提现象可能出现在年度记录里，这是因为公司需要根据合作伙伴间已签定协议的装运计划、按批次提取其份额油气数量。在任意给定财政年度末，一个油公司会处于超提或欠提状态。根据油公司与产量匹配的会计原则，油公司上报的产量应与公司当年实际提取量相一致，而不是当年份额产量。

对于拥有少量权益的油公司，产量的计提是不定期的（间隔有可能超过 1 年），可选择采用应计制记录其份额产量。

9.8.2 天然气产量的平衡

在涉及多个业主拥有开采权益的天然气生产项目中，须考虑到可能发生天然气产量交付失衡的情形。出现失衡的原因，是由于不同业主拥有不同的运营或市场销售合约，使得天然气销售量无法与其应拥有的份额一致。于是一方或多方则出现了超采 / 欠采的情形。例如，某业主可能正将天然气销售给其他业主以外的买方，在等天然气合约或管线安装。该业主就会欠采，而其他业主售出所产气量则出现超采。应随时监控这种产量失衡情况，并依据适用会计程序实现产量的最终平衡。

天然气产量的平衡应考虑以下几点：

（1）在天然气交易往来中，从某一气田早提产量可以和另一气田的晚提产量进行交易。

（2）天然气照付不议意味着，即使天然气未被“提取”（即采出），仍需为产量进行支付。

两种方法记录业主账户收益。基于“份额”的会计处理，对每个业主按工作权益进行产量分成的情况（非实际销售量）进行记账；应保留一个账户记录亏欠业主应从超采业主处获取的收益。基于“销售”的会计处理，对每个业主的实际天然气销售量进行记账，保留一个账户记录超采与欠采量（与实际权益有关）。上述两种情况下，业主记录的产量不同。储量评估师在为单个业主评估储量时，必须考虑所采用的会计方法、当前

the manner of balancing the accounts when determining reserves for an individual owner.

9.9 Shared Processing Facilities

It is not uncommon in gas production operations that several fields may be grouped to supply gas to a central processing facility (gas plant) to remove nonhydrocarbons and recover liquids. Where a company has an equity interest in one or more of the contributing gas fields and also in the processing facility, the allocation of dry gas and NGLs back to the fields (and reservoirs) for estimation of reserves can be complex. While not addressed specifically in PRMS, the basic principle that reserves estimates must be linked to sales products applies. Thus, by measuring the volumes and components of the gas stream leaving each lease and the equity share in the lease, the company can calculate its share of the sales products for purposes of reserves. This share is not affected by the company’s actual equity interest in the gas plant as long as it is greater than zero. If the company has no equity interest in the facility, it is treated as a straddle plant and reserves are estimated in terms of the wet gas and the nonhydrocarbon content accepted at the lease outlet. The allocation of revenues is subject to the contractual agreement among the lease and plant owners.

When the plant ownership and lease working interest are different, booking may be an issue. This can be highly complex, but some general points are captured in the following:

(1) If the plant is associated with unit production and is unit owned, book residual plus liquids.

(2) If the plant is 100% owned by the company sending produced volumes to the facility, then that company books the volumes processed by the plant as residual plus liquids.

(3) If the contract directly stipulates the retention, by the producer, of products through plant processing, then the volumes are booked according to contract.

(4) If plant ownership and lease ownership interests are different, and existing contracts do not conclusively specify product allocation, the issues may be complex. In this case, where the trail is not clear, the booking of wet gas is recommended. The asset team responsible for handling the produced stream is afforded, however, the opportunity to present information that describes a specific instance in which the booking of residual plus liquids is reasonable and adheres to applicable contract terms. Where processed volumes are significant, this reconciliation is required.

失衡状况以及账户平衡的处理方式。

9.9 共享处理设施

在天然气生产作业中，多个气田共用某一中心处理设施（如天然气处理厂）去除非烃物质并回收液烃的情形屡见不鲜。当某一公司在一个或多个气田以及处理设施中持有权益时，将干气和天然气液回配到气田（和气藏）进行储量估算的过程十分复杂。虽然 PRMS 未特别说明，但基本原则是储量估算必须与销售产品挂钩。因此，通过计量各矿区产出的天然气体积数量与组份，测算公司在矿区拥有的权益，就可计算出其在产品销售量中的份额，并计算相应储量。只要公司在天然气处理厂的实际权益大于零，该份额就不受其影响。如果公司不拥有天然气处理设施的权益，则按使用“ 第三方处理厂 ”对待，储量按矿区出口湿气与允许非烃含量进行估算。收益按照矿权主与处理厂业主间的合同协议进行分配。

当天然气处理厂的所有权与合同区工作权益不同时，储量的登记可能会变得非常复杂，通用做法为：

（1）若天然气处理厂与某生产单位的产量有关，且属该生产单位所有，则可登记剩余可销售气量和液量。

（2）若天然气处理厂 100% 属于输送产量至处理厂的某公司，那该公司可登记天然气厂的处理量作为剩余可销售气量和液量。

（3）若油气生产商直接在合同里规定了处理厂的产品留存量，那么按合同登记气量。

（4）若天然气处理厂所有权与矿区所有权不同，且现有合同未规定产品的最终分配，那问题就变得复杂。在这种情况下，由于依据不清，推荐按湿气登记。当然，负责产量处理的资产小组可以提供信息说明具体情况，以遵循适用合同条款合理登记剩余可销售气量和液量。当天然气处理量规模很大时，需要进行对账调整。

9.10 Hydrocarbon Equivalence Issues

9.10.1 Gas Conversion to Oil Equivalent

Converting gas volumes to an oil equivalent is customarily performed on the basis of the heating content or calorific value of the fuel. There are a number of methodologies in common use.

Before aggregating, the gas volumes first must be converted to the same temperature and pressure. It is customary to convert to standard conditions of temperature and pressure (STP) associated with the system of units being used.

In those parts of the industry that report gas volumes in typical oilfield units of millions of standard cubic feet (MMscf), Imperial Unit standard conditions are 60°F and 14.696 psia (1 atm). Standard conditions in the metric system are 15°C and 1 atm. Normal conditions used in part of continental Europe are 0°C and 1 atm. Note that care needs to be taken in converting from std m^3 and Nm^3 to scf or vice versa, as the conversion factors are different depending on the temperature and gas composition. For std m^3, the factor is generally 35.3*xxx*, and for Nm^3, the conversion factor is normally 37.*xxx* (the last three places vary according to the effect of gas composition on compressibility behavior).

A common gas conversion factor for intercompany comparison purposes is 1 bbl of oil equivalent (BOE) = 5.8 thousand standard cubic feet (Mscf) of gas at STP (15°C and 1 atm).

Another factor in use, presumably rounded from the above, is 1 BOE = 6 Mscf.

Derivation of the Conversion Factor. First, some facts:

1 Btu = 1,055.06 J
1,000 Btu/scf = 1.055 MJ/scf
= 1.055 MJ/scf × 35.3147 ft^3/m^3
= 37.257 MJ/m^3 at STP (15°C and 1 atm).

From Figure 9.2, an approximate 35°API oil has a heat content of some 5.8 million Btu/bbl. Thus,

1 BOE = 5.8MBtu = 5.8 x 10^6 × 1,055.06 J
= 6,119 MJ
= 164.238 m^3 (at 37.257 MJ/m^3)
= 5,800 ft^3 (at STP, viz. 15°C and 1 atm).

Hence, the conversion factor 5.8 Mscf/BOE is based on the heat content of approximately a 35°API crude and a gas with a calorific value of 1,000 Btu/scf (37.3 MJ/m^3) at STP (15°C and 1 atm).

A reasonable approximation of 5.8 Mscf/BOE is recommended for gases where the condition of the gas is dry at the point of sale. Where one field is being converted (or in the case of a portfolio of fields where a material proportion of the gas is wet or has a calorific

9.10 油气当量换算

9.10.1 天然气换算为油当量

习惯上，天然气体积可根据含热量或热值换算为油当量。常用方法有多种。

汇并前，天然气体积首先必须转换为相同温度与压力下的体积。通常采用生产单位设施系统的标准温度与压力（STP）。

行业内报告天然气体积常用的典型油田单位为百万标准立方英尺（MMscf），该英制单位标准条件为 60 ℉和 14.696 psia（1atm）。公制单位标准条件为 15℃和 1 个标准大气压（1atm）。部分欧洲大陆采用的标准单位（Nm^3）条件为 0℃和 1 个标准大气压（1atm）。请注意，由于不同温度与气体组分条件下的换算系数不同，在将公制标准立方米（std m^3）和标准立方米（Nm^3）转换为英制标准立方英尺（scf）时要特别小心，反之亦然。公制标准立方米的换算系数一般为 35.3xxx，而标准立方米（Nm^3）的换算系数通常是 37.xxx（后 3 位数根据气体组分对气体压缩性的影响而变化）。

油公司对比常用气体转换系数为：1 桶油当量（BOE）=5.8 千标准立方英尺（Mscf）标准温度与压力（15℃和 1atm）状态的天然气。

将上述关系取整，可得到另一个转换系数：1 桶油当量（BOE）= 6 千标准立方英尺（Mscf）。

转换系数的推导。首先，基本关系为：

1 英热单位（Btu）= 1055.06 焦耳（J）
1000 英热单位 / 标准立方英尺（Btu/scf）
= 1.055 百万焦耳 / 标准立方英尺（MJ/scf）
= 1.055 百万焦耳 / 标准立方英尺（MJ/scf）
× 35.3147 立方英尺 / 立方米（ft^3/m^3）
= 37.257 百万焦耳 / 立方米（MJ/m^3）标准温度与压力（15℃和 1atm）

由图 9.2 可知，35° API 的原油热值含量约为 5.8 百万英热单位 / 桶（MBtu/bbl）。因此，

1 桶油当量（BOE）= 5.8 百万英热单位
= 5.8×10^6×1055.06 焦耳
= 6119 百万焦耳
= 164.238 立方米（37.257 MJ/m^3 条件下）
= 5800 立方英尺（标准温度与压力下，即 15℃和 1atm）。

因此，转换系数 5.8 千标准立方英尺 / 桶油

value materially different to 1,000 Btu/scf), it is necessary to calculate a conversion factor for all fields in the portfolio on the basis of the actual calorific value of each gas at its point of sale. For convenience, a weighted average conversion factor, based for example on the remaining Proved Reserves, could be calculated and used for a company with a large number of holdings.

An alternative conversion factor of 5.62 Mscf/BOE is used by some companies reporting in the metric system of units. It is based on 1000 std m^3 of gas per 1 std m^3 of oil. This different factor can possibly be justified by the observation that price parities tend to weigh up oil energy relative to gas energy, or by picking a lighter-gravity oil as a reference—but what has carried weight in practice for the users is that 1,000 is a round and extremely convenient number to use as long as BOE remains a measurement quantity with no market or customer.

A useful formula for changing calorific value from Imperial to metric units at STP (15°C and 1 atm) is $MJ/m^3 = Btu/scf \times 35.3\ scf/m^3 \times 1\ kJ / 0.948\ Btu \times 1\ MJ/1000\ kJ$.

Another approach for calculation of gas reserves in terms of BOE is described below:

Depending on the type of crude oil and the quality of gas produced from a reservoir, the BOE factor may vary significantly. It may be possible to estimate BOE factor for each reservoir separately and then average-weight it with reserves figure to be used for conversion of gas reserves number in terms of oil equivalent.

If calorific values of gas volumes are not available at gas sales point, multistage PVT experimental data on gas liberation process as per separation conditions of the field gathering system may be used. The first step is to calculate the weighted average gross calorific value of gas based on composition obtained for each stage of separation of gas.

The mole fraction of each component of gas for particular separation pressure obtained from the multistage PVT study is then multiplied by standard properties of gross calorific value of the respective component obtained from standard gas properties chart (Gas Processors Suppliers Association gas properties chart may be used). The calorific value for each component is added, to obtain the gross calorific value of gas for that particular stage of separation pressure.

The calorific value for each component in each stage is summed up to obtain the Gross Calorific Value for that stage of separation

$$\Sigma(\text{Component CV}) = \text{Gross Stage CV}(*)$$

Total calorific value for the gas is then obtained by average weighting the gas obtained from each stage with Gas Oil Ratio (GOR) numbers obtained from the same multistage PVT data from the experiment.

当量（Mscf/BOE）是基于 35° API 原油的热值含量以及标准温度与压力（15℃与 1atm）下天然气热值含量（1000 Btu/scf, 37.3MJ/m^3）。

当销售点天然气为干气，建议选取 5.8 千标准立方英尺 / 桶油当量（Mscf/BOE）作为合理转换系数。当某一气田（或多个气田的组合，湿气为主，热值与 1000 Btu/scf 差异大）转换时，有必要根据销售点各气田天然气实际热值来为气田组合计算转换系数。为方便起见，大股东可基于证实储量计算加权平均转换系数。

采用公制单位系统报告的公司可使用另一个转换系数：5.62 Mscf/BOE。该转换系数是基于每标准立方米原油对应 1000 标准立方米天然气。该系数的合理性待观察：定价方倾向于重油轻气，或选取轻质油作为参照——实践中该系数广受青睐，只要 BOE 无市场或客户，1000 作为一个约整数，可以很方便使用。

将热值由英制单位变换为标准温度与压力（15℃与 1atm）下公制单位的有用公式为：

$1\ MJ/m^3 = 1\ Btu/scf \times 35.3\ scf/m^3 \times 1\ kJ/0.948\ Btu \times 1\ MJ/1000\ kJ$。

另一种计算天然气储量桶油当量的方法是：

根据不同原油类型和产出气质量，桶油当量的系数变化很大。在将天然气储量转换为桶油当量时，可能需要分别估算每个油气藏的桶油当量转换系数，然后按储量加权平均作为天然气储量桶油当量的转换系数。

如果没有销售点的天然气热值数据，可根据油气田集输系统的分离条件采用多级高压物性（PVT）闪蒸实验数据。第 1 步是根据每一级分离气的组分加权平均天然气总热值。

将多级 PVT 实验某一压力分离的每种气体的组分摩尔分数乘以其标准热值（可查询《天然气加工供应商协会天然气性质图表》），然后每一气体组分的热值相加，得到该分离压力下天然气总热值。

将每一级分离气组分热值相加，则得到该级分离气体的总热值：

$$\Sigma(\text{组分 CV}) = \text{该级总 CV}(*)$$

然后，将多级 PTV 实验得到的每级分离气的热值与同一实验测得的气油比（GOR）加权平均，则得到天然气总热值：

Avg. Wt. Gross CV = (Stage 1 CV × GOR_1 + Stage 2 CV × GOR_2

$+ \ldots +$ Stage n CV × GOR_n) (*)(*)

$\text{GOR}_1 + \text{GOR}_2 + \ldots + \text{GOR}_n$

The calorific value obtained using these formulas can be cross-checked by taking actual calorific value measurements of some gas samples from the sales point.

The calorific value obtained by the process described above can be used for estimating BOE with a more customized approach, by taking into consideration the crude oil characteristics of the same reservoir (API and Heating value). This will enhance the reporting of gas in terms of oil equivalent, as a change in BOE factors affects the overall volume of gas in terms of oil.

Avg. Wt. Gross CV = (Stage 1 CV×GOR_1 + Stage 2 CV×GOR_2

$+ \cdots +$ Stage n CV×GOR_n) (*)(*)

$\text{GOR}_1 + \text{GOR}_2 + \cdots + \text{GOR}_n$

这些公式计算的热值可以用销售点天然气样品的实际热值测量结果进行校验。

上述过程考虑了同一油气藏的原油性质（°API和热量），所获得的热值可用于客户化的油气当量估算。由于桶油当量（BOE）系数的变化会影响天然气的总体积（折算为原油），这样可以改善以桶油当量形式进行披露的天然气信息。

Table 9.1　Abbreviations
表 9.1　缩写词

Abbreviations 缩写词	Definition 定义
atm	Atmosphere=1.01325 bar=101325 Pa 大气压 =1.01325 bar=101352 Pa
BOE	Barrel of oil equivalent 桶油当量
Btu	British thermal unit 英制热值单位
ft^3	Cubic feet 立方英尺
m^3	Cubic meter 立方米
Sm^3	Standard cubic meter at 15℃ and l atm 15℃与 latm 下的标准立方米
Nm^3	Normal cubic meter at 0℃ and l atm 0℃与 latm 下的标准立方米
J	Joule 焦耳
kJ	kilo（10^3）Joule 千（10^3）焦
MJ	Mega (10^6) Joule 百万（10^6）焦
Mscf	Thousand standard cubic feet 千标准立方英尺
MMscf	Million standard cubic feet 百万标准立方英尺
scf	standard cubic feet 标准立方英尺

For further details on the units and conversion factors refer to The SI Metric System of Units and SPE Metric Standard, SPE, Richardson, Texas (1984), and Chapter. 6, Sec. 6.6.

9.10.2 Liquid Conversion to Oil Equivalent

Regulatory reporting usually stipulates that liquid and gas hydrocarbon reserves volumes be reported separately, liquids being the sum of the crude oil, condensate, and NGL. For internal company reporting purposes and often for intercompany analysis, the combined volumes for crude oil, condensate, NGL, and gas as an oil equivalent value offer a convenient method for comparison.

Often, the combination of crude oil, condensate, and NGL reserves volumes are simply added arithmetically to provide an oil equivalent volume. This is normally satisfactory when one product dominates and the other two streams are not material in comparison. A more correct, but imperfect, method in terms of value, involves taking account of the different densities of the fluids.

Further improvement in combining crude oil, condensate, and NGL can be achieved by considering the heating equivalent of the three fluids and combining accordingly.

The correlation between the Btu heat content of crudes, condensates, fuel oils, and paraffins in Figure 9.2 is based on a combination of data from a number of sources: Katz, Table A-1, Basic data for compounds; EIA/International Energy Annual (1995); and Alaska Dept. of Natural Resources (April 1997).

有关单位与转换系数的详细内容，请参见《SI公制单位系统》与《SPE公制标准》（SPE，Richardson，1984）以及第6章的第6.6节。

9.10.2 液烃的油当量转换

监管披露规则通常规定，液烃与天然气储量应分别报告，“液”是指原油、凝析油、天然气液的合称。对于公司内部报告和常规公司之间的分析，若将原油、凝析油、天然气液和天然气体积数量汇并为油当量，就可方便地进行对比。

通常，原油、凝析油和天然气液储量可进行简单的算术加合，得到油当量的数量。当其中一种产品占绝大多数而其余两种数量相对较少时，该方法通常是可行的。另一种更准确，但尚不完善的价值核算方法，是考虑不同流体的密度。

进一步完善原油、凝析油和天然气液量的汇并还可以考虑三种液体热值当量的相应加合。

图9.2为原油、凝析油、燃料油和烷烃热值含量的对比图，是基于多种来源的组合数据，包括：Katz，表A-1，化合物基础数据；EIA/国际能源年报（1995）；以及自然资源（阿拉斯加分部报告，1997年4月）。

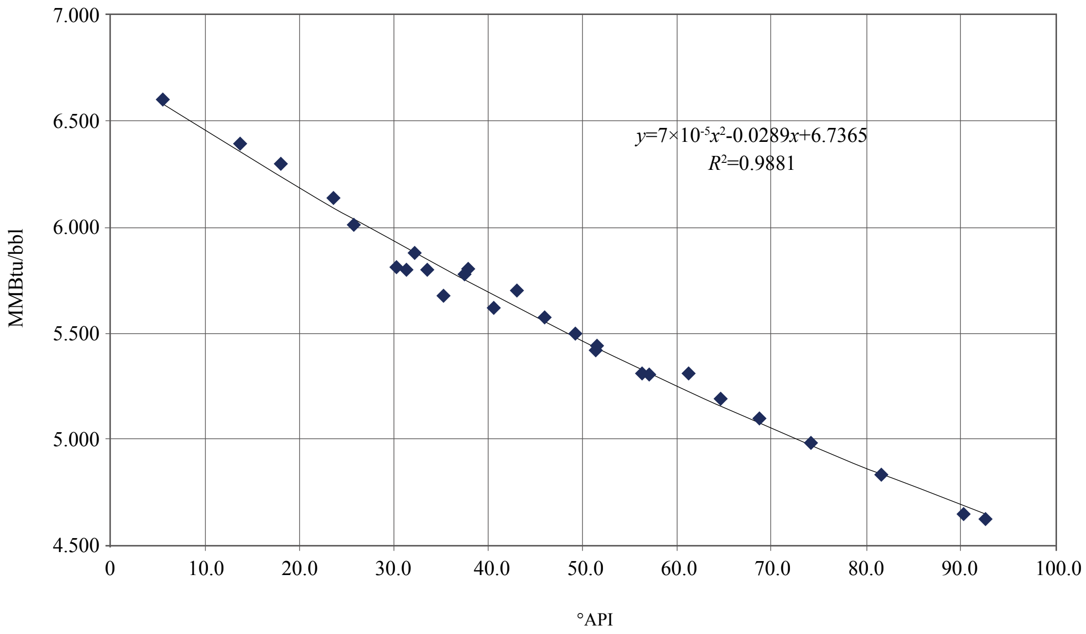

Figure 9.2—Btu content of crudes, condensates, fuel oils, and paraffins. (Graph provided through personal communication with Chapman Cronquist.)

图9.2 原油、凝析油、燃料油与烷烃的API度与热值含量关系图（Chapman Cronquist提供）

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Petroleum Resources Management System 2007. SPE, Richardson, Texas, USA.

第 10 章
CHAPTER 10

资源的份额及认定
Resources Entitlement and Recognition

Elliott Young 著， 原瑞娥 译

10.1 Foreword

This chapter is an update to Chapter 9 of *Guidelines for the Evaluation of Petroleum Reserves and Resources* published by SPE in 2001. Drawing heavily on the original text, it has been updated to reflect refinements in generally accepted industry practices commonly used when determining entitlement to production and recognizable quantities of reserves and resources under a range of agreement types and fiscal terms. It is not the intent of SPE, or the cosponsors of the Petroleum Resources Management System (PRMS) (SPE 2007), to comment on the individual disclosure regulations promulgated by specific government agencies regarding entitlement to production or the ability to report reserves. As a consequence, emphasis has been placed on principles for reserves and resources recognition under PRMS and determination of net quantities, rather than specific government regulations, financial reporting guidelines, or the classification of Reserves and Contingent Resources into the various certainty categories of PRMS.

10.2 Introduction

The ability to discover, develop, and economically produce hydrocarbons is the primary goal of the upstream petroleum industry. Aggressive competition, ever-sharpening scrutiny by the investment community, and volatility in product prices drive companies to search for attractive new exploration and producing venture opportunities that will add the greatest value for a given investment. As a consequence, contracts and agreements for these opportunities are becoming increasingly complex, further increasing the focus on the ability to recognize reserves and resources.

Production-sharing and other nontraditional agreements have become popular given the flexibility they provide host countries in tailoring fiscal terms to fit their sovereign needs while enabling contracting companies to recover their costs and achieve a desired rate of return. However, actual agreement terms, including those that relate to royalties or royalty payments, cost recovery, profit sharing, and taxes, can have a significant impact on the ability to recognize and report hydrocarbon reserves. This chapter focuses on reserves and resources recognition and reporting under the more common fiscal systems being used throughout the industry. The various types of production-sharing, service, and other types of common contracts are reviewed to illustrate their impact on recognition and reporting of oil and gas reserves and resources in the context of the PRMS framework.

Oil and gas reserves and resources are the fundamental assets of producing companies and host countries alike. They are literally the fuel that drives economic growth and prosperity. When produced and sold,

10.1 前言

本章为国际石油工程师协会（SPE）2001 年发布的《石油储量 / 资源量评估指南》第 9 章的修订版，大部分内容与原稿一致，重点根据业界广泛采用的行业实践更新了不同合同模式和财税条款下油气份额产量与储量 / 资源量认定的评估方法和披露原则。SPE 或其他《石油资源管理系统（PRMS 2007）》的协作机构并无意评论任何政府机构有关产量份额核定或储量报告资质的规则。因此，本章强调的是 PRMS 储量 / 资源量认定以及份额量确定的原则，而并非政府机构具体规定和财务披露准则，或是按 PRMS 规则将储量与条件资源量划分为不同的不确定性级别。

10.2 引言

石油行业上游业务的主要目标是发现、开发和经济生产油气资源。行业日趋激烈的竞争、向来严厉的投资监管以及起伏不定的产品价格，促使油公司寻求有吸引力的新勘探目标和在产新项目，给既定投资带来最大价值，这也造成这些投资机会所涉及的合同条款日益复杂，更加聚焦其油气储量 / 资源量的认定资格。

产品分成和其他非传统的合同模式广受欢迎，资源国可方便地定制财税条款以满足其主权需求，同时也使投资企业能够回收成本并获得期望的回报。然而，与矿费、矿费支付方式、成本回收、利润分成和各种税负相关的实际合同条款对油气储量的认定与披露有很大影响。本章重点阐述油气行业通用的常见财税制度下油气储量 / 资源量的认定与披露，也回顾了产品分成、服务合同和其他通用合同模式对 PRMS 框架下油气储量和资源量认定与披露的影响。

油气储量与资源量是油公司和资源国的重要资产，是经济增长和繁荣的推动力，当油气储量采出并销售后，可为未来的勘探开发项目提供重要资金来源。投资方高度关注资源储量存量及项

they provide the crucial funding for future exploration and development projects. With the sharpening focus of the investment community on reserves and resources inventories and the value of externally reported, project-related reserves that are added each year, many companies are reluctant to undertake a project that does not provide the opportunity to report reserves.

10.3 Regulations, Standards, and Definitions

In defining reserves, it is important to distinguish between the specific regulations that govern the reporting of reserves externally and internal company use for technical and business-planning purposes. The term “reserves” is used throughout the industry but has many different and often conflicting meanings. The explorationist may refer to the reserves of an undrilled prospect, the engineer refers to the reserves of a producing property, the financial analyst refers to the reserves of a company, and governments refer to the reserves of the country. Rarely do all these groups mean the same thing, even though they use the same term. One of the key strengths of PRMS is the framework it provides to clarify what is being referred to. In any assessment, the basis used, assumptions, and purpose for which reserves and resources are recognized and reported must be defined. Figure 10.1 summarizes the PRMS reserves and resources categories with the reserves categories that many government regulatory agencies allow in required disclosures. Figure 10.2 (SPE 1979; Martinez et al. 1987; SPEE 1998) provides a summary of the more widely recognized regulatory reporting agencies, standards, and technical definitions.

10.3.1 Host Government Regulations

Numerous national regulatory bodies have developed regulations and standards for reporting oil and gas reserves within their respective countries (Martinez et al. 1987; SEC Guidelines, Rules, and Regulations 1993; FASB 1977; APPEA 1995; UK Oil Industry Accounting Committee 1991; Johnston 1994). These standards provide detailed descriptions of the categories of reserves to be reported, required supporting information, and the format to be used for the disclosures. However, these standards and regulations do not generally provide much guidance on the type or extent of rights to the underlying resource or production that is required for reporting. For some unique types of agreements, it may not be clear whether a company is even entitled to report the related reserves. This is particularly the case with agreements in which reserve ownership and control resides, by law, with the host country rather than with the contracting party. Analysis of the key elements and fiscal terms of these contracts and comparison to those in more widespread use is a good approach to determine whether reserves and resources can be recognized and subsequently reported.

目储量不断增长的披露价值，许多油公司不愿承接不能披露储量的项目。

10.3 规定、标准和定义

定义储量时，要注重区分储量对外披露的监管规定和公司技术与业务规划所用的内部规范。“储量”一词的使用贯穿着整个油气行业，有许多不同的、往往相互冲突的含义。勘探家可能认为储量应为未钻井目标区所蕴藏的油气量，工程师认为储量应指正生产合同区即将采出的油气量，财务分析师认为储量为公司资产，而政府部门认为的储量应为国家的资源，尽管所使用的术语相同，但含义很少一致。PRMS 主要优势就是其分级分类框架澄清了储量所代表的含义。在所有评估中，都必须明确储量和资源量认定与披露所采用的基本原则、假设条件和目的。图 10.1 汇总了 PRMS 各级别储量与条件资源量，其中各级储量是许多政府监管机构允许披露的。图 10.2（SPE，1979；Martinez 等，1987；SPEE，1998）汇总了广泛认可的披露监管机构、标准与技术定义。

10.3.1 资源国政府规章制度

许多国家的政府监管机构制定了其境内的油气储量报告登记的规定与标准（Martinez 等，1987；SEC 指南、规则和规定，1993；美国财务会计准则委员会，1977；APPEA，1995；英国石油行业会计委员会，1991；Johnston，1994），这些标准对要披露的储量级别、所需基础支持信息以及具体填报格式做了详细说明。然而，这些标准和规定通常并不会对资源量或产量的披露权限提供更多指导性意见，根据法律，一些特殊合同模式的油气储量所有权和控制权属于资源国，而不属于合同方，油公司并不确定是否拥有储量披露权。分析合同要素和财税条款并与广泛应用的合同进行对比，是确定是否可认定和随后披露储量与资源量的好办法。

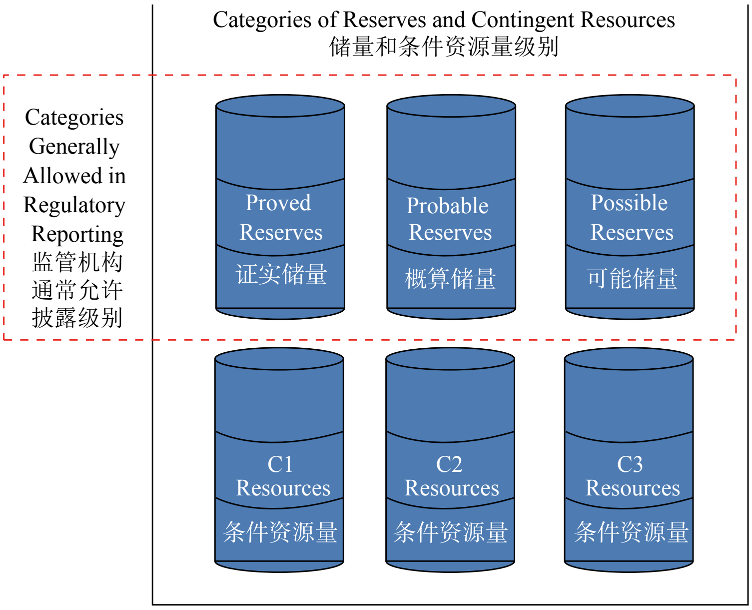


Figure 10.1 PRMS Classification Categories
图 10.1 PRMS 级别划分

■Regulatory Reporting 监管机构披露规则

- US Securities and Exchange Commission
  美国证券交易委员会
- US Financial Accounting Standards Board
  美国财务会计准则委员会
- International Accounting Standards Board
  国际会计准则委员会
- UK Accounting Standards Board
  英国会计准则委员会
- Australian Securities Exchange
  澳大利亚证券交易所
- Canadian Securities Administrators
  加拿大证券管理委员会
- China Petroleum Reserves Office
  中国石油储量办公室
- Norwegian Petroleum Directorate
  挪威石油理事会

■Technical 技术体系

- SPE/WPC/AAPG/SPEE PRMS
  石油资源管理系统(SPE/WPC/AAPG/SPEE)
- United Nations Classification Framework
  联合国资源分类框架
- Host Country Technical Definitions
  资源国技术定义

Figure 10.2 Regulations, Standards, and Definitions
图 10.2 储量监管机构、标准和术语定义

PRMS recognizes the concept of an economic interest as the basis for recognizing and reporting reserves and resources. To determine when an economic interest exists, many companies have referred to the SEC Section S-X, Rule 4-10b, "Successful Efforts Method" (US SEC 1993) [or Financial Accounting Standard 19 (FASB 1977)]. While Rule 4-10b was revised in the 2008 SEC rule modernization, the fundamental principles contained in the definition of a mineral interest provide a very useful framework and criteria for establishing when an interest in a property exists and guidance on when reserves and resources can be recognized under PRMS and government regulations:

SEC Section S-X, Rule 4-10b Successful Efforts Method:

Mineral Interests in Properties. Including:

(1) a fee ownership or lease, concession or other interest representing the right to extract oil or gas subject to such terms as may be imposed by the conveyance of that interest;

(2) royalty interests, production payments payable in oil or gas, and other nonoperating interests in properties operated by others; and

(3) those agreements with foreign governments or authorities under which a reporting entity participates in the operation of the related properties or otherwise serves as producer of the underlying reserves (as opposed to being an independent purchaser, broker, dealer or importer). Properties do not include other supply agreements or contracts that represent the right to purchase, rather than extract, oil and gas.

PRMS 认可经济权益（Economic Interest）的概念，并将其作为油气储量 / 资源量认定与披露的依据。为了确定是否拥有油气经济权益，许多油公司均参照 SEC 第 S-X 节第 4-10b 条款“成果法”(美国 SEC 1993)（或财会标准第 19 条 (FASB 1977）。第 4-10b 条款在 2008 年的《SEC 油气披露最新规定》进行了修订，其矿产权益定义中包含的基本原则为界定资产权益和指导 PRMS 和政府规则下油气储量 / 资源量认定提供了非常有用的框架和条件标准。

SEC 第 S-X 节第 4-10b 条款“成果法”中，合同区油气资产的矿产权益包括：

（1）拥有获得油气收益的所有权或租赁权、租让权或其他按照权益转让条款规定的体现油气开采权利的权益；

（2）矿费权益、油气产量支付以及在其他方作业的资产中拥有的非作业者权益；

（3）根据与外国政府和权威机构签署的协议，披露实体参与相关油气资产的经营或承担地下储量的开发（不同于作为独立购买者、经纪人、经销商或进口商的情形）。其他体现购买权而不是油气开采权的供应协议或合同不能包含在披露资产中。

10.4 Reserves and Resources Recognition

Regulation SEC Section S-X, Rule 4-10b can be summarized into elements that support and establish an economic interest and the ability to recognize reserves and resources. These include the following:

(1) The right to extract oil or gas

(2) The right to take produced volumes in kind or share in the proceeds from their sale

(3) Exposure to market risk and technical risk

(4) The opportunity for reward through participation in producing activities

In addition, the regulation establishes specific elements that do not support an economic interest and preclude the recognition of reserves and resources. These include the following:

(1) Participation that is limited only to the right to purchase volumes

(2) Supply or brokerage arrangements

(3) Agreements for services or funding that do not contain aspects of risk and reward or convey an interest in the minerals

Note that the US Financial Accounting Standards Board (Topic 932) permits reporting of Proved Reserves received under long-term supply agreements with governments, provided that the enterprise wishing to report the reserves participates in the operation or otherwise serves as the operator. Applying PRMS to this type of agreement, recoverable amounts could be classified as Reserves and/or Resources depending on project maturity and technical certainty.

The right to extract hydrocarbons and the exposure to elements of risk and the opportunity for reward are key elements that provide the basis for recognizing reserves and resources. Many companies use these elements to differentiate between agreements that would allow reserves to be recognized and reported to regulatory agencies from those purely for services that would not allow recognition of reserves and resources. Risks and rewards associated with oil and gas production activities stem primarily from the variation in revenues from technical and economic risks. Technical risk affects a company's ability to physically extract and recover hydrocarbons, and is usually dependent on a number of technical parameters. Economic risk is a function of the success of a project and is critically dependent on the ability to economically recover the in-place hydrocarbons. It is highly dependent on the economic environment over the life of the project and fluctuates with the prevailing price and cost structures. It should be noted that risk associated with variations in operating cost alone is not generally sufficient to fulfill the requirements of risk and reward and allow reserves to be reported. It should also be noted that the ability or obligation to report reserves to regulatory agencies does not necessarily imply ownership of the underlying resources.

10.4 储量与资源量的认定

根据 SEC 第 S-X 节第 4-10b 条款，可以把判别能否获得经济权益和认定储量 / 资源量资格的要素归纳为下列几点：

(1) 拥有开采油气的权利；

(2) 能够获得实物产量或油气销售收益分成的权利；

(3) 承担市场风险和技术风险；

(4) 通过参与生产活动有机会获得回报。

此外，4-10b 条款还指出下列情况不支持获得经济权益和认定储量和资源量：

(1) 参与权仅限于购买产量；

(2) 供应或佣金协议；

(3) 服务或融资协议，不涉及风险及回报，或矿产权益转让。

请注意，美国财务会计准则委员会（议题 932）允许愿披露储量的企业在参与经营或担任作业者的情形下，可披露其与政府所签长期供应协议所获得的证实储量。根据 PRMS，此类协议可根据项目成熟度和技术确定性将可采量划分为储量和 / 或资源量。

拥有油气开采的权利、承担风险以及有机会获得回报是储量 / 资源量认定的 3 个关键要素，许多公司利用这些要素来区分哪些协议允许储量 / 资源量的认定，并上报监管机构；哪些是纯服务性的协议，没有储量和资源量披露和认定的权利。与油气生产活动相关的风险和回报主要源于技术和经济风险导致的收益变化。技术风险通常取决于一系列技术参数，影响公司开采油气的实际技术能力；经济风险是项目成功率的函数，并主要取决于经济开采地下油气的能力。经济风险在很大程度上依赖于项目生命期内的经济环境，并随市场价格和成本构成的变化而波动。应当指出的是，仅与操作成本变化相关的风险通常不能满足风险与回报要求，因而也不允许披露储量。应注意，有权利或义务向监管机构披露储量并不意味着拥有地下资源。

10.4.1 Taxes and Reserves

In general, net working interest reserves and resources are recognized in situations where there is an economic interest, and after deduction for any royalty owed to others. Production sharing or other types of operating agreements lay out the conditions and formulas for calculating the share of produced volumes to which a contracting company will be entitled. These volumes are normally divided into cost recovery and profit volume components. The summation of the cost and profit volumes that the contractor will receive through the term of the contract represents the reserves and resources that the contractor is entitled to. In many instances, these agreements may also contain clauses that provide that host country income taxes will be paid by the government or the national oil company on behalf of the contractor. While details on the specific hydrocarbons produced and revenues that are used to fund the payments are not usually specified in the agreement, they are inferred to come from the government's share of production. By virtue of the economic interest that the contractor has in these additional volumes, common practice is to include the related quantities in the contractor's share. This also typically requires reporting of the value related to the tax payment that is received in the financial reporting statements.

10.4.2 Royalties and Reserves

Royalties are typically paid to the owner of the mineral rights in exchange for the granting of the rights to extract and produce hydrocarbons. Royalties are a form of a nonoperating interest in the underlying hydrocarbons that is free and clear of all exploration, development, and operating costs. They are generally a fixed percentage or may have some form of a sliding scale basis. Royalty volumes that are payable either in-kind or in monetary terms to the owner of the mineral rights are normally excluded from net reserves and resources. However, in many agreements and/or fiscal systems, the wording that describes this obligation may be in the language of the host country and may not translate well into English. As a consequence, the defined payments or obligation may, in reality, be an additional form of tax. While there are no published standards to differentiate between royalties and taxes, examination of the specific attributes and the intent of the payment or obligation in comparison to other established and recognized royalties and taxes is one approach often used to make the distinction. For example, if the obligation is based on project profitability rather than a defined interest, or costs are deductible from the obligation, an argument can be made that the obligation has attributes of a tax rather than a royalty. Where the payment is concluded to be a tax, the related reserves and resources are included in amounts recognized by the contractor.

10.4.3 Mineral Property Conveyances

A mineral interest in a property may be conveyed to others to spread risks, to obtain financing, to improve operating efficiency, or

10.4.1 税负和储量

通常，在拥有经济权益的情况下，净工作权益储量/资源量可在扣减应付其他各方矿费后进行认定。产品分成合同和其他类型经营合同模式规定了合同方计算产量份额的条件和公式，份额产量通常由成本油和利润油两部分构成。合同者在整个合同期内所获得的成本油和利润油之和即为其油气储量/资源量的份额。在许多情况下，这些合同也可能包含这样的条款，合同者在资源国的所得税由资源国政府或国家油公司以合同者的名义代缴。通常，协议中不会明确指出代缴税的资金出自哪部分产量和收入，可推测其取自资源国政府的产量分成。鉴于合同者拥有这些额外油气量的经济权益，通常做法是将税负相应量计入合同者份额储量/资源量中。一般也要求在财务报表中披露得到的税负对应的价值。

10.4.2 矿费和储量

矿费通常支付给矿权所有者，以换取油气开采和生产的权利。矿费是一种对于地下油气的非作业权益，与所有的勘探、开发和操作成本无关，矿费费率通常是一个固定的百分比或滑动比例。矿费可以以实物或货币形式支付给矿权所有者，往往不包含在份额储量/资源量中。然而，在许多合同和/或财税制度中，矿费义务可能是用资源国语言表述，未能准确译为英文，结果该费用或义务可能在现实中就被视作了另外一种税负的形式。虽然目前尚无公开颁布的标准区分矿费和税负，但通常采用的做法是通过与其他已经确立、认可的矿费及税负进行对比，分析其具体属性和支出目的，从而确定费用的类别。例如，若该义务费用是基于项目利润而不是规定的利率或者成本可以在该义务费用中抵扣，那么有理由说该费用的性质属于税负而非矿费。当支出费用为税负时，相应的储量/资源量计入合同者的份额量。

10.4.3 矿产转让

油气资产的矿产权益可以转让给他人，从而达到分担风险、融资、提升经营效率、享受税负优惠等目的。有一些类型的转让实质上是融资协议或贷款，并不涉及储量/资源量认定或披露权。

for tax benefits. Some types of conveyances are essentially financial arrangements or loans and do not carry with them the ability to recognize or report reserves or resources. Other forms may involve the transfer of all or a part of the rights and responsibilities of operating a property or an operating interest and the ability to recognize reserves or resources. While intended for US SEC reserves reporting, the following text from the US Financial Accounting Standards Board, Standard 19 (FASB 1977), (paragraph 47a) provides useful guidance on when reserves and resources may be recognized in PRMS categories.

Other transactions convey a mineral interest and may be used for the recognition and reporting of oil and gas reserves. These types of conveyances differ from those described above in that the seller's obligation is not expressed in monetary terms but as an obligation to deliver, free and clear of all expenses associated with operation of the property, a specified quantity of oil or gas to the purchaser out of a specified share of future production. Such a transaction is a sale of a mineral interest for which the seller has a substantial obligation for future performance. The purchaser of such a production payment has acquired an interest in a mineral property that shall be recorded at cost and amortized by the unit-of-production method as delivery takes place. The related reserves estimates and production shall be reported as those of the purchaser of the production payment and not of the seller.

If an agreement satisfies the requirements of FASB Standard 19, Paragraph 47a, the purchaser of a production payment is able to recognize the related reserves and resources and would be permitted to externally report the related reserves per applicable regulatory agency regulations. However, if the agreement is purely a financial arrangement or loan, the purchaser would not be able to recognize reserves and resources or report them externally. Production payments have been widely used as a hedging vehicle in periods of price volatility.

10.5 Agreements and Contracts

Agreements and contracts cover a wide spectrum of fiscal and contractual terms established by host countries to best meet their sovereign needs. Currently, there is no consistent industry approach or established practice for determining when reserves or resources can be recognized under the wide variety of these contracts. The purpose of this section is to expand on the text contained in PRMS 3.3.2 by providing more detailed information for the various agreement types noted and to promote consistency in the recognition of reserves and resources under them. The focus is on the specific elements of the agreements that enable recognition of reserves and resources but not on the classification into specific PRMS certainty categories.

This section follows the classification system template proposed by Johnston (Johnston 1994; Johnston 1995; McMichael and Young 1997) as shown in Figure 10.3. This template has also been expanded to include three additional types of agreements: purchase agreements, loan

还有一些类型的转让可能是转让全部或部分矿产的经营权与责任或作业权益，同时储量 / 资源量的认定资格也被转让。下面摘自美国财务会计准则委员会第 19 号准则（FASB，1977）第 47a 段的文字，虽用于美国 SEC 储量信息披露，但对储量和资源量何时可按 PRMS 的级别进行认定给出了有用的指导意见。

“其他转让矿产权益的交易，可用于油气储量的认定和披露。这类转让与前面提及的不同点是，出让方的义务不以货币形式体现，但作为义务，出让方从未来产量的具体分成中，交付给受让方一定数量的油气，这些油气与所有作业成本无关。这样的交易实际是矿权出售，出让方应对其未来经营状况负实质性责任。一旦产量支付交易成功，受让方即收购资产的矿产权益，须将费用记录在案，并以产储法进行折旧摊销。相应的储量和产量应由产量支付交易的受让方披露，而不是出让方。”

如果协议满足美国财务会计准则委员会（FASB）第 19 号准则第 47a 段的要求，产量支付交易的受让方可以认定相应的储量 / 资源量，并允许根据监管机构的适用规定对外披露相关储量和资源量。但是，如果该协议仅限于融资协议或贷款，受让方则不能认定和对外披露储量和资源量。在价格波动时期，产量支付已成为人们广泛采用的一种套期保值工具。

10.5 协议与合同

油气合作协议与合同涉及各种各样财税与合同条款，资源国制定这些条款是为了最大程度地满足其主权需求。当前，对各种合同模式下储量或资源量的认定，行业尚无统一做法或惯例。本节旨在补充 PRMS 第 3.3.2 节的相关内容，为提及的各种合同模式提供更详细的说明，并促进其储量和资源量认定的一致性。讨论重点是协议所涉及的储量 / 资源量认定关键要素，而不是按 PRMS 划分不确定性级别。

本节介绍了 Johnston（Johnston，1994；Johnston，1995；McMichael 和 Young，1997）提出的油气财税制度分类模板（图 10.3）。该模板进一步扩展增加了 3 类协议模式：采购协议、贷

agreements, and production payments and conveyances. The expanded template of agreement types along with their ranking in terms of the ability to recognize reserves and resources and report them to regulatory agencies is shown in Figure 10.4 (McMichael and Young 1997). Key aspects of each type of agreement are summarized in Table 10.1 (McMichael and Young 1997).

款协议以及产量支付与转让。将扩展的协议模式按储量与资源量认定和向监管机构报告的资格排序，结果如图10.4所示（McMichael 和 Young，1997）。表10.1总结了每种协议的关键特点（McMichael 和 Young，1997）。

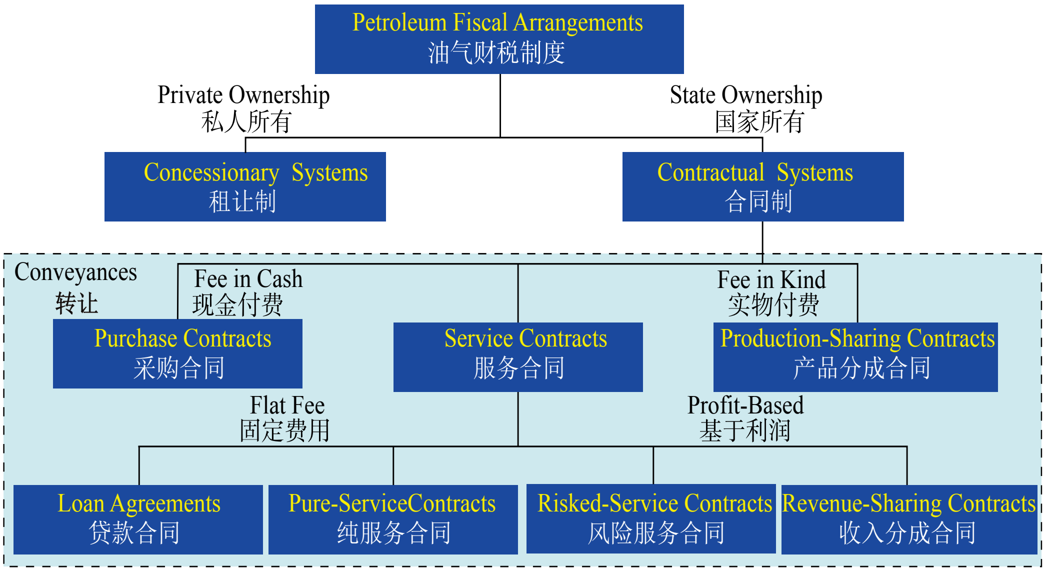


Figure 10.3 Classification of Petroleum Fiscal Systems
图 10.3 油气财税制度分类图

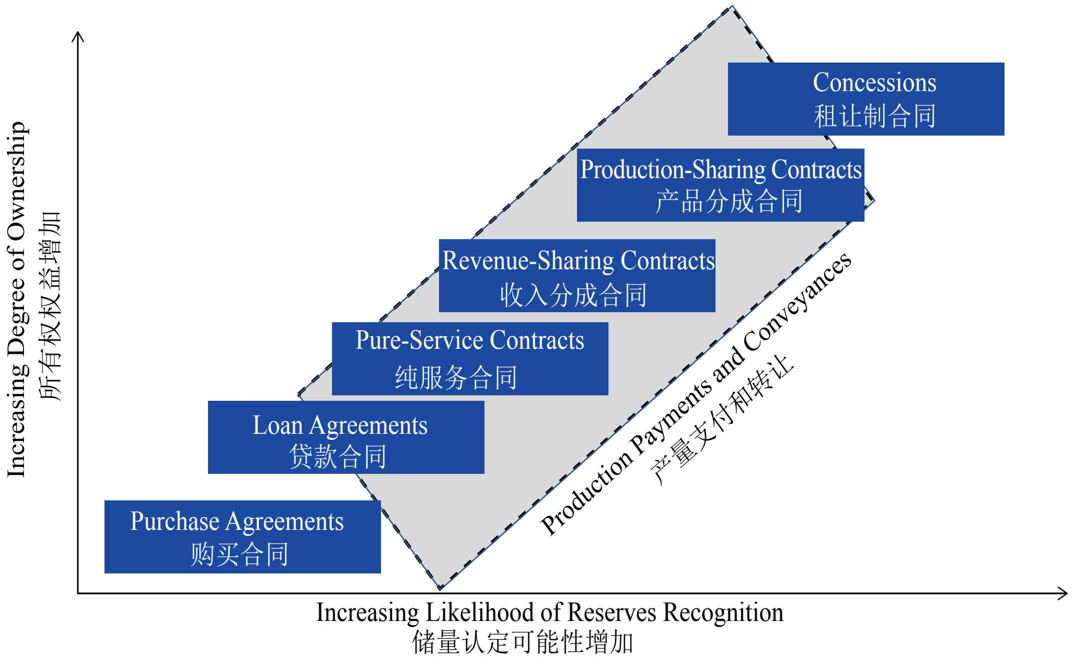


Figure 10.4 Spectrum of Petroleum Fiscal Systms
图 10.4 不同财税制度属性特点变化情况

Table 10.1 Contract Summary
表 10.1 合同类型汇总表

Contract Type 合同类型	Ownership 所有权	Payment 支付方式	Reserves 储量
Concession 租让制合同	Contractor 合同者	In-Kind 实物	Yes 是
Production Share 产品分成合同	Contractor (When Produced) 合同者（投产时）	In-Kind 实物	Yes 是
Revenue Share 收入分成合同	Government 政府	Share of Revenue 收入分成	Yes 是
Risked Service 风险服务合同	Government 政府	Fee-Based 基于报酬费	Likely 可能
Pure Service 纯服务合同	Government 政府	Fee-Based 基于报酬费	No 否
Purchase 采购合同	Government 政府	Product Cost 生产成本	No 否
Loan 借贷合同	Government 政府	Interest 利息	No 否
Conveyance 转让合同	Government 政府	Production Payment 产量支付	Likely 可能

10.5.1 Concessions, Mineral Leases, and Permits

Historically, leases and concessions have been the most commonly used agreements between oil companies and governments or mineral owners. In such agreements, the host government or mineral owner grants the producing company the right to explore for, develop, produce, transport, and market hydrocarbons or minerals within a fixed area for a specific amount of time. The production and sale of hydrocarbons from the concession are then typically subject to rentals, royalties, bonuses, and taxes. Under these types of agreements, the company typically bears all risks and costs for exploration, development, and production and generally would hold title to all resources that will be produced while the agreement is in effect. Reserves consistent with the net working interest (after deduction of any royalties owned by others) that can be recovered during the term of the agreement are typically recognized by the upstream contractor. Ownership of the reserves producible over the

10.5.1 租让合同、矿产租赁合同和许可证

历史上，租赁和租让合同是油公司与资源国政府或矿产主之间最常用的协议类型。在这种协议中，资源国政府或矿产主授予油公司在规定时间段内固定区域的勘探、开发、生产、运输和销售油气或者矿产的权利。租让区油气的生产和销售通常用来支付地租、矿费、红利和税负。在这种协议下，油公司承担油气勘探、开发和生产中的所有风险和成本，并在合同期内对采出的所有油气量拥有所有权。通常由从事上游业务合同者将合同期内可采量认定为储量，并与净工作权益保持一致（需扣减其他各方拥有的所有矿费）。正常情况下，油公司享有协议期内可采储量的所有权。但是，据 PRMS 第 3.3.3 节表述，合同期

term of the agreement is normally taken by the company. However, as described in PRMS 3.3.3, volumes recoverable after the term of the contract would normally be classified as resources and be contingent on the successful negotiation of an agreement extension. If the contract contained provisions for extension and the likelihood of extension was judged to be reasonably certain, additional reserves would likely be recognized for the length of the extension period, provided requirements for project commitment and funding were satisfied.

10.5.2 Production-Sharing Contracts

In a production-sharing agreement between a contractor and a host government, the contractor typically bears all risks and costs for exploration, development, and production. In return, if exploration is successful, the contractor is given the opportunity to recover the investment from production (cost hydrocarbons), subject to specific limits and terms. The contractor also receives a stipulated share of the production remaining after cost recovery (profit hydrocarbons). Ownership of the underlying resource is almost always retained by the host government. However, the contractor normally receives title to the prescribed share of the volumes as they are produced. Subject to technical certainty, reserves in one or more of the PRMS categories based on cost recovery plus a profit element for hydrocarbons that are recoverable under the terms of the contract are typically recognized by the contractor. Resources may also be recognized for future development phases where project maturity is not sufficiently advanced or for possible extensions to the contract term where this would not be a matter of course.

Under a production-sharing contract, the contractor’s entitlement to production generally decreases with increasing prices because a smaller share of production is required to recover investments and costs. These agreements commonly contain terms that reduce entitlement as production rate (production tranches) and/or cumulative production increases (“R” factors). Figure 10.5 is a schematic indicating the distribution of yearly project production between contractor and government. As in the case of a concession, volumes recoverable after the term of the contract would normally be classified as Resources unless the contract contained provisions for extension and there was continued commitment to the project.

10.5.3 Revenue-Sharing/Risked-Service Contracts

Revenue-sharing contracts are very similar to the production-sharing contracts described earlier, with the exception of contractor remuneration. With a risked-service contract, the contractor usually

结束之后可采量正常情况下应划归为资源量，取决于合同延期谈判是否成功。若合同含有延期条款，而延期的可能性是合理确定的，那么在项目承诺和资金到位的情况下，合同延期后可采量有可能认定为储量。

10.5.2 产品分成合同

在合同者和资源国政府间签订的产品分成合同中，通常，由合同者承担油气勘探、开发和生产中所有的风险和成本。作为回报，如果勘探成功，合同者将有机会根据具体的限制条款从产量中回收投资（成本油）。在成本回收之后，合同者还可对扣减成本油后剩余的产量（利润油）按规定进行分成。资源国政府总是拥有油气资源所有权，但合同者通常有权获得合同期内规定的产量分成。根据勘探开发技术的确定性程度，合同者通常可以认定 PRMS 标准的各级份额储量；份额量大小是按照合同条款计算的成本油加上利润油得到的。当项目成熟度不够或者合同延期并非理所当然的情况下，未来开发阶段估算的可采量可认定为资源量。

在产品分成合同下，合同者的份额产量一般会随着价格的上涨而降低，因为需要更少的份额产量即可回收投资和成本。随着产量（各阶段产量）和 / 或累计产量（R 因子）的增加，协议中往往有降低合同者份额的条款，参见合同者与资源国政府项目年度产量分配流程示意图（图 10.5）。与租让制合同一致，合同期之后的可采量通常被归为资源量，除非合同包括延期条款，且项目承诺继续投资开发。

10.5.3 收入分成合同 / 风险服务合同

除了合同者报酬费外，收入分成合同与之前所述的产品分成合同非常相似。在风险服务合同中，合同者通常得到的是规定的油气收入分成而

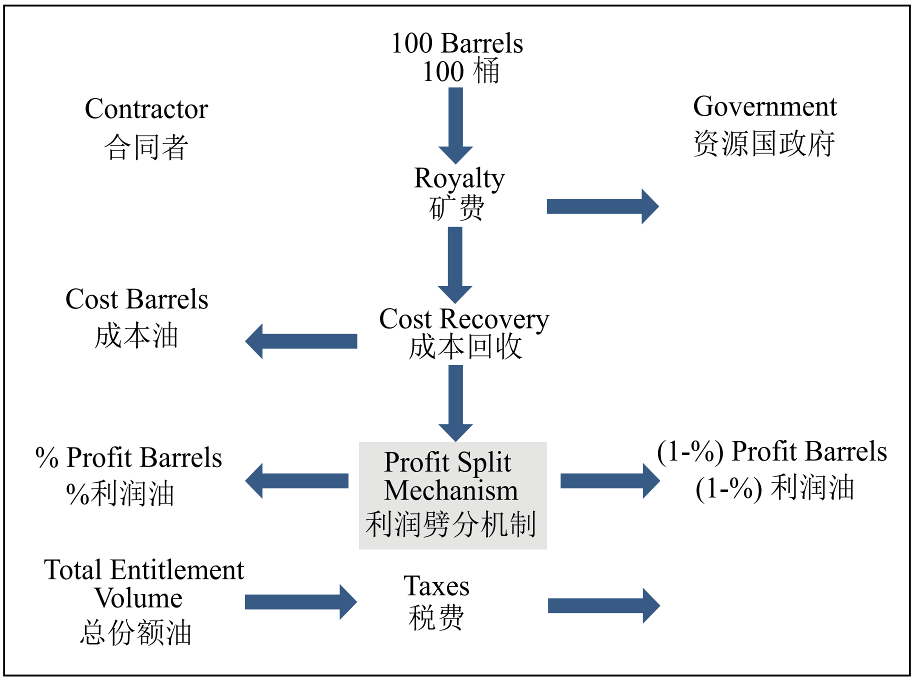


Figure 10.5　Example Production-Sharing Contract
图 10.5　产品分成合同年度产量分配示意图

receives a defined share of revenue rather than a share of the production. The contractor has an economic or revenue interest in the production and hence can recognize reserves and resources. As in the production-sharing contract, the contractor provides the capital and technical expertise required for exploration and development. If exploration efforts are successful, the contractor can recover those costs from sales revenues. Also similar to a production-sharing contract, resources may be recognized for future development phases or possible extensions to the contract term.

Figure 10.6 is a schematic of the distribution of yearly project revenue between contractor and government. This type of agreement is also often used where the contracting party provides expertise and capital to rehabilitate or institute improved recovery operations in an existing field and has rights and obligations and bears risks similar to those in the previously noted agreement types.

Reserves and resources recognized under PRMS and those reported to regulatory agencies would be based on the economic interest held or the financial benefit received, as shown in Figure 10.7. Depending on the specific contractual terms, the reserves and resources equivalent to the value of the cost-recovery-plus-revenue-profit split are normally reported by the contractor.

不是实物产量的分成。由于合同者拥有产量的经济权益或收入权益，因此可以认定储量 / 资源量。与产品分成合同相似，合同者承担勘探和开发所需的资金和专业技术。如果勘探成功，合同者可从产品销售收入中回收已支付成本。与产品分成合同类似，未来的开发期或可能的合同延期可认定为资源量。

图 10.6 所示为合同者和资源国政府之间的项目年度收入分配示意图，这种类型的合同也常用于合同方为现有油田复产或提高采收率项目提供资金和技术支撑，同时具有与前述其他协议类型相似的权利和义务并承担风险。

PRMS 储量和资源量的认定和提交监管机构的披露数据应该基于拥有的经济权益或获得的经济收益，如图 10.7 所示。根据具体合同条款，与成本回收和利润分成价值之和相对应的储量 / 资源量，一般由合同者披露。

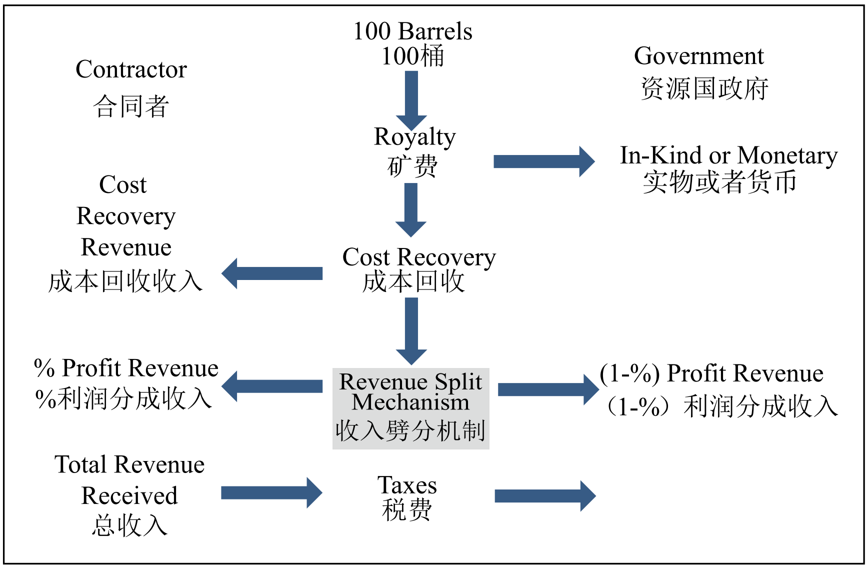


Figure 10.6　Example Revenue-Sharing Contract
图 10.6　收入分成合同年度收入分配示意图

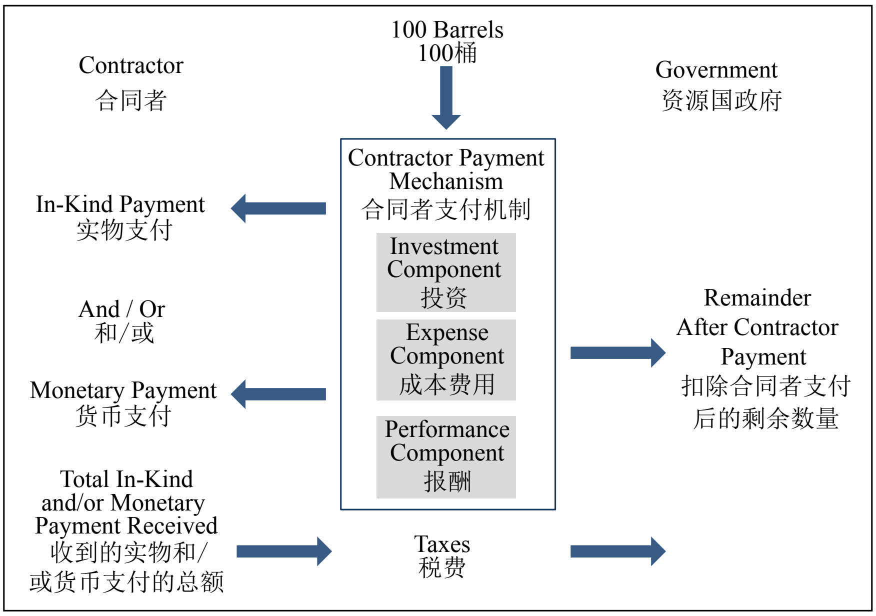


Figure 10.7　Example Risked-Service Contract
图 10.7　风险服务合同年度收入分配示意图

10.5.4 Pure-Service Contracts

A pure-service contract is an agreement between a contractor and a host government that typically covers a defined technical service to be provided or completed during a specific period of time. The service company investment is typically limited to the value of equipment, tools, and personnel used to perform the service. In most cases, the service contractor's reimbursement is fixed by the terms of the contract with little exposure to either project performance or market factors. Payment for services is normally based on daily or hourly rates, a fixed

10.5.4 纯服务合同

纯服务合同通常是合同者与资源国政府之间关于指定时期提供或完成规定技术服务所签订的一种协议。服务公司的投资一般仅限于用来履行规定服务的设备、工具和执行业务的人员费用。在多数情况下，服务承包商的报酬按合同条款是固定的，很少受到项目执行情况或市场因素的影响。通常，服务酬金按日费率或者小时费率、固

turnkey rate, or some other specified amount. Payments may be made at specified intervals or at the completion of the service. Payments, in some cases, may be tied to the field performance, operating cost reductions, or other important metrics. In many cases, payments are made from government general revenue accounts to avoid a direct linkage with field operations.

Risks of the service company under this type of contract are usually limited to nonrecoverable cost overruns, losses owing to client breach of contract, default, or contract dispute. These agreements generally do not normally have exposure to production volume or market price; consequently, reserves and resources are not usually recognized under this type of agreement. The service company may, however, have an obligation to report gross (total working interest basis) reserves and resources to the host countries' regulatory agencies. Figure 10.8 is a schematic of the distribution of yearly project revenue between contractor and government.

定总包费率或者其他商定方式计费，酬金的支付可以在指定时间或服务业务完成时。有时，酬金可绑定油气田生产情况、操作成本减少量（与预期相比）或者其他一些重要指标。许多情况下，支付给服务商的酬劳往往来自政府的总收入，以避免与油田的经营直接关联。

服务公司在这种类型的合同中承担的风险通常仅限于不可回收的超支成本、由客户违约造成的损失、违约金或者合同纠纷方面。此类协议一般不受产量或市场价格的影响，因此，在这种合同类型下，合同者通常不能认定储量 / 资源量。尽管如此，服务公司可能仍然有义务向资源国监管机构上报项目总储量 / 资源量（基于总工作权益）。图 10.8 是项目年度收入在合同者和政府之间的分配示意图。

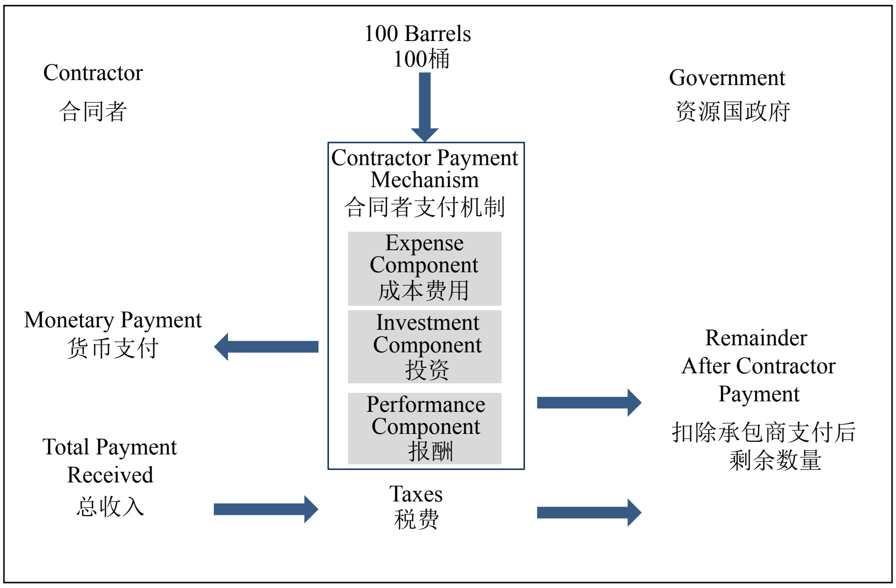


Figure 10.8　Example Pure-Service Contract
图 10.8　纯服务合同示例

10.5.5 Loan Agreements

A loan agreement is typically used by a bank, other financial investor, or partner to finance all or part of an oil and gas project. Compensation for funds advanced is typically limited to a specified interest rate. The lender does not participate in profits earned by the project above this interest rate. There is normally a fixed repayment schedule for the amount advanced, and repayment of the obligation is usually made before any return to equity investors. Risk is limited

10.5.5 贷款协议

贷款协议一般指为油气项目筹措全部或部分资金而同银行、其他金融投资者或合作伙伴签订的协议。贷款资金的偿还通常只限于规定利率，贷方不参与利息之外的项目利润分成。正常情况下，贷款的偿还是按固定时间表，权益投资者通常在获得回报之前履行偿还义务。风险仅限于借

to default of the borrower or failure of the project. Variations in production, market prices, and sales do not normally affect compensation. Reserves and resources would not be recognized in any PRMS categories by the lender under this type of agreement.

10.5.6 Production Loans, Forward Sales, and Similar Arrangements

There are a variety of forms of transactions that involve the advance of funds to the owner of an interest in an oil and gas property in exchange for the right to receive the cash proceeds of production, or the production itself, arising from the future operation of the property. In such transactions, the owner almost invariably has a future performance obligation, the outcome of which is uncertain to some degree. Determination of whether the transaction represents a sale or financing rests on the particular circumstances of each case.

If the risks associated with future production, particularly those related to ultimate recovery and price, remain primarily with the owner, the transaction should be accounted for as financing or contingent financing. In such circumstances, the repayment obligation will normally be defined in monetary terms and would not enable recognition of reserves and resources under PRMS. If the risks associated with future production, particularly those related to ultimate recovery and price, rest primarily with the purchaser, the transaction should be accounted for either as a contingent sale or as a disposal of fixed assets. Reserves and resources would be recognized under PRMS by the purchaser. The ability to report reserves to applicable government agencies may be permissible; however, the specific accounting standards for the jurisdiction should be consulted for appropriate treatment.

10.5.7 Carried Interests

A carried interest is an agreement under which one party (the carrying party) agrees to pay for a portion or all of the preproduction costs of another party (the carried party) on a license in which both own a portion of the working interest. This arises when the carried party is either unwilling to bear the risk of exploration or is unable to fund the cost of exploration or development directly. Owners may enter into carried-interest arrangements with existing or incoming joint venture partners at the exploration stage, the development stage, or both.

If the property becomes productive, then the carrying party will be reimbursed either (a) in cash out of the proceeds of the share of production attributable to the carried party or (b) by receiving a disproportionately high share of the production until the carried costs

贷方的违约或者项目的失败。产量、市场价格和销售的变化一般不影响贷款的偿还。在这类协议中，贷方不能认定 PRMS 任何级别的储量与资源量。

10.5.6 生产贷款、远期销售及类似协议

现实中存在各种交易形式，可通过向油气合同区资产权益所有者预付资金，获取其未来运营产量的现金收益或实物产量的权利。此类交易中，油气权益所有者总是对未来负有经营义务，但经营成效具有一定的不确定性。该交易是出售还是融资取决于交易的具体情况。

如果矿权所有者承担与未来生产有关的风险，特别是与最终可采量及价格有关的风险，这类交易应认作融资 / 或有融资。在这种情况下，还款义务通常以货币的形式体现，不能认定 PRMS 储量和资源量。如果受让方承担与未来生产有关的风险，特别是与最终可采量及价格有关的风险，则此类交易为或有销售或者固定资产的处置，受让方则可认定 PRMS 储量和资源量，允许向有关政府机构上报储量，但应咨询相关的具体会计准则。

10.5.7 干股权益

干股权益是一种协议，按照该协议，在双方均拥有工作权益的矿权区，合同一方（义务承担方）同意替另一方（义务转出方）支付一部分或全部的投产前成本费用。此类协议通常发生在义务转出方不愿承担勘探风险，或者无法直接支付勘探与开发费用的情况。矿权主可在勘探阶段、开发阶段或勘探开发两个阶段与现有或者即将合作的伙伴方签署干股协议。

如果油气资产商业性投产，义务承担方可通过以下两种方式得到补偿：（1）从义务转出方的油气份额产量收益中获得现金补偿；（2）义务承担方获取不成比例的高份额产量，直至垫付

have been recovered. The carrying party normally recognizes the additional production received in one or more of the PRMS reserves categories. If project maturity is not sufficient to classify the amounts as Reserves, the PRMS resources categories would be used according to the agreed reimbursement terms.

10.5.8 Purchase Contracts

A contract to purchase oil and gas provides the right to purchase a specified volume at an agreed price for a defined term. Under purchase contracts, exposure to technical and market risks are borne by the seller. While a purchase or supply contract can provide long-term access to reserves and resources through production, it does not convey the right to extract, nor does it convey a financial interest in the reserves. Consequently, reserves and resources would not be recognized under PRMS for this type of agreement.

10.5.9 Production Payments and Conveyances

In addition to the contracts and agreements noted previously, there is a wide range of arrangements that have features of property trades, loans, and production purchase contracts. These are more commonly called production payments and conveyances and provide terms where assets are transferred between participants, assets are pooled, or loans are provided in return for the right to purchase volumes. In certain specific cases, as described in Sec. 10.4.3, reserves and resources may be recognized by the purchaser of the production payment. Figure 10.9 gives an example of a typical conveyance.

费用全部回收。义务承担方通常可以将额外的份额产量认定 PRMS 相应级别的储量。若项目成熟度不能满足储量类别的要求，可根据商定的补偿条款认定为相应级别的 PRMS 资源量。

10.5.8 采购合同

指购买原油和天然气的合同，它赋予买方在规定期限内按商定价格采购一定油气数量的权利。在采购合同中，卖方承担相关技术和市场风险，尽管购买或供应合同可通过长期获得产量而涉及储量和资源量的动用，但并没有油气开采权和储量资产的经济权益的转让。因此，此类协议不能认定任何级别 PRMS 储量和资源量。

10.5.9 产量支付与转让

除了上述合同和协议之外，还有许多其他具有资产交易、借贷和产量采购合同特点的协议，更普遍地称作产量支付和转让合同，为合作伙伴之间的资产流动、资产集中利用、或贷款以换取产量采购权提供条款依据。如第 10.4.3 节所述，在某些特定情况下，产量支付的受让方可能有权认定获得的储量 / 资源量。图 10.9 是一个典型的转让协议示意图。

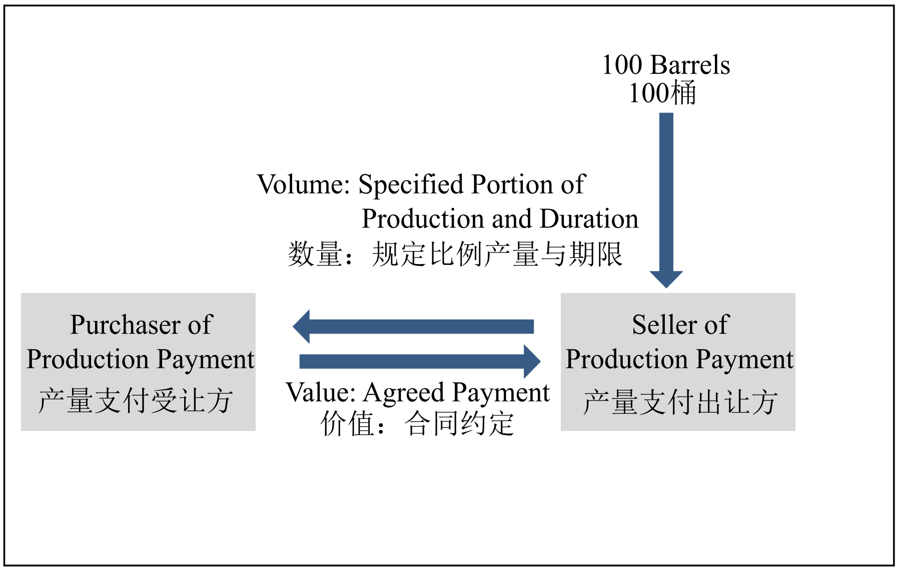


Figure 10.9　Example Conveyance—Production Payment
图 10.9　转让案例 - 产量支付示意图

10.6 Example Cases

10.6.1 Base-Case Example

The following example illustrates the approach used to calculate reserves and resources under a nonconcessionary production-sharing agreement. In this example, the contractor develops and operates the field and is entitled to a share of production that is based on cost recovery and profit share components. The contractor takes his share of product in-kind. The contractor does not have ownership of the underlying resources being produced but does earn an economic interest by virtue of the exposure to technical, financial, and operational risks and is therefore able to recognize reserves and resources for the project under PRMS. Due to the difficulty in predicting prices, this example uses a base case oil price of USD 60 and sensitivity cases USD 10 above and below this price. While these are unlikely to represent the actual prices in effect, they do provide a good illustration of how entitlement and contract terms respond to prices changes.

The base case is a 500-million-bbl oil field, of which 400 million bbl, for the purposes of this example, are reflected in the PRMS Proved Reserves category. The contract provides for an initial exploration period, with the contract term lasting 20 years from the start of production. The general field data are summarized in Table 10.2.

10.6 案例

10.6.1 案例基础方案

接下来的案例将阐述非租让制的产品分成合同模式下储量和资源量的评估方法。本例中，合同者开发经营油田，并通过成本回收和利润分成以实物形式获得份额产量。合同者没有正生产的地下油气资源的所有权，但由于承担了技术、财务和经营风险，因而拥有经济权益，可以为该项目认定PRMS储量和资源量。鉴于原油价格的预测存在难度，本案例基础方案采用60美元/桶的原油价格，并分别用70美元/桶和50美元/桶的油价进行敏感性分析。虽然这不可能代表实际价格，但可以很好展示价格变化对份额储量和合同经济有效期的影响。

基础方案油田的可采量为5亿桶，在本示例研究中，其中4亿桶为PRMS证实储量。合同初期为勘探期，商业投产之后的开发合同期限为20年。表10.2汇总了油田基本信息。

Table 10.2 Example Field Information Summary
表10.2 案例油田基本信息

Parameters 参数	Value 数值
Field Size 油田规模（可采量）	500 million bbl 5亿桶
Production During PSC 产品分成合同期产量	400 million bbl 4亿桶
Exploration Cost 勘探成本	$450 million 4.5亿美元
Drilling Cost 钻井成本	$600 million 6亿美元
Development Cost 开发成本	$750 million 7.5亿美元
Fixed Operating Cost 固定操作成本	$1,800 million ($90 MM/yr) 18亿美元（9000万美元/年）
Variable Operating Cost 可变操作成本	$4.55/bbl 4.55美元/桶

The production forecast is based on the Proved Reserves, while the remaining 100 million bbl is captured as PRMS 1C and 2C resources. These resources are related to a potential contract extension. In this simplified example, no additional drilling is required; therefore, there is no Probable or Possible Reserves to migrate to the Proved category. However, in actual field development, a portion of the reserves would likely be captured in the Probable (and perhaps Possible) PRMS reserves categories, depending on supporting information and technical certainty.

For example, some Probable (or Possible) Reserves may be captured for better-than-expected recovery or perhaps for undrilled blocks where technical certainty was not sufficient to classify the reserves as Proved. In this instance, modeling two cases, one for the Proved plus Probable flow streams and a separate model for the Proved-only case, will give the Probable Reserves entitlement by difference. Table 10.3 shows the project production forecast and full-life cost summary.

Production startup is midyear in the second year of the project and builds to a peak rate of 95,000 BOPD (34.7 million bbl annualized) in the eighth year. Project exploration costs are USD 450 million for exploratory drilling. The total development costs are USD 1,350 million for both project facilities and development drilling. Operating costs comprise a fixed cost of USD 90 million per year and a variable cost of USD 4.55/bbl.

The contractor’s share of reserves and resources will be evaluated in the following with evaluation for the effect of price and alternative tax treatment on recognizable reserves.

10.6.2 Production-Sharing Contract Terms—Normal Tax Treatment

The example contract contains many common contractual terms affecting the industry today. These include royalty payments, limitations on the revenue available for cost sharing, a fixed profit-share split, and income taxes. The example case is a typical production-sharing agreement in which the contractor is responsible for the field development and all exploration and development expenses. In return, the contractor recovers investments and operating expenses out of the gross production stream and is entitled to a share of the remaining profit oil. The contractor receives payment in oil production and is exposed to both technical and market risks.

Figure 10.10 shows the general terms of the contract. The contract is for a 20-year production term with the possibility of an extension until project termination. The terms include a royalty payment on gross production of 15%. Yearly cost recovery is limited to a maximum of 50% of the annual gross revenue, with the remaining cost carried forward to be recovered in future years. The contractor’s profit share is a based on a simple split: 20% to the contractor and 80% to the host government.

预测产量剖面以证实储量为基础，同时剩余的 1 亿桶可采量划为 PRMS 的 1C 和 2C 资源量。这部分条件资源量与可能的合同延期有关。在这个简化案例中，没有额外的钻井计划，因此没有概算储量或可能储量会升级为证实储量。然而，在实际的油田开发中，部分储量可能会被划为 PRMS 的概算储量（或可能储量）级别中，这取决于评估时的支撑数据和技术确定性。

例如，乐观的或不满足证实储量技术确定性要求的未钻井区域的油气预期产量可划为概算储量（或可能储量）。此类情况下，需要分别模拟证实储量 + 概算储量和仅有证实储量两种情景，两者相减可得到份额概算储量。表 10.3 所列为项目合同期内产量预测和全生命期成本汇总表。

项目在第 2 年年中投产，在第 8 年达到高峰产量，日产原油 9.5 万桶（年产约 3470 万桶），项目的勘探成本（探井钻探）为 4.5 亿美元，总开发成本（项目地面设施和开发钻井）为 13.5 亿美元，操作成本包括固定成本 9000 万美元 / 年，可变成本 4.55 美元 / 桶。

下面将估算合同者的储量和资源量份额，并评估价格和不同税负缴纳方式对储量认定的影响。

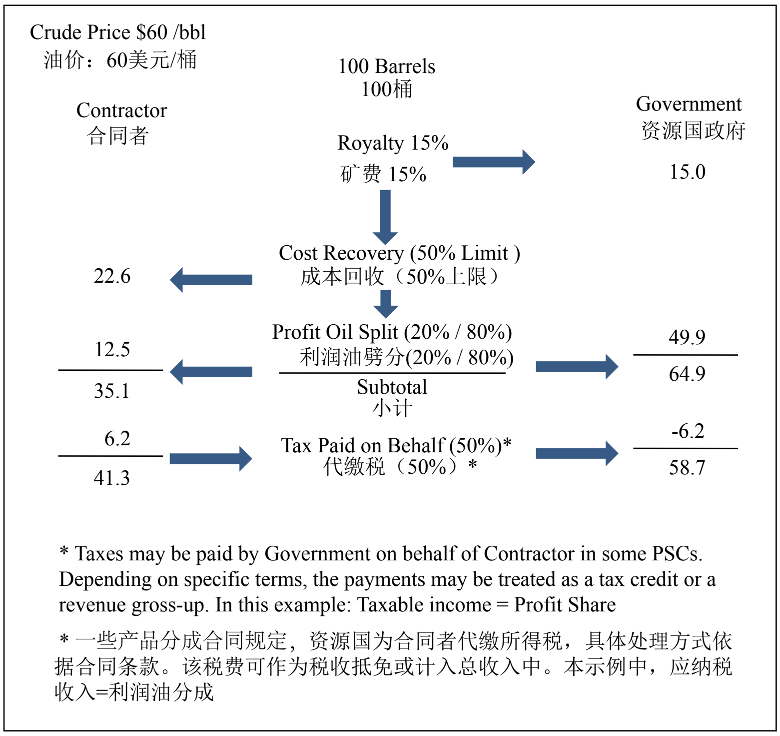
10.6.2 产品分成合同条款—常规纳税处理

案例合同包括了当前油气行业有影响的常见合同条款，包括矿费支付、成本回收上限、固定的利润分配机制以及所得税。该案例是一个典型的产品分成协议，其中，合同者负责油田开发，承担所有勘探和开发费用；作为回报，合同者从总产量中回收投资和操作成本，并在剩余的利润油中分成。合同者获得实物原油产量，并承担技术和市场的风险。

图 10.10 所示为该合同的基本条款，合同的生产期限为 20 年，并有可能延期至项目废弃。合同条款规定包括支付的矿费占总产量的 15%，年度成本回收最多不超过每年总收入的 50%，剩余未回收的成本可结转至下一年回收。合同者的利润分成模式比较简单：合同者 20%，资源国政府 80%。

Table 10.3 Project Production and Cost Schedule
表 10.3 项目产量和成本预测表

Year 年份	Annual Oil Production 年产量（百万桶）	Exploration Costs 勘探成本 (百万美元)	Capital 资本成本（百万美元）	Drilling 钻井成本（百万美元）	Op.Cost, Fixed 固定操作成本 (百万美元)	Op.Cost, Variable 可变操作成本（百万美元）	Total 成本合计（百万美元）
1	0	300	0	0	0	0	300
2	2.7	150	105	120	90	12	477
3	11.5		369	180	90	52	691
4	19.9		276	300	90	90	756
5	30.4				90	138	228
6	33.3				90	152	242
7	34.5				90	157	247
8	34.7				90	158	248
9	31.3				90	142	232
10	28.1				90	128	218
11	25.3				90	115	205
12	22.8				90	104	194
13	20.5				90	90	183
14	18.5				90	84	174
15	16.6				90	76	166
16	14.9				90	68	158
17	13.5				90	61	151
18	12.1				90	55	145
19	10.9				90	50	140
20	9.8				90	45	135
21	8.8				90	40	130
Total 总计	400	450	750	600	1800	1820	5420



* Taxes may be paid by Government on behalf of Contractor in some PSCs. Depending on specific terms, the payments may be treated as a tax credit or a revenue gross-up. In this example: Taxable income = Profit Share

* 一些产品分成合同规定，资源国为合同者代缴所得税，具体处理方式依据合同条款。该税费可作为税收抵免或计入总收入中。本示例中，应纳税收入=利润油分成

Figure 10.10　Production-Sharing Contract (PSC) Base Case
图 10.10　产品分成合同条款基础方案

10.6.3 Contractor Entitlement Calculation

The terms of a production-sharing contract determine the contractor's yearly entitlement or share of the project production based on the yearly cost recovery and profit split. Table 10.3 shows the anticipated production, investment, and cost profiles for the project. The calculation of the contractor's revenue entitlement for the peak year with 34.72 million bbl of production is shown in Table 10.4. At USD 60/bbl, the gross revenue from 34.72 million bbl in Year 8 is USD 2,083 million. At a royalty rate of 15%, the government would receive as royalty 5.2 million bbl valued at USD 312 million (before cost recovery or profit split). The remaining USD 1,771 million would remain for cost recovery and profit split according to the terms of the contract. In the production-sharing contract, revenue available for cost recovery is limited to 50% after royalty, or USD 886 million. Costs and expenses for the year total USD 248 million, including costs carried forward from previous years. The yearly costs are fully recoverable. In the case of unrecovered costs, they would be carried forward by the contractor for recovery in future years. The remaining revenue after royalty and cost recovery is shared by the contractor and government according to the contract profit split. In this case, the contractor's profit share is USD 305 million, or 20% of the available revenue after royalty and costs. The contractor's revenue entitlement is the sum of the contractor's cost recovery and profit.

10.6.3 合同者的份额计算

产品分成合同关于成本回收与利润分成的条款决定了合同者在项目年度产量中的份额或分成。表 10.3 为项目产量、投资和成本的预测剖面，高峰产量为 3472 万桶。合同者收入份额的计算见表 10.4。油价为 60 美元 / 桶的情况下，第 8 年产量 3472 万桶的总收入是 20.83 亿美元，矿费费率为 15%，资源国政府应得矿费对应的原油量为 520 万桶，价值相当于 3.12 亿美元（在回收成本和分配利润之前缴纳）；剩余的 17.71 亿美元将根据合同条款的规定被用作成本回收和利润分配基础。在该产品分成合同中，成本回收上限为支付矿费后年收入的 50%，即 8.86 亿美元。全年投资和成本合计 2.48 亿美元（包括历史结转成本），可完全回收所有成本。若存在未能回收成本，合同者可结转至下一年回收。扣除矿费和成本回收之后的剩余收入由合同者和资源国政府根据合同的利润分配条款劈分。在本案例中，合同者的利润分成是 3.05 亿美元，占扣除矿费和成本后可分成利润总额的 20%。合同者收入份额为成本回收与利润分成之和。

Table 10.4　Project Cost and Profit-Share Schedule
表 10.4　项目成本和利润分配表

Year 年份	Total Revenue ($Million) 年度总收入（百万美元）	Net Revenue After Royalty ($million) 扣除矿费后净收入（百万美元）	Recoverable Costs ($Million) 可回收成本（百万美元）	Costs Carried Forward ($Million) 结转的可回收成本（百万美元）	Contractor Recovered Costs ($Million) 合同者回收的成本（百万美元）	Available For profit Sharing ($Million) 可劈分的利润（百万美元）	Contracor Profit Share ($Million) 合同者分得的利润（百万美元）	Contracor Cost+ Profit Share ($Million) 合同者回收的成本与分得的利润之和（百万美元）	Contractor Share% 合同者份额比例 (%)	Contractor Entitlement (Mbbls) 合同者份额油（千桶）
1	0	0	300	300	0	0	0	0	n/a	0
2	161	137	477	709	69	69	14	82	51	1.37
3	687	584	691	1108	292	292	58	351	51	5.84
4	1192	1014	756	1357	507	507	101	608	51	10.14
5	1824	1550	228	810	775	775	155	930	51	15.50
6	1999	1699	242	202	850	850	170	1020	51	16.99
7	2069	1759	247		449	1310	262	711	34	11.85
8	2083	1771	248		248	1523	305	553	27	9.21
9	1875	1594	232		232	1362	272	505	27	8.41
10	1688	1434	218		218	1216	243	461	27	7.69
11	1519	1291	205		205	1086	217	422	28	7.04
12	1367	1162	194		194	968	194	387	28	6.45
13	1230	1046	183		183	862	172	356	29	5.93
14	1107	941	174		174	767	153	327	30	5.46
15	996	847	166		166	681	136	302	30	5.03
16	897	762	158		158	604	121	279	31	4.65
17	807	686	151		151	535	107	258	32	4.30
18	726	617	145		145	472	94	240	33	3.99
19	654	556	140		140	416	83	223	34	3.71
20	588	500	135		135	366	73	208	35	3.46
21	530	450	130		130	320	64	194	37	3.24
总计 Total	24000	20400	5420	n/a	5420	14981	2996	8416	35	140.27

In the base case, the calculated average contractor cost plus profit share value in Year 8 is USD 553 million, or about 27% of the project gross revenue. Because the cost and revenue vary yearly, the calculated entitlement applies only to the year in question. In addition, the contractor is obligated to pay income tax out of his share, which amounts to USD 152 million at the tax rate of 50%.

10.6.4 Contractor Reserves Calculations

The preceding calculation represents the contractor's share of the yearly project revenue. In production-sharing contracts, however, the contractor usually takes payment in kind, and the cost and profit share must be converted to an equivalent volume of the production. The crude price may vary over the year and the method for calculating the price for each settlement period is normally defined in the agreement. For the purposes of this example, the crude price is assumed to be fixed at USD 60/bbl. The contractor's crude entitlement is equal to the profit share before tax plus cost recovery oil divided by the crude price. For Year 8, with crude at USD 60/bbl, the contractor's entitlement is 9.2 million bbl. In this example, this would be reflected in the PRMS Proved Reserves category. In an actual field development, part of these entitlement volumes may be sourced from portions of the reservoir that are not considered Proved at the time of classification, as noted in Sec. 10.6.1. In this situation, the non-Proved portion would be reflected in the PRMS Probable (or Possible) categories until reclassification to Proved is justified.

This calculation provides only the contractor's share of the annual production for the year in question. Because reserves represent ultimate future recovery from the project, forecasts of future production, investments, and operating expenses are required to determine future annual entitlements. The contractor's reserves are obtained by the summation of the estimated annual volume entitlements over the remaining life of the project. Table 10.4 shows the forecasted entitlements from project initiation to the end of the contract term. They were calculated with the forecasted production schedule, exploration and drilling costs, the anticipated project investment schedule, and the forecasted operating expense through the term of the agreement. For this case, the contractor's Proved PRMS Reserves are estimated at 140 million bbl, or 35% of the total project Proved Reserves of 400 million bbl.

In the example case, prices and profit splitting were held constant over the period and the effect of the recovery of initial capital investments can be seen on the effective net entitlement interest. At the onset of production, entitlement (economic) interest is approximately 51% and declines over the next several years to a low of 27% in Year 8. The entitlement interest then increases to 37% by the end of the term. This increase is due to the natural decline in the production rate and the need to have a greater portion of the production to reimburse fixed operating costs. In general, production-sharing contract entitlements are highest at the point of first production and tend to decrease as a project becomes cost current. Entitlements tend to increase as costs increase and prices decline; however, many agreements contain "R"

在这基础方案中，合同者第 8 年获得的成本回收和利润分成之和为 5.53 亿美元，大约占项目总收入的 27%。因为每年的成本和收入会发生变化，份额的计算结果仅适用于该分析年份。另外，合同者有义务从其利润份额中缴纳所得税，税率为 50%，应缴纳税额为 1.52 亿美元。

10.6.4 合同者份额储量计算

前面的计算结果代表着合同者在项目年度收入中的分成。但是，在产品分成合同中，合同者通常是以实物形式支取这些收入，成本回收和利润分成都需转换成等价的产品数量。原油的价格可能每年变化，在协议中通常要规定每一结算期原油价格的计算方法。为了本例研究的目的，假定原油价格固定为 60 美元 / 桶。合同者的份额油等于税前利润油收入加上成本回收之和再除以油价。在第 8 年，原油价格 60 美元 / 桶，则合同者的份额油为 920 万桶，在本例中对应 PRMS 的证实储量级别。如第 10.6.1 节所述，在实际的油田开发中，部分份额油有可能来源于评估时油藏的非证实储量。在这种情况下，非证实部分对应 PRMS 的概算储量（或可能储量），直至可以升级为证实储量。

目前计算得到的仅是合同者评估当年获得的份额年产量。由于储量代表的是项目的未来最终可采量，需要预测未来的产量、投资和操作费用，从而确定未来各年度的份额产量。合同者的份额储量等于估算的项目剩余合同期年度份额产量之和，表 10.4 所示为项目启动到合同期结束所预测的年度份额油，是根据协议期内预测的产量剖面、勘探 / 钻井成本、预计的项目投资计划和操作费而计算得出的。在该案例中，合同者的 PRMS 份额证实储量为 1.4 亿桶，占项目总证实储量 4 亿桶的 35%。

案例中，价格和利润劈分比例在整个评价期内保持不变，可以看到初始资本投资的回收对实际净份额权益影响。在生产初期，经济或份额权益约为 51%，在后续几年中持续下降，第 8 年降至最低值 27%。随后，由于产量自然递减，使得用于偿还固定操作成本的产量比例增大，合同期末份额权益增加至合同期的 37%。一般情况下，在产品分成合同中合同者的份额权益在投产时最高，然后随着项目收入（只有成本支出）减少而降低。合同者的份额一般随成本增加和价格下降而上升。但是，

terms and/or stepwise tranches that tend to reduce the profit share allocation to the contractor over time. These take many different forms, but generally tend to be related to cumulative production or cumulative reimbursements or to higher production rates.

10.6.5 Crude-Price Sensitivity

Contractor reserves are sensitive to the assumed production schedule, crude-price projections, and cost forecasts. The most volatile of these factors is the crude price. Table 10.5 demonstrates the relationship between crude price and contractor reserves. For a USD 10/bbl increase in crude price, the contractor's reserves decrease from 140 million to 130 million bbl. Such swings in reserves can be expected when prices are volatile. A number of other commonly used financial metrics have also been included in Table 10.5 to illustrate how they also change with price. Subject to specific pricing requirements in the production-sharing-contract agreement, the ability to use average prices over a year, as provided by PRMS, helps dampen price-related reserves changes. The contractor's actual ultimate recovery will, however, be determined by the weighted average crude price over the project life.

许多协议加入了 R 因子和 / 或其他分步核算条款，减少合同者在整个合同期的利润分成。这样的条款形式很多，但通常与累计产量、累计回报或较高的开采速度存在关联。

10.6.5 原油价格敏感性分析

合同者的份额储量对产量剖面、原油价格和成本具有敏感性，其中原油价格是最不稳定的。表 10.5 说明了合同者份额储量随原油价格的变化情况，如果原油价格上涨 10 美元 / 桶，则合同者的份额储量会从 1.4 亿桶下降到 1.3 亿桶。在价格不稳定时，可以预期合同者的份额储量也上下波动，表 10.5 中还包含了其他一些常用财务指标随价格变化情况。根据产品分成合同中的具体定价要求，在 PRMS 下，可使用年度平均价格来降低与价格相关的储量波动。但是，合同者的实际最终可采量将取决于项目生命期的原油加权平均价格。

Table 10.5　Base Case, Oil Price, and Tax Sensitivity
表 10.5　基础方案和油价与税收敏感性分析表

Parameter 参数	Low Case, $50 Oil Price 低方案，油价 50 美元 / 桶		Base Case, $60 Oil Price 基础方案 , 油价 60 美元 / 桶		High Case, $70 Oil Price 高方案，油价 70 美元 / 桶	
	Normal Tax 常规纳税	Carried Tax 所得税代缴	Normal Tax 常规纳税	Carried Tax 所得税代缴	Normal Tax 常规纳税	Carried Tax 所得税代缴
Reserves (million bbl) 份额储量 (百万桶)	155	178	140	165	130	156
Cost of Finding&Dev. ($/bbl) 发现开发成本 (美元 / 桶)	11.63	10.12	12.83	10.89	13.85	11.52
Profit/bbl ($/bbl) 分成利润 (美元 / 桶)	14.97	19.53	21.36	27.20	28.29	35.30
Production Costs ($/bbl) 生产成本 (美元 / 桶)	23.40	20.35	25.81	21.91	27.86	23.18
Net Production Income ($/bbl) 净产量收入 (美元 / 桶)	7.48	13.02	10.68	18.13	14.14	23.53
NPV@10% (FASB) ($MM) NPV@10% (FASB)(百万美元)	87	493	260	788	419	1070
SMOG/BBL ($/bbl) 标准化计量值 (美元 / 桶)	0.56	2.78	1.86	4.77	3.23	6.85
Contractor IRR(%) 合同者内部收益率（%）	11.9	18.8	15.7	24.3	19.5	29.6

10.6.6 Production-Sharing Contract—Carried Tax Treatment

In the normal case, the contractor is obligated to pay income tax out of his share of the project profit. In such cases, the contractor's tax obligation impacts the project's economics but has no impact on the reserves calculations because reserves are calculated on a before-tax basis. In some production-sharing agreements, however, the government or state-owned oil company agrees to pay tax on behalf of the contractor. If the tax payment is a purely financial arrangement and the payments cannot be attributed to a portion of the government's production revenues, an economic interest would not exist; therefore, no additional reserves would be recognized by the contractor. In this case, the carried tax reserves will equal those obtained in the normal tax case, as shown in Table 10.5.

If under the terms of the contract the contractor derives a benefit from and has an economic interest in the government's share of hydrocarbon volumes used to fund the tax payments, those volumes may be considered as the contractor's reserves. Table 10.5 shows the impact on both the project financial indicators and reserves. The contractor's cost recovery and profit share are computed in the standard fashion, but would now include the economic benefit related to the taxes paid on behalf of the contractor. With a tax-paid-on-behalf arrangement, the contractor's base-case Proved Reserves would increase by 25 million to 165 million bbl. In an actual field development, part of these additional entitlement volumes may be sourced from portions of the reservoir that are not considered Proved at the time of classification. As discussed previously, the non-Proved portion would be reflected in the PRMS Probable (or Possible) category until reclassification to Proved is justified.

10.6.7 Reserves Sensitivity

The preceding reserves calculation illustrates the general approach that can be used for production-sharing contracts at all levels of project maturity. It accounts for varying yearly investment levels and the relative relationship between project costs and project revenue. In a mature project, with relatively stable prices and the relationship between project costs and project revenues relatively constant, some companies simplify the process by assuming that the reserves share is equal to an average entitlement percentage. In general, this approach is believed to be sufficiently accurate, and corrections would be applied when accounts are trued-up for actual production and realizations on the regular intervals prescribed in the agreement.

10.6.8 Assessing Other Categories of Reserves and Resources

In the production-sharing-contract example case, 100 million bbl was noted to be related to the potential extension of the original contract agreement. If significant additional new investments were

10.6.6 产品分成合同—代缴所得税的处理

一般情况下，合同者有义务从其项目利润分成中缴纳所得税。这样，合同者的纳税义务将影响项目的经济指标，但对于份额储量计算没有影响，因为储量是在税前计算。但是在某些产品分成协议中，资源国政府或国有石油公司会同意代合同者缴纳所得税。如果纳税金额只是财务账面上的变化，并非来自资源国政府在此项目中的一部分实物产量收入，则合同者对所得税对应的油气量没有经济权益，所以不能认定此部分份额储量。在这种情况下，所得税代缴的储量与常规纳税方式（表 10.5 所示）认定的份额储量相等。

如果根据合同条款，合同者对政府支付所得税的油气量份额拥有经济权益并受益，则这部分油气量可认定为合同者份额储量。表 10.5 展示了这种情形的财务指标和份额储量。合同者的成本回收和利润分成以标准方式计算，但现在要增加政府代缴税负带来的经济收益。在此代缴税协议方案中，合同者基础方案证实储量的份额增加 2500 万桶，达到 1.65 亿桶。在实际油田开发中，部分增加的份额储量可能来源于评估时油藏的非证实储量，如前面所述，可能对应 PRMS 概算储量（或可能储量），直至升级为证实储量。

10.6.7 储量敏感性分析

前面阐述了产品分成合同项目在不同成熟度阶段的份额储量计算的基本方法，该计算过程受不同的年度投资水平以及项目成本和收入之间的相对关系影响。对于成熟项目，由于价格相对稳定，项目成本和收入的关系相对稳定，一些公司简化份额储量计算过程，假定份额储量比例等于平均年度份额比例。一般而言，这种方法被认为是足够准确的，可按协议规定的间隔，定期根据实际生产和现实情况进行修正调整。

10.6.8 其他级别储量与资源量的评估

在此产品分成合同案例中，还有 1 亿桶原油是原来的合同如果延期可采出的部分。若这部分油需较大的额外投资才能开采和 / 或项目是否延

required to produce this volume and/or there was some doubt that the agreement would be extended, the related volume would most likely be categorized as a Contingent Resource in one or more of the 1C, 2C, or 3C scenarios, depending on the level of technical certainty. There may also be a question of whether the same or different terms will apply to the extension. Consequently, judgment must be used when estimating the entitlement interest that will be used to determine the net share of PRMS resources potentially available to the contractor.

In a different scenario, if the 100 million bbl were related to potentially higher recovery efficiency from the reservoir within the original term, and no additional debottlenecking or development investments were required, the volume could be classified as Probable (and/or Possible) Reserves (assuming appropriate technical certainty). To determine the effective net interest for this Probable increment, a two-step process is commonly used. In the first step, the Proved flowstream is evaluated using the production-sharing-contract model described in the preceding subsections. In the second step, the forecast Proved plus Probable flowstream is then evaluated with the production-sharing-contract model and the results from the Proved case are subtracted. This provides the entitlement and revenues related to the discrete Probable component. This approach can be used with multiple categories and in cases where additional investments may also be required. It may also be used where there are multiple fields being developed within the same production-sharing-contract ring fence.

10.7 Conclusions

Production-sharing, risked-service, and other related contracts offer the host country and the contractor alike considerable flexibility in tailoring agreement terms to best meet sovereign and corporate requirements.

When considering projects, each fiscal system must be reviewed on a case-by-case basis to determine whether there is an opportunity to recognize reserves and resources for internal use, regulatory reporting, or public disclosure. Particular care should be taken to ensure that the contractual terms satisfy the company’s business objectives and that the impact of alternative agreement structures is understood and considered.

The SEC Section S-X, Rule 4-10b, “Successful Efforts Method,” provides criteria and a useful framework for determining when a mineral interest in hydrocarbon reserves and resources exists. These criteria can be used to supplement PRMS to help determine when an economic interest in hydrocarbons exists, allowing reserves and resources to be recognized and reported. However, the distinction between when reserves and resources can or cannot be recognized

期尚未确定，则根据其技术确定性程度，相关油气量很可能被划分为 1C、2C 或 3C 中一种或多种级别的条件资源量。这里还可能存在合同延期条款是否相同的问题。因此，在评估合同者可能拥有的 PRMS 资源量的净份额时，需要作出判断。

另一种情形下，按照原有条款，如果上述 1 亿桶油可由可能的提高采收率方法开采，不需额外的去瓶颈工程或开发投资，那么这一部分原油数量可划为概算储量（和 / 或可能储量）（假定技术确定性符合相关要求）。确定概算储量增量对应的净份额权益时，一般可采用两步法。第一步，采用前面所描述的产品分成合同模型来评估份额证实储量；第二步，用产品分成合同模型评估预测份额 2P 储量（证实储量 + 概算储量），减去证实储量的结果，则可得到离散概算储量的份额数量和相应收入。这种方法可用于多种级别并存和可能需要额外投资的情形，同时也可适用于多个开发油田共用同一个产品分成合同篱笆圈的情况。

10.7 结论

产品分成、风险服务以及其他相关合同可为资源国和合同者提供相当大的灵活性来定制协议条款，以便最大限度地满足资源国主权监管和油气公司管理要求。

在考虑项目时，每种财税制度都必须具体情况具体分析，以确定是否可以为内部使用、监管报告和对外披露等多种目的认定储量和资源量。应特别注意确保合同条款满足公司的经营目标，同时确保对替代协议的架构及其影响有充分的了解和考虑。

SEC 第 S-X 节第 4-10b 条款“ 成果法 ”，提供了油气储量 / 资源量矿产权益认定的标准与框架，这些条件可以作为 PRMS 的补充，用来确定何时存在油气经济权益并允许储量的认定和披露。然而，在许多服务合同模式下，储量 / 资源量的认定可能没有明确的界限，很大程度上要根

under many service-type contracts may not be clear and may be highly dependent on subtle aspects of contract structure and wording.

Unlike traditional agreements, the cost-recovery terms in production-sharing, risked-service, and other related contracts typically reduce the production entitlement (and hence reserves) obtained by a contractor in periods of high price and increase the volumes in periods of low price. While this ensures cost recovery, the effect on investment metrics may be counterintuitive. The treatment of taxes and the accounting procedures used can also have a very significant impact on the reserves and resources recognized and production reported from these contracts.

Given the complexity of these types of agreements, determination of the net company share of hydrocarbons recognized for each PRMS classification requires economic modeling of the flowstreams with the related costs and investments for each cumulative PRMS classification (1P, 2P, 3P and 1C, 2C, 3C). The net amount for each discrete PRMS category can then be determined by difference from the model results (i.e., net Probable Reserves = 2P – 1P).

据具体合同条款细节和措辞而定。

与传统协议不同，产品分成、风险服务以及其他相关合同中的成本回收条款通常会在油价高时使合同者的份额产量减少（因而份额储量也相应减少），而油价低时份额量增加。尽管可确保成本回收，但对投资指标的影响可能会有悖常理。税负处理和会计程序也会对这些合同模式的储量与资源量认定以及产量统计产生重要影响。

鉴于此类合同协议的复杂性，公司的 PRMS 各类净油气份额的认定需要对每个 PRMS 累计情景（1P、2P、3P 及 1C、2C、3C）考虑相应投资和成本，建立现金流经济模型。PRMS 各级离散份额值则可以通过模型结果的差值来确定（即，份额概算储量 = 份额 2P- 份额 1P）。

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参考术语

Reference Terms

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参考术语

Note: The column USED IN THESE GUIDELINES provides the chapter where the term is used (first number) and the number of times the term appears in that chapter (number after the period). For example, 4.12 means the term appears in Chapter 4 and is used 12 times.

说明：“本指南”一列所给出的数字表示使用该术语的章（第一个数字）和本章中使用的次数（点后的数字）。例如“4.12”，则表示该术语在第4章出现了12次。

Term 术语	Reference* 参考文献 *	Used in These Guidelines 本指南引述情况	Definition 定义
1C	2007-2.2.2	1.1, 2.8, 4.12, 5.3, 6.1, 8.1, 10.3	Denotes low estimate scenario of Contingent Resources. 表示条件资源量的低估值情景。
2C	2007-2.2.2	1.1, 2.6, 4.12, 5.3, 6.1, 8.1, 10.3	Denotes best estimate scenario of Contingent Resources. 表示条件资源量的最佳估值情景。
3C	2007-2.2.2	1.1, 2.4, 4.12, 5.3, 6.1, 8.1, 10.2	Denotes high estimate scenario of Contingent Resources. 表示条件资源量的高估值情景。
1P	2007-2.2.2	1.1, 2.13, 4.18, 5.6, 6.4, 7.9, 8.8, 10.2	Taken to be equivalent to Proved Reserves; denotes low estimate scenario of Reserves. 相当于证实储量，表示储量的低估值情景。
2P	2007-2.2.2	1.1, 2.15, 4.25, 5.6, 6.7, 7.18, 8.10, 10.2	Taken to be equivalent to the sum of Proved plus Probable Reserves; denotes best estimate scenario of Reserves. 相当于证实储量与概算储量之和，表示储量的最佳估值情景。
3P	2007-2.2.2	1.1, 2.12, 4.20, 5.5, 6.2, 7.11, 8.11, 10.1	Taken to be equivalent to the sum of Proved plus Probable plus Possible Reserves; denotes high estimate scenario of reserves. 相当于证实储量、概算储量与可能储量之和，表示储量的高估值情景。
Accumulation 油气聚集体	2001-2.3	2.22, 3.6, 4.9, 5.3, 6.3, 8.37	An individual body of naturally occurring petroleum in a reservoir. 在储层中自然形成的油气单体。
Aggregation 汇并	2007-3.5.1 2001 - 6	1.1, 2.1, 4.1, 5.1, 6.26, 8.1	The process of summing reservoir (or project) level estimates of resource quantities to higher levels or combinations such as field, country, or company totals. Arithmetic summation of incremental categories may yield different results from probabilistic aggregation of distributions. 指对油气藏（或项目）层级的资源估值进行汇总，得到油气田、国家或公司等更高层级的资源总量的过程。不同增量级别的资源数量算术求和，可能与概率分布汇并的结果不同。

Term 术语	Reference* 参考文献 *	Used in These Guidelines 本指南引述情况	Definition 定义
Approved for Development 已批准开发	2007 - Table 1 2007 - 表 1	2.4	All necessary approvals have been obtained; capital funds have been committeed, and implementation of the development project is underway. 指已获得所有必要的批准，投资资金已承诺，开发项目正在实施中。
Analogous Reservoir 类比油气藏	2007 - 3.4.1	2.3, 4.1	Analogous reservoirs, as used in resources assessments, have similar rock and fluid properties, reservoir conditions (depth, temperature, and pressure) and drive mechanisms, but are typically at a more advanced stage of development than the reservoir of interest and thus may provide concepts to assist in the interpretation of more limited data and estimation of recovery. 资源评价中，类比油气藏指与被评估的目标油气藏具有相似岩石与流体性质、油藏条件（深度、温度和压力）和驱动机理，但通常处在开发的更高阶段，因此有助于为数据有限情形下的解释和采出量估算等提供依据。
Assessment 评价	2007 - 1.2	1.2，2.11，3.6，4.60, 5.2, 6.3, 7.5, 8.23, 10.1	See Evaluation. 参见术语“评估 (Evaluation)”。
Associated Gas 伴生气		7.2, 8.2	Associated Gas is a natural gas found in contact with or dissolved in crude oil in the reservoir. It can be further categorized as Gas-Cap Gas or Solution Gas. 伴生气是在储层中与原油接触或溶解在原油中的一种天然气，可进一步划分为气顶气和溶解气。
Barrels of Oil Equivalent (BOE) 桶油当量	2001 - 3.7	4.12, 9.13	See Crude Oil Equivalent. 参见术语“原油当量 (Crude Oil Equivalent)”。
Basin-Centered Gas 盆地中心气	2007 - 2.4	8.2	An unconventional natural gas accumulation that is regionally pervasive and characterized by low permeability, abnormal pressure, gas saturated reservoirs, and lack of a downdip water leg. 指区域性广泛分布，低渗、异常高压、饱和气藏中无下倾水体的非常规天然气聚集体。
Behind-pipe Reserves 管外储量	2007 -2.1.3.1	none—no occurrences 未出现	Behind-pipe reserves are expected to be recovered from zones in existing wells, which will require additional completion work or future recompletion prior to the start of production. In all cases, production can be initiated or restored with relatively low expenditure compared to the cost of drilling a new well. 管外储量是指需要追加完井作业或未来重新完井之后才能从已钻生产井层段中采出的油气数量；无论何种情景（追加或重新完井），投产或复产的费用均比一口新井的费用低。

Term 术语	Reference* 参考文献 *	Used in These Guidelines 本指南引述情况	Definition 定义
Best Estimate 最佳估值	2007 - 2.2.2 2001 - 2.5	2.5, 4.36, 5.2, 6.5, 7.9, 8.1	With respect to resource categorization, this is considered to be the best estimate of the quantity that will actually be recovered from the accumulation by the project. It is the most realistic assessment of recoverable quantities if only a single result were reported. If probabilistic methods are used, there should be at least a 50% probability (P50) that the quantities actually recovered will equal or exceed the best estimate. 在资源分级中，指项目将从某油气聚集体中实际采出数量的最佳估算结果。如果只报告一个估算结果，最佳估值即是最现实的可采量估值；如果使用概率法，则实际采出量等于或超过最佳估值的概率应至少为 50%（P50）。
Bitumen 沥青	2007 - 2.4	1.1, 8.29, 9.2	See Natural Bitumen. 参见术语 “ 天然沥青（Natural Bitumen) ” 。
Buy Back Agreement 回购协议		none—no occurrences 未出现	An agreement between a host government and a contractor under which the host pays the contractor an agreed price for all volumes of hydrocarbons produced by the contractor. Pricing mechanisms typically provide the contractor with an opportunity to recover investment at an agreed level of profit. 指资源国政府和合同者之间达成的一种协议，根据该协议，对合同者所生产的所有油气数量，政府将按照协议价格支付费用。通常定价机制可以让合同者有机会在约定利润范围内回收投资。
Carried Interest 干股权益	2001 - 9.6.7	7.1, 10.3	A carried interest is an agreement under which one party (the carrying party) agrees to pay for a portion or all of the preproduction costs of another party (the carried party) on a license in which both own a portion of the working interest. 干股权益是一种协议，按照该协议，在双方均拥有工作权益的矿权区，合同一方（义务承担方）同意替另一方（义务转出方）支付一部分或全部的投产前成本费用。
Chance 几率	2007 - 1.1	2.36, 4.6, 5.1, 6.4, 8.4	Chance is 1- Risk (See Risk). 几率 =1- 风险；参见术语 “ 风险（Risk） ” 。
Coalbed Methane (CBM) 煤层气	2007 - 2.4	8.49	Natural gas contained in coal deposits, whether or not stored in gaseous phase. Coalbed gas, although usually mostly methane, may be produced with variable amounts of inert or even non-inert gases (Also termed Coal Seam Gas, CSG, or Natural Gas from Coal, NGC). 指煤层中所含的天然气，不管是否以气态形式存在。尽管煤层气的主要成分是甲烷，但也可能在生产过程中伴生数量不等的惰性气体甚至非惰性气体；也称煤层气（CSG）或煤层天然气（NGC）。

Term 术语	Reference* 参考文献 *	Used in These Guidelines 本指南引述情况	Definition 定义
Commercial 商业的	2007 - 2.1.2 and Table 1 2007 - 2.1.2 和表 1	1.1, 2.66, 3.1, 4.5, 5.2, 6.2, 7.10, 8.40	When a project is commercial, this implies that the essential social, environmental, and economic conditions are met, including political, legal,regulatory, and contractual conditions. In addition, a project is commercial if the degree of commitment is such that the accumulation is expected to be developed and placed on production within a reasonable time frame. While 5 years is recommended as a benchmark, a longer time frame could be applied where, for example, development of economic projects are deferred at the option of the producer for, among other things, market-related reasons, or to meet contractual or strategic objectives. In all cases, the justification for classification as Reserves should be clearly documented. 当一个项目是商业的，意味着其运行所需的社会、环境和经济条件得到满足，包括政治、法律、管理规定及合同条件，并承诺在合理期限内进行开发与生产。建议以 5 年作为期限基准，但某些情形下也可延长期限，例如项目的经济开发可根据生产商的选择而推迟，原因包括市场因素、合同或战略目标等。无论什么情形，分类为储量的理由应清楚记录。
Committed Project 已承诺项目	2007 - 2.1.2 and Table 1 2007 - 2.1.2 和表 1	none —no occurrences 未出现	Projects status where there is a demonstrated, firm intention to develop and bring to production. Intention may be demonstrated with funding/financial plans and declaration of commerciality based on realistic expectations of regulatory approvals and reasonable satisfaction of other conditions that would otherwise prevent the project from being developed and brought to production. 指项目处于已证明有确定意向进行开发投产的状态。意向可在现实期望监管部门的批复和满足其他条件基础上（否则会阻碍项目的开发和投产），通过资金 / 财务计划和商业声明来体现。
Completion 完井		4.7, 6.2, 7.2, 8.9	Completion of a well. The process by which a well is brought to its final classification—basically dry hole, producer, injector, or monitor well. A dry hole is normally plugged and abandoned. A well deemed to be producible of petroleum, or used as an injector, is completed by establishing a connection between the reservoir(s) and the surface sothat fluids can be produced from, or injected into, the reservoir. Various methods are utilized to establish this connection, but they commonly involve the installation of some combination of borehole equipment, casing and tubing, and surface injection or production facilities. 指钻井的最后环节——通过该环节确定一口井的最终类型—干井、生产井、注入井或监测井；干井通常是打水泥塞后废弃；油气生产井和注入井的完井是要连通油气藏与地面，使流体能够从油气藏采出或注入油气藏，连通有多种方式，但通常包括安装一些井下组合装置、套管或油管、地面注入或生产设施等。

Term 术语	Reference* 参考文献 *	Used in These Guidelines 本指南引述情况	Definition 定义
Completion Interval 完井层段		none —no occurrences 未出现	The specific reservoir interval(s) that is (are) open to the borehole and connected to the surface facilities for production or injection, or reservoir intervals open to the wellbore and each other for injection purposes. 井下打开的、与地面设施相连通的、能够进行生产和注入的油气藏层段，或者是为了注入目的而在井下打开的互相连通的油气藏层段。
Concession 租让合同	2001- 9.6.1	7.3, 10.7	A grant of access for a defined area and time period that transfers certain entitlements to produced hydrocarbons fromthe host country to an enterprise. The enterprise is generally responsible for exploration, development, production, and sale of hydrocarbons that may be discovered. Typically granted under a legislated fiscal system where the host country collects taxes, fees, and sometimes royalty on profits earned. 指特定区域和时期的准入，资源国把生产油气的某些权益转让给企业，企业通常负责油气勘探、开发、开采和采出量的销售；资源国依据立法规定的财税制度收取相关的税、费，有时还要针对企业所获利润收取矿费。
Condensate 凝析油	2001- 3.2	4.16, 7.1, 8.2, 9.10	A mixture of hydrocarbons (mainly pentanesand heavier) that exist in the gaseous phaseat original temperature and pressure of the reservoir, but when produced, are in the liquid phase at surface pressure and temperature conditions. Condensate differs from natural gas liquids (NGL) in two respects: 1) NGL is extracted and recoveredin gas plants rather than lease separators orother lease facilities; and 2) NGL includes very light hydrocarbons (ethane, propane, butanes) as well as the pentanes-plus that are the main constituents of condensate. Compare to Natural Gas Liquids (NGL) . 凝析油是在原始地层温度和压力条件下以气态存在于储层中的烃混合物（主要是戊烷及以上重组分），但是在采出时，在地面压力和温度条件下以液态存在；凝析油不同于天然气液，主要表现在两个方面：（1）天然气液主要在天然气处理厂提取、回收，而不是在合同区分离器或者其他合同区设施中提取、回收；(2) 天然气液既包含轻烃组分（乙烷、丙烷、丁烷），也包含作为凝析油主要组分的戊烷及以上重组分；对照术语“天然气液（NGL）”。
Conditions 条件	2007- 3.1	2.1, 3.9, 4.6, 5.3, 6.4, 7.17, 8.6, 9.6, 10.1	The economic, marketing, legal, environmental, social, and governmental factors forecast to exist and impact the project during the time period being evaluated (also termed Contingencies). 预计在评价期内存在并对项目产生影响的经济、市场、法律、环境、社会以及政府等因素（也称或有因素）。

Term 术语	Reference* 参考文献 *	Used in These Guidelines 本指南引述情况	Definition 定义
Constant Case 恒定方案	2007 - 3.1.1	7.11	Modifier applied to project resources estimates and associated cash flows when such estimates are based on those conditions (including costs and product prices) that are fixed at a defined point in time (or period average) and are applied unchanged throughout the project life, other than those permitted contractually. In other words, no inflation or deflation adjustments are made to costs, product prices, or revenues over the evaluation period. 对项目资源估算量及相关的现金流的评估是基于评估条件（包括成本和产品价格）在某时间点为固定值（或阶段平均值），并在整个项目生命期内保持不变，合同允许变化除外；换言之，在整个评估期的成本和收入不进行通货膨胀或通货紧缩的相应调整。
Contingency 或有因素	2007- 3.1 and Table 1 2007 - 3.1 和表 1	2.4, 7.1	See Conditions. 参见术语“条件（Conditions）”。
Contingent Project 或有项目	2007 - 2.1.2	none —no occurrences 未出现	Development and production of recoverable quantities has not been committed due to conditions that may or may not be fulfilled. 由于能否满足各种条件尚不确定（可能满足也可能不满足），可采量的开发和生产尚未承诺的项目。
Contingent Resources 条件资源量	2007- 1.1 and Table 1 2007- 1.1 和表 1	2.27, 3.2, 4.29, 5.3, 6.2, 7.4, 8.18, 10.1	Those quantities of petroleum estimated, as of a given date, to be potentially recoverable from known accumulations by application of development projects but which are not currently considered to be commercially recoverable due to one or more contingencies. Contingent Resources are a class of discovered recoverable resources. 截至给定日期评估的，通过实施开发项目，从已知的油气聚集体中潜在可采的石油数量，但由于一个或多个或有条件，目前不被视为是商业可采的；条件资源量是已发现可采资源量类别之一。
Continuous-Type Deposit 连续型沉积体	2007- 2.4 2001- 2.3	8.1	A petroleum accumulation that is pervasive throughout a large area and which is not significantly affected by hydrodynamic or buoyancy influences. Such accumulations are included in Unconventional Resources. Examples of such deposits include “basin-centered” gas, shale gas, gas hydrates, natural bitumen and oil shale accumulations. 一种大面积广泛分布的油气聚集体，不受水动力效应的明显影响。这些聚集体属于非常规资源，例如盆地中心气、页岩气、天然气水合物、天然沥青和油页岩聚集体。

Term 术语	Reference* 参考文献 *	Used in These Guidelines 本指南引述情况	Definition 定义
Conventional Crude Oil 常规原油	2007- 2.4	none —no occurrences 未出现	Crude Oil flowing naturally or capable of being pumped without further processing or dilution [see Crude Oil and compare to Synthetic Crude Oil (SCO)]. 可以自喷或者不需要进一步处理或稀释就可以用泵抽汲出来的原油；参见术语“原油（Crude Oil）”，参照“合成原油(SyntheticCrude Oil)”。
Conventional Gas 常规天然气	2007- 2.4	8.3	Conventional Gas is a natural gas, trapped by buoyancy, occurring in a normal porous and permeable reservoir rock, either in the gaseous phase or dissolved in crude oil, and which technically can be produced by normal production practices. 常规天然气是指以气态或溶解在原油中的形式存在于常规多孔可渗透储层岩石中、靠浮力捕获的天然气，在技术上可以通过常规的生产方式开采。
Conventional Resources 常规资源	2007- 2.4	1.1, 8.3	Conventional resources exist in discrete petroleum accumulations related to localizedgeological structural features and/or stratigraphic conditions, typically with each accumulation bounded by a downdip contactwith an aquifer, and which is significantly affected by hydrodynamic influences such as buoyancy of petroleum in water. 常规资源指离散存在于局部地质构造和（或）岩性地层中的油气聚集体，通常每个油气聚集体的下倾边界有水体，受水动力效应影响明显（如石油在水中受到的浮力）。
Conveyance 转让	2001- 9.6.9	10.11	Certain transactions that are in substance borrowings repayable in cash or its equivalent and shall be accounted for as borrowings and may not qualify for the recognition and reporting of oil and gas reserves. 实质借款并用现金或现金等价物还贷的某些交易，这类交易须以借入项记账，可能不能作为油气储量来认定和报告。
Cost Recovery 成本回收	2001- 9.6.2, 9.7.2	10.21	Under a typical production-sharing agreement, the contractor is responsible for the field development and all exploration and development expenses. In return, the contractor recovers costs (investments and operating expenses) out of the gross production stream. The contractor normally receives payment in oil production and is exposed to both technical and market risks. 在典型的产品分成协议中，合同者负责油田开发并承担所有的勘探开发费用，作为回报，合同者从总产量中回收成本（包括投资和操作费）；合同者一般通过原油产量的形式获得支付，但要承担技术和市场双重风险。

Term 术语	Reference* 参考文献 *	Used in These Guidelines 本指南引述情况	Definition 定义
Crude Oil 原油	2001- 3.1	4.2, 7.1, 8.3, 9.9	Petroleum that exists in the liquid phase in natural underground reservoirs and remains liquid at atmospheric conditions of pressure and temperature. Crude Oil may include small amounts of nonhydrocarbons produced with the liquids but does not include liquids obtained from the processing of natural gas. 以液态存在于天然地下油气藏内且在地面压力温度条件下仍为液态的石油；原油可以包括少量随流体产出的非烃，但不包括在天然气处理过程中得到的液体。
Crude Oil Equivalent 原油当量	2001- 3.7	none —no occurrences 未出现	Conversion of gas volumes to their oil equivalent, customarily done on the basis of the nominal heating content or caloric value of the fuel. Before aggregating, the gas volumes first must be converted to the sametemperature and pressure. Common industry gas conversion factors usually range between 1 barrel of oil equivalent (BOE) = 5,600–6,000 standard cubic feet of gas. (Also termed Barrels of Oil Equivalent.) 将天然气体积换算为相应的原油当量，通常是根据名义热焓或燃料热值来换算；在汇并之前，首先要将天然气体积换算到与油相同的温度、压力条件下，再进一步将其换算为原油当量；常见的行业天然气换算系数范围是 1 桶油当量（BOE）=5600～6000 立方英尺天然气。也称为桶油当量。
Cumulative Production 累计产量	2007- 1.1	4.27, 7.1, 10.2	The sum of production of oil and gas to date (see also Production). 原油和天然气截至目前的产量总和。参见术语“产量”（Production）。
Current Economic Conditions 当前经济条件	2007- 3.1.1	7.3	Establishment of current economic conditions should include relevant historical petroleum prices and associated costs and may involve a defined averaging period. TheSPE guidelines recommend that a one-year historical average of costs and prices shouldbe used as the default basis of “constant case” resources estimates and associated project cash flows. 当前经济条件的建立应包括有关的历史油气价格和相关成本费用，还可能包括所规定的平均期限；SPE 指南建议采用一年的平均历史成本和价格作为“恒定方案”资源量估算和项目现金流的默认基础。

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Cushion Gas Volume 垫底气量		none —no occurrences 未出现	With respect to underground natural gas storage, the gas volume required in a storage field for reservoir management purposes and to maintain adequate minimum storage pressure for meeting working gas volume delivery with the required withdrawal profile. In caverns, the cushion gas volume is also required for stability reasons. The cushion gas volume may consist of recoverable and nonrecoverable in-situ gas volumes and/or injected gas volumes. 在天然气地下储气库中，垫底气量（CGV）是出于气藏管理的需要，为了维持足够的最低储存压力以满足工作气量交付所要求的采出剖面所需气量；在溶洞中，为了保持稳定也需要垫底气量；垫底气量可以包括地下可采气量和不可采气量及注入气量。
Deposit 沉积体	2007– 2.4	5.1, 8.14	Material that has accumulated due to a natural process. In resource evaluations it identifies an accumulation of hydrocarbons in a reservoir (see Accumulation). 自然聚集形成的物质。在资源评价中，指油气藏中的一个油气聚集体；参见术语“ 油气聚集体（Accumulation）”。
Deterministic Estimate 确定法评估	2007– 3.5	2.2, 3.1, 6.2, 7.1	The method of estimation of Reserves or Resources is called deterministic if a discrete estimate(s) is made based on known geoscience, engineering, and economic data. 根据已知的地球科学、工程和经济数据获得储量或资源量的离散估算结果的评估方法。
Developed Reserves 已开发储量	2007– 2.1.3.2 and Table 2 2007– 2.1.3.2 和表 2	3.1, 6.1, 8.1	Developed Reserves are expected to be recovered from existing wells including reserves behind pipe. Improved recovery reserves are considered “ Developed ” only after the necessary equipment has been installed, or when the costs to do so are relatively minor compared to the cost of a well. Developed Reserves may be further subclassified as Producing or Non-Producing. 已开发储量指预计可以从现有井中采出的石油数量，包括管外储量；提高采收率获得的储量只有在所需设施安装后，或当其费用低于一口新钻井费用时，才可视为已开发储量；已开发储量可进一步细分为已开发正生产储量和已开发未生产储量。
Developed Producing Reserves 已开发 正生产储量	2007-2.1.3.2 and Table 2 2007-2.1.3.1 和表 2	2.1, 8.1	Developed Producing Reserves are expected to be recovered from completion intervals that are open and producing at the time of the estimate. Improved recovery reserves are considered producing only after the improved recovery project is in operation. 已开发正生产储量是指预计从评估时已打开并正在生产的完井层段中采出的储量；提高采收率获得的储量只有进入实施阶段才能划分为已开发正生产储量。

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Developed Non-producing Reserves 已开发 未生产储量	2007-2.1.3.2 and Table 2 2007-2.1.3.2 和表 2	2.1	Developed Non-Producing Reserves include shut-in and behind-pipe Reserves. Shut-in Reserves are expected to be recovered from (1) completion intervals that are open at the time of the estimate but which have not yet started producing, (2) wells that were shut in for market conditions or pipeline connections, or (3) wells not capable of production for mechanical reasons. Behind-pipe Reserves are also those expected to be recovered from zones in existing wells that will require additional completion work or future recompletion prior to start of production. In all cases, production can be initiated or restored with relatively low expenditure compared to the cost of drilling a new well. 已开发未生产储量包括关井和管外储量；关井储量是指预计从以下情况采出的量：（1）评估时已打开但尚未投产的完井层段；（2）由于市场条件和管线连接原因而关停的井；（3）由于机械原因不能生产的井；管外储量也包括预计从现有井层段中采出的储量，这些储量需要追加完井或者未来重新完井才能生产；无论何种情况下，投产或恢复生产的费用都比新钻一口井的成本低。
Development not Viable 开发不可行	2007-2.1.3.1 and Table 1 2007-2.1.3.1 和表 1	2.6, 8.3	A discovered accumulation for which there are no current plans to develop or to acquire additional data at the time due to limited production potential. A project maturity sub-class that reflects the actions required to move a project toward commercial production. 一个已发现的油气聚集体，由于生产潜力小，目前没有开发或采集更多数据的计划；它是一个项目成熟度的亚类，反映了项目要实现商业化生产尚需采取的行动。
Development Pending 待开发	2007-2.1.3.1 and Table 1 2007-2.1.3.1 和表 1	2.4	A discovered accumulation where project activities are ongoing to justify commercial development in the foreseeable future. A project maturity subclass that reflects the actions required to move a project toward commercial production. 一个已发现的油气聚集体，其项目活动正在论证其近期的商业开发合理性；它是一个项目成熟度的亚类，反映了项目要实现商业化生产尚需采取的行动。
Development Plan 开发方案	2007-1.2	1.1, 2.12, 3.2, 4.5, 5.2, 6.1, 8.4, 9.1	The design specifications, timing, and cost estimates of the development project that can include, but is not limited to, well locations, completion techniques, drilling methods, processing facilities, transportation and marketing. (See also Project.) 项目进行开发的设计说明、时间安排和成本评估，包括（但不限于）井位、完井技术、钻井方法、处理设施、运输和市场情况等；参见“项目（Project）”。

Term 术语	Reference* 参考文献 *	Used in These Guidelines 本指南引述情况	Definition 定义
Development Unclarified or on Hold 开发不明确或延迟开发	2007-2.1.3.1 and Table 1 2007-2.1.3.1 和表 1	2.3	A discovered accumulation where project activities are on hold and/or where justification as a commercial development may be subject to significant delay. A project maturity subclass that reflects the actions required to move a project toward commercial production. 一个已发现的油气聚集体，其项目活动暂停和 / 或商业开发合理性的论证可能长期推迟；它是一个项目成熟度的亚类，反映了项目要实现商业化生产所需采取的行动。
Discovered 已发现	2007-2.1.1	2.10, 4.5, 5.1, 6.1, 7.3, 8.8	A discovery is one petroleum accumulation, or several petroleum accumulations collectively, for which one or several exploratory wells have established through testing, sampling, and/or logging the existence of a significant quantity of potentially moveable hydrocarbons. In this context, “ significant ” implies that there is evidence of a sufficient quantity of petroleumto justify estimating the in-place volume demonstrated by the well(s) and for evaluating the potential for economic recovery. (See also Known Accumulations.) 指通过已钻的一口或者几口探井，经过测试、取样或测井确认存在相当数量的潜在可动油气的一个油气藏或者几个油气藏的集合；“ 相当数量 ” 意味着通过钻井资料确认地下存在充足的可经济开采的油气数量；参见术语 “ 已知油气聚集体（Known Accumulations） ”。
Discovered Petroleum Initially-In-Place 已发现石油原始原地量	2007-1.1	none —no occurrences 未出现	Discovered Petroleum Initially-In-Place is that quantity of petroleum that is estimated, as of a given date, to be contained in known accumulations prior to production. Discovered Petroleum Initially-In-Place may be subdivided into Commercial, Sub-Commercial, and Unrecoverable, with the estimated commercially, recoverable portion being classified as Reserves and the estimated subcommercial recoverable portion being classified as Contingent Resources. 在规定日期所估算的已知油气聚集体在投产前所含的油气数量；已发现石油原始原地量可划分为商业的、次商业的和不可采量，其中商业的可采估算量归类为储量，次商业的可采估算量归类为条件资源量。
Dry Gas 干气	2001- 3.2	8.1, 9.2	Natural gas remaining after hydrocarbons liquids have been removed prior to the Reference Point (see definition). The dry gas and removed hydrocarbon liquids are accounted for separately in resource assessments. It should be recognized that this is a resource assessment definition and not a phase behavior definition. (also called Lean Gas) 干气是指在到达参照点（参见定义）之前脱去液烃的天然气；干气和脱去的液烃在资源评价中应分别记账，应注意这是资源评估的定义，而不是相态定义（干气也称贫气）。

Term 术语	Reference* 参考文献 *	Used in These Guidelines 本指南引述情况	Definition 定义
Dry Hole 干井	2001- 2.5	4.2, 8.1	A well found to be incapable of producing either oil or gas in sufficient quantities to justify completion as an oil or gas well. 被证实不能生产足够的油气数量，而不能作为油井或气井完井的井。
Economic 经济的	2007- 3.1.2 2001- 4.3	2.14, 4.22, 5.6, 6.2, 7.46, 8.25, 9.2, 10.8	In relation to petroleum Reserves and Resources, economic refers to the situation where the income from an operation exceeds the expenses involved in, or attributable to, that operation. 在油气储量和资源量评估中，经济的是指作业的收入超过其相关支出的情景。
Economic Interest 经济权益	2001- 9.4.1	7.2, 10.12	An Economic Interest is possessed in every case in which an investor has acquired any Interest in mineral in place and secures, by any form of legal relationship, revenue derived from the extraction of the mineral to which he must look for a return of his capital. 投资者已获得矿产原地量的权益，并以任何形式的合法关系得到采矿收入，以寻求资本回报时，即持有经济权益。
Economic Limit 经济极限	2007- 3.1.2 2001- 4.3	4.27, 7.10, 8.3, 9.1	Economic limit is defined as the production rate beyond which the net operating cash flows (after royalties or share of production owing to others) from a project, which may be an individual well, lease, or entire field, are negative. 经济极限是指极限产量值，低于该产量，项目（可以是单井、租赁区块或整个油田）的作业净现金流（扣除矿费及其他各方的产量分成后）为负值。
Entitlement 份额	2007- 3.3	1.1, 7.1, 9.4, 10.30	That portion of future production (and thus resources) legally accruing to a lessee or contractor under the terms of the development and production contract with a lessor. 依据与出租人签订的开发和生产合同，合法归属于承租人或合同者的那部分未来产量（即资源数量）。
Entity 实体机构	2007- 3.0	5.1, 7.10, 9.1, 10.1	A legal construct capable of bearing legal rights and obligations. In resources evaluations this typically refers to the lessee or contractor which is some form of legal corporation (or consortium of corporations). In a broader sense, an entity can be an organization of any form and may include governments or their agencies. 实体机构指有能力承担法律权利和义务的合法机构。在资源评价中，主要是指承租人或合同者，即某种形式的合法公司（或公司联盟）；在更广意义上，实体机构可以是任何形式的组织，可以包括政府或其代表机构。

Term 术语	Reference* 参考文献 *	Used in These Guidelines 本指南引述情况	Definition 定义
Estimated Ultimate Recovery (EUR) 估算最终可采量	2007- 1.1	4.85, 5.1, 6.2, 7.1, 8.12	Those quantities of petroleum that are estimated, on a given date, to be potentially recoverable from an accumulation, plus those quantities already produced therefrom. 在给定日期估算的，从一个油气聚集体中将来可能采出的石油数量，加上已经采出的数量。
Evaluation 评估	2007- 3.0	1.4, 2.15, 3.2, 4.4, 5.2, 6.1, 7.42, 8.5, 10.1	The geosciences, engineering, and associated studies, including economic analyses, conducted on a petroleum exploration, development, or producing project resulting in estimates of the quantities that can be recovered and sold and the associated cash flow under defined forward conditions. Projects are classified and estimates of derived quantities are categorized according to applicable guidelines. (Also termed Assessment.) 指对石油勘探、开发或生产项目进行的地球科学、工程和相关研究（包括经济分析等），可得到规定的未来条件下油气可采和销售的估算量以及相关的现金流；可根据适用的指南对项目进行分类，对得到的估算量进行分级；也称为“评估（Assessment）”。
Evaluator 评估师	2007-1.2, 2.1.2	2.2, 4.5, 5.1, 6.1, 7.5, 8.2	The person or group of persons responsible for performing an evaluation of a project. These may be employees of the entities that have an economic interest in the project or independent consultants contracted for reviews and audits. In all cases, the entity accepting the evaluation takes responsibility for the results, including Reserves and Resources and attributed value estimates. 负责执行项目评价的个人或小组；他们可以是拥有项目经济权益的实体的员工，也可以是受合同聘请、进行审查和审计的独立咨询顾问；不管何种情形，接受评估的实体要对包括储量、资源量及其价值等的评估结果负责。
Exploration 勘探		2.8, 3.4, 4.8, 5.6, 6.4, 7.3, 8.7, 10.16	Prospecting for undiscovered petroleum. 对未发现油气资源的勘察。
Field 油气田	2001- 2.3	1.1, 2.7, 3.18, 4.8, 5.4, 6.52, 7.6, 8.15, 9.19, 10.14	An area consisting of a single reservoir or multiple reservoirs all grouped on, or related to, the same individual geological structural feature and/or stratigraphic condition. There may be two or more reservoirs in a field that are separated vertically by intervening impermeable rock, laterally by local geologic barriers, or both. The term may be defined differently by individual regulatory authorities. 由单个油气藏或多个地质构造特征和地层条件相同的油气藏组成的区域；一个油气田可能包含两个或多个油气藏，纵向上由不渗透岩石隔开，横向上由局部地质隔层隔开，或二者兼有；各监管机构可能对该术语有不同定义。

Term 术语	Reference* 参考文献 *	Used in These Guidelines 本指南引述情况	Definition 定义
Flare Gas 火炬气	2007- 3.2.2	9.1	Total volume of gas vented or burned as part of production and processing operations. 生产和处理作业过程中被排放或烧掉的天然气总量。
Flow Test 产能测试	2007- 2.1.1	none —no occurrences 未出现	An operation on a well designed to demonstrate the existence of moveable petroleum in a reservoir by establishing flow to the surface and/or to provide an indication of the potential productivity of that reservoir (such as a wireline formation test). 指通过将石油开采到地面和 / 或得到该油气藏潜在产能指标，为论证油气藏中存在可流动油气而设计的井中作业（例如电缆地层测试）。
Fluid Contacts 流体界面	2007- 2.2.2	3.2, 4.1	The surface or interface in a reservoir separating two regions characterized by predominant differences in fluid saturations. Because of capillary and other phenomena, fluid saturation change is not necessarily abrupt or complete, nor is the surface necessarily horizontal. 油气藏内将流体饱和度具明显差异的两个区域分隔开的表面或界面；由于毛细管和其他现象的影响，流体饱和度变化不一定是突变的或完全的，界面也不一定是水平的。
Forecast Case 预测方案	2007- 3.1.1	7.15	Modifier applied to project resources estimates and associated cash flow when such estimates are based on those conditions (including costs and product price schedules) forecast by the evaluator to reasonably exist throughout the life of the project. Inflation or deflation adjustments aremade to costs and revenues over the evaluation period. 对项目资源估算量及相关现金流的评估是基于评估师对项目整个生命期评估条件（包括成本和产品价格剖面）的合理预测；评价期的成本和收入可进行通货膨胀或通货紧缩的调整。
Forward Sales 远期销售	2001- 9.6.6	10.1	There are a variety of forms of transactions that involve the advance of funds to the owner of an interest in an oil and gas property in exchange for the right to receive the cash proceeds of production, or the production itself, arising from the future operation of the property. In such transactions, the owner almost invariably has a future performance obligation, the outcome of which is uncertain to some degree. Determination as to whether the transaction represents a sale or financing rests on the particular circumstances of each case. 指先向油气资产权益人预付资金，从而有权从未来资产运营中获得产量的现金收入或者实物油气的多种交易形式；在这些交易中，油气权益人几乎总是负有未来开发效果的义务，但其结果有某种程度的不确定性；决定交易是出售还是进行融资取决于各案例具体情况。

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Fuel Gas 燃料气	2007- 3.2.2	4.1, 7.1, 9.1	See Lease Fuel. 参见术语“ 合同区自用燃料（Lease Fuel） ”。
Gas Balance 天然气产量平衡	2007- 3.2.7 2001- 3.10	none —no occurrences 未出现	In gas production operations involving multiple working interest owners, an imbalance in gas deliveries can occur. These imbalances must be monitored over time and eventually balanced in accordance with accepted accounting procedures. 在多业主联合作业的天然气生产中，可能出现天然气产量交付不平衡的情形。因此，必须实时监测这些不平衡；并根据认可的会计程序实现最终的平衡。
Gas Cap Gas 气顶气	2001- 6.2.2	none —no occurrences 未出现	Free natural gas that overlies and is in contact with crude oil in the reservoir. It is a subset of Associated Gas. 位于油气藏顶部，与原油接触的游离天然气。气顶气是伴生气的一种。
Gas Hydrates 天然气水合物	2007- 2.4	1.1, 8.9	Naturally occurring crystalline substances composed of water and gas in which a solid water lattice accommodates gas molecules in a cagelike structure, or clathrate. At conditions of standard temperature and pressure (STP), one volume of saturated methane hydrate will contain as much as 164 volumes of methane gas. Because of this large gas-storage capacity, gas hydrates are thought to represent an important future source of natural gas. Gas hydrates are included in unconventional resources, but the technology to support commercial production has yet to be developed. 天然气水合物是水与天然气组成的天然结晶物，其中固态的水分子晶格与气体分子结合，形成笼状或格状结构；在标准温度和压力条件（STP）下，1 体积饱和甲烷水合物可含多达 164 体积的甲烷气；由于储气容量大，天然气水合物被认为是未来天然气的重要来源；天然气水合物为非常规资源的一种，其商业生产技术尚待开发。
Gas Inventory 天然气库存量		none —no occurrences 未出现	The sum of Working Gas Volume and Cushion Gas Volume in underground gas storage. 对于地下储气库，天然气库存量是工作气量与垫底气量之和。
Gas/Oil Ratio (GOR) 气油比	2007- 3.4.4	4.1, 6.1, 7.1, 8.1, 9.7	Gas to Oil Ratio (GOR) in an oil field, calculated using measured natural gas and crude oil volumes at stated conditions. The gas/oil ratio may be the solution gas/oil ratio (Rs); produced gas/oil ratio (Rp); or another suitably defined ratio of gas production to oil production. 油田的气油比是指在规定条件下测量的天然气和原油体积之比；气油比可能是溶解气油比，符号为 Rs；或生产气油比，符号为 Rp；或其他适当定义的天然气产量与石油产量之比。

Term 术语	Reference* 参考文献 *	Used in These Guidelines 本指南引述情况	Definition 定义
Gas Plant Products 天然气处理厂产品		None -no occurrences 未出现	Gas Plant Products are natural gas liquids (or components) recovered from natural gas in gas processing plants and, in some situations, from field facilities. Gas Plant Products include ethane, propane, butanes, butanes/propane mixtures, natural gasoline and plant condensates, sulfur, carbon dioxide, nitrogen, and helium. 天然气处理厂产品是通过天然气处理厂或油气田设施从天然气中回收的天然气液（或组分）；天然气处理厂产品包括乙烷、丙烷、丁烷、丁烷 / 丙烷混合物、天然汽油以及处理厂回收的凝析油、硫、二氧化碳、氮和氦。
Gas-to-Liquids (GTL) Projects 气制油项目		None -no occurrences 未出现	Projects using specialized processing (e.g., Fischer-Tropsch synthesis) to convert natural gas into liquid petroleum products. Typically these projects are applied to large gas accumulations where lack of adequate infrastructure or local markets would make conventional natural gas development projects uneconomic. 气制油项目指应用专门的处理工艺（例如 Fischer-Tropsch 合成法）将天然气转换为液态石油产品的项目，这类项目一般适用于由于缺乏基础设施和当地市场，使常规天然气不能经济开发的大型天然气聚集体。
Geostatistical Methods 地质统计方法	2001- 7.1	none -no occurrences 未出现	A variety of mathematical techniques and processes dealing with the collection, methods, analysis, interpretation, and presentation of masses of geoscience and engineering data to (mathematically) describe the variability and uncertainties within any reservoir unit or pool; specifically related here to resources estimates, including the definition of (all) well and reservoir parameters in 1, 2, and 3 dimensions and the resultant modeling and potential prediction of various aspects of performance. 多种数学方法，用于收集、分析、解释和表现大量的地学和工程资料、从数学方面描述任意油气藏单元的变异性与不确定性的多种数学方法；这里特指与资源评估有关的地质统计方法，包括所有井和油气藏参数在一维、二维和三维的定义以及相应的地质模型和对各种动态的可能预测结果。
High Estimate 高估值	2007- 2.2.2 2001- 2.5	2.10, 4.27, 5.3, 7.4, 8.2	With respect to resources categorization, this is considered to be an optimistic estimate of the quantity that will actually be recovered from an accumulation by a project. If probabilistic methods are used, there should be at least a 10% probability (P10) that the quantities actually recovered will equal or exceed the high estimate. 在资源分级中，高估值是指项目能够从油气藏中实际采出的油气数量的乐观估计；如果应用概率法，则实际采出量至少有 10% 的概率（P10）等于或超过高估值。

Term 术语	Reference* 参考文献 *	Used in These Guidelines 本指南引述情况	Definition 定义
Highest Known Hydrocarbons 已知烃顶	2007- 2.2.2.	4.1	The shallowest occurrence of a producible hydrocarbon accumulation as interpreted from some combination of well log, flow test, pressure measurement, and core data. Hydrocarbons may or may not extend above this depth. Modifiers are often added to specify the type of hydrocarbons (for instance,“ highest known gas ”). 根据测井、产能测试、压力测量和岩心数据等资料综合解释的具有产能的油气聚集体中的最浅部位；该深度的上覆地层可能有油气，也可能没有；通常添加修饰语说明烃的具体类型（如“ 最浅已知气顶 ”）。
Hydrocarbons 烃	2007- 1.1	2.1, 3.2, 6.1, 8.7, 9.2, 10.14	Chemical compounds consisting wholly of hydrogen and carbon. 由碳和氢组成的化合物。
Improved Recovery (IR) 提高采收率	2007- 2.3.4	2.1, 8.2, 10.1	Improved Recovery is the extraction of additional petroleum, beyond Primary Recovery, from naturally occurring reservoirs by supplementing the natural forces in the reservoir. It includes waterflooding and gas injection for pressure maintenance, secondary processes, tertiary processes, and any other means of supplementing natural reservoir recovery processes. Improved recovery also includes thermal and chemical processes to improve the in-situ mobility of viscous forms of petroleum. (Also called Enhanced Recovery.) 提高采收率是指一次采油之后，通过对天然油气藏补充能量采出更多油气的开采方法；提高采收率方法包括水驱和注气等保持压力的二次采油、三次采油方法，以及其他增加天然油气藏可采量的方法；提高采收率方法还包括用来改善各种稠油地下原油流度的热采和化学采油方法（也称强化开采）。
Injection 注入	2001-3.5 2007- 3.2.5	3.6, 4.36, 5.1, 7.2, 8.4, 9.4	The forcing, pumping, or free flow under vacuum of substances into a porous and permeable subsurface rock formation. Injected substances can include either gases or liquids. 通过加压、泵送或空吸自流方式使物质进入地下的多孔渗透性岩层，注入的物质可包括气体或液体。
Justified for Development 已论证可开发	2007-2.1.3.1 and Table 1 2007-2.1.3.1 和表 1	2.5, 7.1	Implementation of the development project is justified on the basis of reasonable forecast commercial conditions at the time of reporting and that there are reasonable expectations that all necessary approvals/contracts will be obtained. A project maturity subclass that reflects the actions required to move a project toward commercial production. 储量报告（或披露）时，开发项目的实施在合理预测商业条件的基础上经过了论证，且可合理预期会获得所有必要的审批 / 合同；它是项目成熟度亚类，反映项目进入商业生产所需的活动。

Term 术语	Reference* 参考文献 *	Used in These Guidelines 本指南引述情况	Definition 定义
Kerogen 干酪根		8.3	Naturally occurring, solid, insoluble organic material that occurs in source rocks and can yield oil or gas upon subjection to heat and pressure. Kerogen is also defined as the fraction of large chemical aggregates in sedimentary organic matter that is insoluble in solvents (in contrast, the fraction that is soluble in organic solvents is called natural bitumen). (See also Oil Shales.) 天然形成于烃源岩内的固态、不溶性有机质，在高温高压下可生成油或气；干酪根也可定义为有机沉积物中不溶于溶剂的高分子化合物（相反，溶于有机溶剂的组分叫天然沥青）；参见术语“油页岩（Oil Shales）”。
Known Accumulation 已知油气聚集体	2007- 2.1.1 2001- 2.2	2.1, 3.2, 8.1	An accumulation is an individual body of petroleum-in-place. The key requirement to consider an accumulation as “known,” and hence containing Reserves or Contingent Resources, is that it must have been discovered, that is, penetrated by a well that has established through testing, sampling, or logging the existence of a significant quantity of recoverable hydrocarbons. 一个油气聚集体是指拥有石油原地量的单个地质体，将一个油气聚集体视作已知（因而含有储量或条件资源量）的关键要求是该油气聚集体必须已被发现，也就是说有井钻遇，通过测试、取样或测井确证该油气聚集体含有大量可开采的油气数量。
Lead 潜在有利区	2007- 2.1.3.1 and Table 1 2007- 2.1.3.1 和表 1	2.1	A project associated with a potential accumulation that is currently poorly defined and requires more data acquisition and/or evaluation in order to be classified as a prospect. A project maturity subclass that reflects the actions required to move a project toward commercial production. 与潜在油气聚集体相关的项目，这类油气聚集体目前尚不确定，需要更多数据采集和 / 或评价才能归为“目标区（Prospect）”；它是项目成熟度亚类，反映项目向商业生产转化所需的活动。
Lease Condensate 合同区凝析油		none -no occurrences 未出现	Lease Condensate is condensate recovered from produced natural gas in gas/liquid separators or field facilities. 合同区凝析油是通过气 / 液分离器或油气田设施，从采出的天然气中回收的凝析油。

Term 术语	Reference* 参考文献 *	Used in These Guidelines 本指南引述情况	Definition 定义
Lease Fuel 合同区自用燃料	2007- 3.2.2	9.1	Oil and/or gas used for field and processing plant operations. For consistency quantities consumed as lease fuel should be treated as part of shrinkage. However, regulatory guidelines may allow lease fuel to be included in Reserves estimates. Where claimed as Reserves, such fuel quantities should be reported separately from sales and their value must be included as an operating expense. 用于油气田和处理厂作业（消耗）的油和 / 或气；为了保持一致性，合同区消耗的自用燃料的数量应该作为损耗来处理；不过，监管机构的指南可能允许将自用燃料纳入储量估算；当申报为储量时，自用燃料应与销售量分别报告，其价值必须纳入操作费。
Lease Plant 合同区处理厂		none -no occurrences 未出现	A general term referring to processing facilities that are dedicated to one or more development projects and the petroleum is processed without prior custody transfer from the owners of the extraction project (for gas projects, also termed “ Local Gas Plant ”). 用于一个或多个开发项目的油气处理设施的统称；油气处理时无需事先从开采项目的所有者手中进行监护权移交（对于天然气项目，也称“ 当地天然气厂 ”）。
Liquefied Natural Gas (LNG) Project 液化天然气项目		9.2	Liquefied Natural Gas projects use specialized cryogenic processing to convert natural gas into liquid form for tanker transport. LNG is about 1/614 the volume of natural gas at standard temperature and pressure. 液化天然气项目是指通过专门的低温处理将天然气转化为液态，以便储罐运输的项目。液化天然气（LNG）的体积大约是在标准温度和压力下天然气体积的 1/614。
Loan Agreement 贷款协议	2001- 9.6.5	10.5	A loan agreement is typically used by a bank, other investor, or partner to finance all or part of an oil and gas project. Compensation for funds advanced is limited to a specified interest rate. 贷款协议通常用于银行、其他投资者或合作伙伴筹措全部或部分油气开发项目的资金，预付资金的补偿只限于规定的利息。

Term 术语	Reference* 参考文献 *	Used in These Guidelines 本指南引述情况	Definition 定义
Low/Best/High Estimates 低 / 最佳 / 高估值	2007-2.2.1, 2.2.2	1.1, 2.5, 3.1, 4.9, 5.1, 7.2, 8.2	The range of uncertainty reflects a reasonable range of estimated potentially recoverable volumes at varying degrees of uncertainty (using the cumulative scenario approach) for an individual accumulation or a project. 不确定性范围，反映一个单一油气聚集体或项目的潜在可采量估值合理范围的不同不确定性程度（使用累积情景法）。
Low Estimate 低估值	2007-2.2.2 2001- 2.5	2.4, 4.18, 5.2, 7.5	With respect to resource categorization, this is considered to be a conservative estimate of the quantity that will actually be recovered from the accumulation by a project. If probabilistic methods are used, there should be at least a 90% probability (P90) that the quantities actually recovered will equal or exceed the low estimate. 资源分级中，低估值指项目能够从油气聚集体中开采出的油气数量的保守估计；如果应用概率法，则实际采出量等于或超过低估值的概率应至少有 90%（P90）。
Lowest Known Hydrocarbons 已知烃底	2007- 2.2.2.	3.1, 5.1	The deepest occurrence of a producible hydrocarbon accumulation as interpreted from well log, flow test, pressure measurement, or core data. 按照测井、产能测试、压力测量或岩心数据解释的具有产能的油气聚集体最深部位。
Marginal Contingent Resources 边际条件资源量	2007- 2.1.3.3	2.1	Known (discovered) accumulations for whicha development project(s) has been evaluated as economic or reasonably expected to become economic but commitment is with held because of one or more contingencies (e.g., lack of market and/or infrastructure). 已知（已发现）油气聚集体，其开发项目经评价是经济可行的，或者可合理预期经济可行，但是由于一种或多种或有因素（例如缺少市场和 / 或基础设施），没有承诺启动开发项目。
Measurement 计量	2007- 3.0	4.4, 5.4, 6.3, 8.1, 9.14	The process of establishing quantity (volumeor mass) and quality of petroleum products delivered to a reference point under conditions defined by delivery contract or regulatory authorities. 按照交付合同或监管机构规定条件确定交付到参照点的石油产品数量（体积或质量）和品质的过程。

Term 术语	Reference* 参考文献 *	Used in These Guidelines 本指南引述情况	Definition 定义
Mineral Interest 矿产权益	2001- 9.3	7.4, 10.6	Mineral Interests in properties including (1) afee ownership or lease, concession, or other interest representing the right to extract oil or gas subject to such terms as may be imposed by the conveyance of that interest; (2) royalty interests, production payments payable in oil or gas, and other non-operating interests in properties operated by others; and (3) those agreements with foreign governments or authorities under which a reporting entity participates in the operation of the related properties or otherwise serves as producer of the underlying reserves (as opposed to being an independent purchaser, broker, dealer, or importer). 合同区资产的矿产权益包括：（1）收益的所有权、租赁权、租让权，或按照权益转让条款规定的其他体现油气开采权利的权益；（2）矿费、油 / 气产品支付，以及在其他作业者经营资产中拥有的其他非作业权益；（3）与外国政府或权威部门签署的协议，根据所签协议，披露实体参与相关油气资产经营或开采地下储量（不同于作为独立的买家、经纪人、经销商或进口商的情形）。
Monte Carlo Simulation 蒙特卡洛模拟法	2001-5 2007-3.5	2.3, 6.2, 7.1	A type of stochastic mathematical simulation that randomly and repeatedly samples input distributions (e.g., reservoir properties) to generate a resulting distribution (e.g., recoverable petroleum volumes). 一种随机数学模拟方法，对输入参数（如油气藏物性）的分布进行随机、重复抽样，产生结果分布（如石油可采量）。
Natural Bitumen 天然沥青	2007- 2.4	2.1, 8.3	Natural Bitumen is the portion of petroleum that exists in the semisolid or solid phase in natural deposits. In its natural state, it usually contains sulfur, metals, and other nonhydrocarbons. Natural Bitumen has a viscosity greater than 10,000 milliPascals per second (mPa.s) (or centipoises) measured at original temperature in the deposit and atmospheric pressure, on a gas-free basis. In its natural viscous state, it is not normally recoverable at commercial rates through a well and requires the implementation of improved recovery methods such as steam injection. Natural Bitumen generally requires upgrading prior to normal refining. (Also called Crude Bitumen.). 指天然沉积矿藏中，以半固态或固态形式存在的石油。在自然状态下，天然沥青通常含有硫、金属及其他非烃类物质；在原始沉积环境温度和大气压力下，脱气天然沥青的黏度超过 10000mPa.s（或 cp）。按照天然沥青的自然黏度，通过井开采的常规方法通常达不到商业产量，需要实施注蒸汽驱等提高采收率方法；进行常规炼制之前，通常需要对天然沥青进行改质处理（也称为原油沥青）。

Term 术语	Reference* 参考文献 *	Used in These Guidelines 本指南引述情况	Definition 定义
Natural Gas 天然气	2007-3.2.3 2001-6.6, 9.4.4	1.1, 4.3, 8.4, 9.8	Natural Gas is the portion of petroleum that exists either in the gaseous phase or is in solution in crude oil in natural underground reservoirs, and which is gaseous at atmospheric conditions of pressure and temperature. Natural Gas may include someamount of nonhydrocarbons. 石油在地下的天然油气藏中，以气态存在或溶解于原油的部分，其在常温常压条件下为气态。天然气中可能含有一些非烃组分。
Natural Gas Inventory 天然气库存量		none -no occurrences 未出现	With respect to underground natural gas storage operations “ inventory ” is the total of working and cushion gas volumes. 对于地下储气库作业，天然气库存量是工作气量和垫底气量的总和。
Natural Gas Liquids (NGL) 天然气液	2007-A13 2001-3.2, 9.4.4	4.2, 6.1, 7.1, 9.3	A mixture of light hydrocarbons that exist in the gaseous phase at reservoir conditions but are recovered as liquids in gas processing plants. NGL differs from condensate in two principal respects: (1) NGL is extracted and recovered in gas plants rather than lease separators or other lease facilities; and (2) NGL includes very light hydrocarbons (ethane, propane, butanes) as well as the pentanes-plus (the main constituent of condensates). 天然气液（NGL）是指在油气藏条件下以气态存在，但在天然气处理厂作为液体回收的轻烃组分混合物。NGL 与凝析油有两个方面的不同：（1）NGL 是在天然气处理厂提取和回收，而不是在合同区分离器或其他合同区设施提取和回收；（2）NGL 既包含轻烃（乙烷、丙烷、丁烷），也包含作为凝析油主要组分的戊烷及以上重组分。
Natural Gas Liquids to Gas Ratio 天然气液与天然气之比		none -no occurrences 未出现	Natural gas liquids to gas ratio in an oil or gas field, calculated using measured natural gas liquids and gas volumes at stated conditions. 油气田中的天然气液与天然气之比是指在规定条件下计量的天然气液量和天然气量的体积之比。
Net-back 净回价	2007-3.2.1	none -no occurrences 未出现	Linkage of input resource to the market price of the refined products. 指（参照点）输入端资源价格与成品油市场价格之间的关联关系。
Net Profits Interest 净利润权益	2001- 9.4.4	none -no occurrences 未出现	An interest that receives a portion of the net proceeds from a well, typically after all costs have been paid. 从井生产石油所获净利润（一般指已支付全部成本后）中分得一部分的权益。
Net Working Interest 净工作权益	2001- 9.6.1	10.2	A company ’ s working interest reduced by royalties or share of production owing to others under applicable lease and fiscal terms. (Also called Net Revenue Interest.) 根据适用的租赁和财税条款，将公司的工作权益扣除矿费或其他各方份额产量(也称为净收入权益)后拥有的权益(也称为净收入权益）。

Term 术语	Reference* 参考文献 *	Used in These Guidelines 本指南引述情况	Definition 定义
Non-Hydrocarbon Gas 非烃气体	2007-3.2.4 2001- 3.3	4.1, 9.12	Natural occurring associated gases such as nitrogen, carbon dioxide, hydrogen sulfide, and helium. If nonhydrocarbon gases are present, the reported volumes should reflect the condition of the gas at the point of sale. Correspondingly, the accounts will reflect the value of the gas product at the point of sale. 天然存在的伴生气，如氮气、二氧化碳、硫化氢和氦气。如果存在非烃气，则报告的体积应反映气体在销售点的条件。相应地，会计账目要反映气体产品在销售点的价值。
Non-Associated Gas 非伴生气		None -no occurrences 未出现	Non-Associated Gas is a natural gas found in a natural reservoir that does not contain crude oil. 非伴生气是指不含原油的天然气藏中的天然气。
Normal Production Practices 常规开采活动		none —no occurrences 未出现	Production practices that involve flow of fluids through wells to surface facilities that involve only physical separation of fluids and, if necessary, solids. Wells can be stimulated, using techniques including, but not limited to, hydraulic fracturing, acidization, various other chemical treatments, and thermal methods, and they can be artificially lifted (e.g., with pumps or gas lift). Transportation methods can include mixing with diluents to enable flow, as well as conventional methods of compression or pumping. Practices that involve chemical reforming of molecules of the produced fluids are considered manufacturing processes. 生产活动指将流体通过井采至地面设施的过程，它只涉及流体（若需要，也包括固体）的物理分离；常规生产可以对井实施增产技术，包括但不限于采用水力压裂、酸化、各种其他化学处理以及热采方法，也可以采用人工举升（例如泵抽或气举）；运输方法除了压缩或泵输等常规方法外，也可以加入稀释剂增强流动性；如果对采出的流体分子进行化学重整，则被认为是制造工艺。
Offset Well Location 补偿井位		8.4	Potential drill location adjacent to an existing well. The offset distance may be governed by well spacing regulations. In the absence of well spacing regulations, technical analysis of drainage areas may be used to define the spacing. For Proved volumes to be assigned to an offset well location, there must be conclusive, unambiguous technical data that supports the reasonable certainty of production of hydrocarbon volumes and sufficient legal acreage to economically justify the development without going below the shallower of the fluid contact or the lowest known hydrocarbon. 紧邻现有生产井井位的潜在钻井位置，补偿距离可以根据井距控制；当不知井距确定规则时，可根据对泄油面积的技术分析来确定补偿距离；对于补偿井位所圈定的证实储量（范围），必须要有确凿的技术数据，支持油气产量的合理确定性，以及有足够的合法面积，证明开发经济可行，且不会低于流体界面或已知烃底。

Term 术语	Reference* 参考文献 *	Used in These Guidelines 本指南引述情况	Definition 定义
Oil Sands 油砂		8.7	Sand deposits highly saturated with natural bitumen. Also called “ Tar Sands. ” Note that in deposits such as the western Canada “ oil sands, ” significant quantities of natural bitumen may be hosted in a range of lithologies including siltstones and carbonates. 富含天然沥青的沉积砂，也称为“ 焦油砂（Tar Sands） ”；请注意有些沉积（如加拿大西部的“ 油砂 ”）中大量天然沥青可能存在于粉砂岩和碳酸盐岩等多种岩性中 。
Oil Shales 油页岩	2007- 2.4	8.13	Shale, siltstone, and marl deposits highly saturated with kerogen. Whether extracted by mining or in-situ processes, the material must be extensively processed to yield a marketable product (synthetic crude oil). 富含干酪根的页岩、粉砂岩和泥灰岩沉积；无论是通过露天挖掘或地下开采，都必须对油页岩进行大量加工才能获得可销售的产品（合成原油）。
On Production 正生产	2007- 2.1.3.1 and Table 1 2007-2.1.3.1 和表 1	2.4, 3.2, 4.2, 7.3, 8.2	The development project is currently producing and selling petroleum to market. A project status/maturity subclass that reflects the actions required to move a project toward commercial production. 指开发项目目前正在生产，并向市场销售石油；它是项目状态 / 成熟度亚类，反映推进项目进入商业生产所需的活动。
Operator 作业者		2.1, 4.2, 7.1, 8.2, 10.1	The company or individual responsible for managing an exploration, development, or production operation. 负责管理勘探、开发或生产作业的公司或个人。
Overlift / Underlift 超提 / 欠提	2007- 3.2.7 2001- 3.9	9.5	Production overlift or underlift can occur in annual records because of the necessity for companies to lift their entitlement in parcel sizes to suit the available shipping schedules as agreed among the parties. At any given financial year-end, a company may be in overlift or underlift. Based on the production matching the company’s accounts, production should be reported in accord with and equal to the liftings actually made by the company during the year, and not on the production entitlement for the year. 产量超提 / 欠提可在年度记录中出现，因为公司打包提取份额油量必须满足伙伴们一致同意的船运计划量；在任一给定的财务年底，公司可能出现超提或者欠提；在与公司账目相符的产量基础上，披露的产量应该与公司当年实际提取的油量一致，而不是与公司当年的产量份额一致。
Penetration 钻遇	2007- 1.2	2.1	The intersection of a wellbore with a reservoir. 井筒与油气藏的交会。

Term 术语	Reference* 参考文献 *	Used in These Guidelines 本指南引述情况	Definition 定义
Petroleum 石油	2007- 1.0	1.12，2.11，3.1，4.31，5.3，7.28，8.18, 9.1, 10.4	Petroleum is defined as a naturally occurring mixture consisting of hydrocarbons in the gaseous, liquid, or solid phase. Petroleum may also contain nonhydrocarbon compounds, common examples of which are carbon dioxide, nitrogen, hydrogen sulfide, and sulfur. In rare cases, nonhydrocarbon content could be greater than 50%. 石油是自然形成的由气态、液态或固态烃组成的混合物；石油也可能包含非烃化合物，其中常见的如二氧化碳、氮气、硫化氢和硫；在极少数情况下，非烃组分的含量可能大于 50%。
Petroleum Initially-In-Place 石油原始原地量	2007- 1.1	2.2	Petroleum Initially-In-Place is the total quantity of petroleum that is estimated to exist originally in naturally occurring reservoirs. Crude oil in-place, natural gas in-place and natural bitumen in-place are defined in the same manner (see Resources). (Also referred as Total Resource Base or Hydrocarbon Endowment.) 石油原始原地量是指天然油气藏中原始存在的石油估算总量；原油原地量、天然气原地量和天然沥青原地量定义的方式相同；参见术语“资源（Resources）”（也称为总资源基础或油气禀赋）。
Pilot Project 先导试验项目	2007-2.3.4，2.4	2.5, 4.6, 8.3	A small-scale test or trial operation that is used to assess the suitability of a method for commercial application. 用于评价某种方法商业适用性的小规模试验或试运行。
Play 远景区	2007- 2.1.3.1 and Table 1 2007-2.1.3.1 和表 1	2.1, 8.15	A project associated with a prospective trend of potential prospects, but which requires more data acquisition and/or evaluation in order to define specific leads or prospects. A project maturity subclass that reflects the actions required to move a project toward commercial production. 指有潜力成为潜力目标区的项目，但需要更多的数据采集和 / 或评价才能确定为具体的潜在有利区或目标区，它是项目成熟度亚类，反映项目向商业生产转化所需的活动。
Pool 油气聚集单体		3.5, 6.1	An individual and separate accumulation of petroleum in a reservoir. 油气藏中，单个离散的油气聚集体。

Term 术语	Reference* 参考文献 *	Used in These Guidelines 本指南引述情况	Definition 定义
Possible Reserves 可能储量	2007- 2.2.2 and Table 3 2007 - 2.2.2 和表 3	1.1, 2.5, 4.1, 5.1, 10.4	An incremental category of estimated recoverable volumes associated with a defined degree of uncertainty. Possible Reserves are those additional reserves that analysis of geoscience and engineering datasuggest are less likely to be recoverable than Probable Reserves. The total quantitiesultimately recovered from the project have a low probability to exceed the sum of Proved plus Probable plus Possible (3P), which is equivalent to the high estimate scenario. When probabilistic methods are used, there should be at least a 10% probability that the actual quantities recovered will equal or exceed the 3P estimate. 与指定不确定性程度相关联的可采估算量增量级别。可能储量，指通过地球科学和工程数据分析表明其开采可能性低于概算储量的储量增量；项目的最终可采量超过证实储量、概算储量与可能储量之和（3P）的概率较低，这相当于高估值的情景；当采用概率法时，实际采出量等于或超过 3P 估值的概率应至少为 10%。
Primary Recovery 一次开采		2.1, 4.1	Primary recovery is the extraction of petroleum from reservoirs utilizing only the natural energy available in the reservoirs to move fluids through the reservoir rock to other points of recovery. 一次开采是指仅利用油气藏天然能量将流体从储层送入井底、采出地面的石油开采方式。
Probability 概率	2007- 2.2.1	2.19, 3.1, 5.44, 6.23, 7.16, 8.1	The extent to which an event is likely to occur, measured by the ratio of the favorable cases to the whole number of cases possible. SPE convention is to quote cumulative probability of exceeding or equaling a quantity where P90 is the small estimate and P10 is the large estimate. (See also Uncertainty.) 一个事件发生的可能程度，用出现的有利案例数与所有可能案例数之比表示；SPE 的惯用做法是引用超过或等于某一数量的累积概率，其中 P90 为低估值，P10 为高估值；参见术语“不确定性（Uncertainty）”。
Probabilistic Estimate 概率法评估	2007- 3.5	5.3, 7.1	The method of estimation of Resources is called probabilistic when the known geoscience, engineering, and economic data are used to generate a continuous range of estimates and their associated probabilities. 用已知的地球科学、工程和经济数据产生一个连续的估值范围及其相应概率的资源评估方法。

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Probable Reserves 概算储量	2007- 2.2.2 and Table 3 2007 - 2.2.2 和表 3	1.1, 2.4, 6.2, 8.3, 10.3	An incremental category of estimated recoverable volumes associated with a defined degree of uncertainty. Probable Reserves are those additional Reserves that are less likely to be recovered than Proved Reserves but more certain to be recovered than Possible Reserves. It is equally likely that actual remaining quantities recovered will be greater than or less than the sum of the estimated Proved plus Probable Reserves (2P). In this context, when probabilistic methods are used, there should be at least a 50% probability that the actual quantities recovered will equal or exceed the 2P estimate. 一种与规定的不确定性程度相关的可采估算量的增量级别；概算储量是通过地球科学和工程数据分析表明其采出的可能性低于证实储量，但确定性高于可能储量的储量增量；实际剩余采出量大于或小于证实储量加概算储量（2P）的可能性相同；就是说，当采用概率法时，实际采出量等于或超过 2P 估值的概率应至少为 50%。
Production 产量	2007- 1.1	1.1, 2.13, 3.12, 4.151, 5.12, 6.10, 7.44, 8.89, 9.42, 10.78	Production is the cumulative quantity of petroleum that has been actually recovered over a defined time period. While all recoverable resource estimates and production are reported in terms of the sales product specifications, raw production quantities (sales and nonsales, including nonhydrocarbons) are also measured to support engineering analyses requiring reservoir voidage calculations. 产量是指在规定时间段已实际采出的累计石油数量；虽然所有可采资源估算量和产量都是以销售产品量报告的，但也需要计量井口原料产量（销售部分和非销售部分，包括非烃产量），以计算油藏亏空、支持油藏工程分析。
Production-Sharing Contract 产品分成合同	2007- 3.3.2 2001- 9.6.2	10.33	In a production-sharing contract between a contractor and a host government, the contractor typically bears all risk and costs for exploration, development, and production. In return, if exploration is successful, the contractor is given the opportunity to recover the incurred investment from production, subject to specific limits and terms. Ownership is retained by the host government; however, the contractor normally receives title to the prescribed share of the volumes as they are produced. 在合同者与资源国政府签订的产品分成合同中，通常由合同者承担勘探、开发和生产的所有风险和费用，作为回报，如果勘探获得成功，合同者则有机会根据合同具体条款和限制从石油产量中回收投资；石油的所有权属于资源国政府，但正常情况下，合同者可以按规定获得石油产量分成。

Term 术语	Reference* 参考文献 *	Used in These Guidelines 本指南引述情况	Definition 定义
Profit Split 利润劈分	2001- 9.6.2	10.7	Under a typical production-sharing agreement, the contractor is responsible for the field development and all exploration and development expenses. In return, the contractor is entitled to a share of the remaining profit oil or gas. The contractor receives payment in oil or gas production and is exposed to both technical and market risks. 典型产品分成合同中，合同者负责油气田的开发，并承担所有勘探和开发费用，作为回报，合同者有权分享剩余的利润油或气；合同者获得油或气产量支付，并承担技术和市场双重风险。
Project 项目	2007-1.2 2001- 2.3	1.2, 2.184, 3.2, 4.172, 5.5, 6.12, 7.158, 8.59, 9.10, 10.47	Represents the link between the petroleum accumulation and the decision-making process, including budget allocation. A project may, for example, constitute the development of a single reservoir or field, or an incremental development in a producing field, or the integrated development of a group of several fields and associated facilities with a common ownership. In general, an individual project will represent aspecific maturity level at which a decision is made on whether or not to proceed (i.e., spend money), and there should be an associated range of estimated recoverable resources for that project. (See also Development Plan.) 项目体现了油气聚集体与决策过程（包括财务预算拨款）之间的联系；举例来说，一个项目可能是单个油气藏或油气田的开发，或者是一个正生产油气田的增量开发，亦或是所有权相同的多个油气田及其地面设施的综合开发；一般而言，一个独立项目将代表一个具体的成熟度水平，以此作为支持是否继续推进项目的决策依据（例如投资），应有一个项目可采估算量的相应范围（参见“开发方案”）。
Property 资产	2007- 1.2 2001- 9.4	2.1, 3.6, 6.3, 7.9, 8.3, 9.1, 10.11	A volume of the Earth ’ s crust wherein a corporate entity or individual has contractual rights to extract, process, and market a defined portion of specified in-place minerals(including petroleum). Defined in general as an area but may have depth and/or stratigraphic constraints. May also be termed a lease, concession, or license. 地壳内的一个区域，在这里，某公司实体或个人已取得合同权利来开采、处理和出售指定地下矿产（包括石油）的规定部分；通常规定的是一个面积区域，但可以有深度和层位方面的限制，也可以称为租赁区、租让区、许可证区等。
Prorationing 配额		none -no occurrences 未出现	The allocation of production among reservoirs and wells or allocation of pipeline capacity among shippers, etc. 指油气藏和井之间的产量分配或交运货物者之间的管输量分配等。

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Prospect 目标区	2007-2.1.3.1 and Table 1 2007-2.1.3.1 和表 1	2.4, 4.3, 5.9, 8.1, 10.1	A project associated with a potential accumulation that is sufficiently well defined to represent a viable drilling target. A project maturity sub-class that reflects the actions required to move a project toward commercial production. 一个与潜在油气聚集体相关的项目，经充分落实，为一个可行的钻井目标；它是项目的成熟度亚类，反映项目向商业生产转化所需的活动。
Prospective Resources 远景资源量	2007- 1.1 and Table 1 2007- 1.1 和表 1	1.1, 2.16, 3.2, 4.8, 6.2, 7.1, 8.5	Those quantities of petroleum that are estimated, as of a given date, to be potentially recoverable from undiscovered accumulations. 在给定日期估算的，可能从未发现的油气聚集体中采出的石油数量。
Proved Economic 证实经济的	2007- 3.1.1	none -no occurrences 未出现	In many cases, external regulatory reporting and/or financing requires that, even if only the Proved Reserves estimate for the project is actually recovered, the project will still meet minimum economic criteria; the project is then termed as “ Proved Economic. ” 多数情况下，外部监管报告规定和 / 或融资要求，即使项目只实际采出证实储量估算量，项目仍能满足经济极限条件，则该项目称为“ 证实经济的 ”。
Proved Reserves 证实储量	2007- 2.2.2 and Table 3 2007- 2.2.2 和表 3	1.1, 2.4, 4.2, 5.3, 6.24, 7.5, 8.4, 9.1, 10.7	An incremental category of estimated recoverable volumes associated with a defined degree of uncertainty. Proved Reserves are those quantities of petroleum which, by analysis of geoscience and engineering data, can be estimated with reasonable certainty to be commercially recoverable, from a given date forward, from known reservoirs and under defined economic conditions, operating methods, and government regulations. If deterministic methods are used, the term reasonable certainty is intended to express a high degree of confidence that the quantities will be recovered. If probabilistic methods are used, there should be at least a 90% probability that the quantities actually recovered will equal or exceed the estimate. Often referred to as 1P, also as “ Proven. ” 与指定不确定性程度相关联的可采量增量级别。证实储量，指通过地球科学和工程数据分析，自给定日期起，在确定的经济条件、作业方式及政府规定下，能合理确定地从已知油气藏中商业开采的石油估算数量。如果采用确定法，则“ 合理确定性 ”这一术语旨在表明采出这些数量的置信度高；若采用概率法，则实际采出量等于或超过估算量的概率应至少是 90%，常称 1P，或“ 证实的 ”。

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Purchase Contract 采购合同	2001- 9.6.8	10.4	A contract to purchase oil and gas provides the right to purchase a specified volume of production at an agreed price for a defined term. 指购买油气的合同，它为买方提供在规定期限内按商定价格购买一定产量的权利。
Pure-Service Contract 纯服务合同	2001- 9.7.5	10.5	A pure-service contract is an agreement between a contractor and a host government that typically covers a defined technical service to be provided or completed during a specific period of time. The service company investment is typically limited to the value of equipment, tools, and expenses for personnel used to perform the service. In most cases, the service contractor’s reimbursement is fixed by the terms of the contract with little exposure to either project performance or market factors. 纯服务合同是合同者和资源国政府之间的一种协议，其内容通常是在指定时期内提供或完成规定的技术服务；服务公司的投资一般只限于设备、工具以及执行服务的人员费用；多数情况下，服务承包商的报酬按合同条款是固定的，基本与项目执行效果或市场因素无关。
Range of Uncertainty 不确定性范围	2007- 2.2 2001- 2.5	2.28, 3.1, 4.3, 5.4, 6.2, 8.2	The range of uncertainty of the recoverable and/or potentially recoverable volumes may be represented by either deterministic scenarios or by a probability distribution. (See Resource Uncertainty Categories.) 可采量和 / 或潜在可采量的不确定性范围可由确定性情景法或概率分布法来表述（参见术语“ 资源不确定性级别 ”）。
Raw Natural Gas 原料天然气	2007- 3.2.1	4.2	Raw Natural Gas is natural gas as it is produced from the reservoir. It includes water vapor and varying amounts of the heavier hydrocarbons that may liquefy in lease facilities or gas plants and may also contain sulfur compounds such as hydrogen sulfide and other nonhydrocarbon gases such as carbon dioxide, nitrogen, or helium, but which, nevertheless, is exploitable for its hydrocarbon content. Raw Natural Gas is often not suitable for direct utilization by most types of consumers. 直接从油气藏中产出的天然气，其包含水蒸气、不同含量的重烃组分（可在合同区设施或天然气处理厂液化），也可能包含硫化物（如硫化氢）和其他非烃气体（如二氧化碳、氮气或氦气），尽管含有非烃组分，但其所含的烃组分是值得开发利用的；原料天然气往往不适合大多数类型消费者直接利用。

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Reasonable Certainty 合理确定性	2007- 2.2.2	4.3, 6.2, 8.1	If deterministic methods for estimating recoverable resource quantities are used, then reasonable certainty is intended to express a high degree of confidence that the estimated quantities will be recovered. 使用确定法评估可采资源量时，合理确定性是指估算的量能被采出有高置信度。
Reasonable Expectation 合理预期	2007- 2.1.2	7.3	Indicates a high degree of confidence (low risk of failure) that the project will proceed with commercial development or the referenced event will occur. 表明该项目进行商业开发或引用事件的发生有高置信度（失败风险低）。
Reasonable Forecast 合理预测	2007- 3.1.2	7.1	Indicates a high degree of confidence in predictions of future events and commercial conditions. The basis of such forecasts includes, but is not limited to, analysis of historical records and published global economic models. 表明对未来事件和商业条件的预测置信度高；合理预测的基础包括（但不限于）对历史记录和已公布的全球经济模型的分析 。
Recoverable Resources 可采资源量	2007- 1.2	2.1, 5.1, 6.1, 8.1	Those quantities of hydrocarbons that are estimated to be producible from discovered or undiscovered accumulations. 可从已发现或未发现油气聚集体中采出的油气估算量。
Recovery Efficiency 采收率	2007- 2.2	2.4, 4.19, 5.1, 8.7, 10.1	A numeric expression of that portion of in-place quantities of petroleum estimated to be recoverable by specific processes or projects, most often represented as a percentage. 采收率是估算的石油原地量中通过特定过程或项目可采出部分的数值表达，其最常用表述方式为百分比。
Reference Point 参照点	2007- 3.2.1	7.1, 9.13	A defined location within a petroleum extraction and processing operation where quantities of produced product are measured under defined conditions prior to custody transfer (or consumption). Also called Point of Sale or Custody Transfer Point. 石油开采与加工处理作业链中的一个指定位置；石油产品在此处进行交付（或消费）之前按规定条件进行计量；也称销售点或交付点。

Term 术语	Reference* 参考文献 *	Used in These Guidelines 本指南引述情况	Definition 定义
Reserves 储量	2007- 1.1	1.15, 2.63, 3.16, 4.106, 5.22, 6.68, 7.50, 8.53, 9.37, 10.112	Reserves are those quantities of petroleum anticipated to be commercially recoverable by application of development projects to known accumulations from a given date forward under defined conditions. Reserves must further satisfy four criteria: They must be discovered, recoverable, commercial, and remaining (as of a given date) based on the development project(s) applied. 储量是指在规定条件下，自指定日期起，可通过开发项目从已知油气聚集体商业开采的石油数量；根据实施的开发项目，储量须满足四个条件：已发现、可采的、商业的、剩余的（截至指定日期）。
Reservoir 油气藏	2001- 2.3	1.1, 2.15, 3.68, 4.208, 5.35, 6.55, 7.2, 8.143, 9.16, 10.3	A subsurface rock formation containing an individual and separate natural accumulation of moveable petroleum that is confined by impermeable rocks/formations and is characterized by a single-pressure system. 含有单个、独立、可流动油气聚集体的岩性地层，由非渗透性岩石 / 地层分隔，并具有单一压力系统。
Resources 资源	2007- 1.1	1.10, 2.5, 3.4, 4.15, 5.5, 6.6, 7.7, 8.17, 9.2, 10.66	The term “ resources ” as used herein is intended to encompass all quantities of petroleum (recoverable and unrecoverable) naturally occurring on or within the Earth ’ s crust, discovered and undiscovered, plus those quantities already produced. Further, it includes all types of petroleum whether currently considered “ conventional ” or “ unconventional ” (see Total Petroleum Initially-In-Place). (In basin potential studies, it may be referred to as Total Resource Base or Hydrocarbon Endowment.) 这里所用术语“ 资源 ”是指地壳中自然形成的所有石油数量（可采的和不可采的），包括已发现和未发现的石油数量，以及已经产出的数量。此外，资源包括所有类型的石油资源，无论是目前的“ 常规 ”还是“ 非常规 ”（参见石油总原始原地量）（在盆地潜力研究中，它也指总资源基础或油气禀赋）。
Resources Categories 资源级别	2007-2.2 and Table 3 2007- 2.2 和表 3	4.8, 5.1, 10.2	Subdivisions of estimates of resources to be recovered by a project(s) to indicate the associated degrees of uncertainty. Categories reflect uncertainties in the total petroleum remaining within the accumulation(in-place resources), that portion of the in-place petroleum that can be recovered by applying a defined development project or projects, and variations in the conditions that may impact commercial development (e.g., market availability, contractual changes). 项目可采资源估算量的相关不确定性程度的资源量细分；不同级别反映了油气聚集体内总剩余石油量（原地量）的不确定性、通过实施规定的某一（些）开发项目可采出石油原地量的那一部分数量的不确定性，以及各种可能影响商业开发的条件（如市场可获得性、合同的变化等）的不确定性。

Term 术语	Reference* 参考文献 *	Used in These Guidelines 本指南引述情况	Definition 定义
Resources Classes 资源类别	2007- 1.1, 2.1 and Table 1 2007- 1.1, 2.1 和表 1	6.1	Subdivisions of Resources that indicate the relative maturity of the development projects being applied to yield the recoverable quantity estimates. Project maturity may be indicated qualitatively by allocation to classes and subclasses and/or quantitatively by associating a project's estimated chance of reaching producing status. 所实施的开发项目采出可采估算量的相对成熟度的资源量细分；项目成熟度可以定性地用类别和亚类来表示，和 / 或定量地用其达到生产状态的几率来表示。
Revenue-Sharing Contract 收入分成合同	2001- 9.6.3	10.3	Revenue-sharing contracts are very similar to the production-sharing contracts described earlier, with the exception of contractor payment. With these contracts, the contractor usually receives a defined share of revenue rather than a share of the production. 收入分成合同和前文介绍的产品分成合同非常相似，只是合同者的支付方式不同；通常合同者从这种合同得到的是规定的油气收入的分成而不是产量分成。
Reversionary Interest 可复归权益		7.1	The right of future possession of an interest in a property when a specified condition has been met. 指将来在满足指定条件时拥有资产权益的权利。
Risk 风险	2001- 2.5	2.24, 3.3, 4.3, 5.6, 6.23, 7.1, 8.7, 10.23	The probability of loss or failure. As “ risk ” is generally associated with the negative outcome, the term “ chance ” is preferred for general usage to describe the probability of a discrete event occurring. 指损失或失败的概率；由于“ 风险（Risk） ”通常与负面结果有关，术语“ 几率 (Chance) ”一般更常用于表述离散事件发生的概率。
Risk and Reward 风险与回报	2001- 9.4	10.2	Risk and reward associated with oil and gas production activities stems primarily from the variation in revenues due to technical and economic risks. Technical risk affects a company ’ s ability to physically extract and recover hydrocarbons and is usually dependent on a number of technical parameters. Economic risk is a function of the success of a project and is critically dependent on cost, price, and political or other economic factors. 与油气生产活动有关的风险和回报主要来源于技术和经济风险引起的收入变化；技术风险影响公司实际开采油气的能力，且常常取决于一些技术参数；经济风险是项目成功的函数，主要取决于成本、价格和政治或其他经济因素。
Risked-Service Contract 风险服务合同	2007- 3.3.2 2001- 9.7.4	10.4	These agreements are very similar to the production-sharing agreements with the exception of contractor payment, but risk is borne by the contractor. With a risked-service contract, the contractor usually receives a defined share of revenue rather than a share of the production. 风险服务合同与产品分成合同很相似，只是合同者的支付方式不同，但合同者要承担风险；在风险服务合同中，合同者通常是获得规定的收入分成而不是产量分成。

Term 术语	Reference* 参考文献 *	Used in These Guidelines 本指南引述情况	Definition 定义
Royalty 矿费	2007- 3.3.1 2001- 3.8	7.16, 9.1, 10.16	Royalty refers to payments that are due to the host government or mineral owner (lessor) in return for depletion of the reservoirs and the producer (lessee/contractor) for having access to the petroleum resources. Many agreements allow for the producer to lift the royalty volumes, sell them on behalf of the royalty owner, and pay the proceeds to the owner. Some agreements provide for the royalty to be taken only in kind by the royalty owner. 矿费指资源国政府或矿产所有者（出租人）从生产者（承租人 / 合同者）开采油气藏获得石油资源的收益中得到的回报；有些协议允许生产者提取矿费对应的产量，代表矿费所有者将其出售，然后向矿费所有者支付收益；有些协议规定矿费只能以实物形式支付给矿费所有者。
Sales 销售量	2007- 3.2	2.6, 4.3, 6.3, 7.9, 9.38, 10.3	The quantity of petroleum product delivered at the custody transfer (reference point) with specifications and measurement conditions as defined in the sales contract and/or by regulatory authorities. All recoverable resources are estimated in terms of the product sales quantity measurements. 按照销售合同和 / 或监管当局规定的规格和计量条件，在交付点（参照点）交付的石油产品的数量；所有可采资源量都按计量的产品销售量评估。
Shut-in Reserves 关井储量	2007- 2.1.3.2 and Table 2 2007- 2.1.3.2 和表 2	none —no occurrences 未出现	Shut-in Reserves are expected to be recovered from (1) completion intervals which are open at the time of the estimate, but which have not started producing; (2) wells which were shut-in for market conditions or pipeline connections; or (3) wells not capable of production for mechanical reasons. 关井储量是期望从以下情况采出的储量：（1）评估时已经打开、尚未投产的完井层段；(2) 由于市场或管线原因而关闭的井；或 (3) 因机械原因而不能生产的井。
Solution Gas 溶解气		4.28, 6.3, 7.1, 8.2	Solution Gas is a natural gas that is dissolved in crude oil in the reservoir at the prevailing reservoir conditions of pressure and temperature. It is a subset of Associated Gas. 溶解气是指在地层压力和温度条件下溶解于储层原油中的天然气，它是伴生气的一种。
Sour Natural Gas 酸性天然气	2001- 3.4	none —no occurrences 未出现	Sour Natural Gas is a natural gas that contains sulfur, sulfur compounds, and/or carbon dioxide in quantities that may require removal for sales or effective use. 酸性天然气是指含硫、硫化物和 / 或二氧化碳达到一定程度的天然气，需要去除后才能销售或有效利用。
Stochastic Estimate 随机评估	2001- 5	2.1, 6.6	Adjective defining a process involving or containing a random variable or variables or involving chance or probability such as a stochastic stimulation. 指涉及或包含一个或一组随机变量，或涉及几率或概率（如随机模拟）的过程。

Term 术语	Reference* 参考文献 *	Used in These Guidelines 本指南引述情况	Definition 定义
Subcommercial 次商业的	2007- 2.1.2	2.2	A project is Subcommercial if the degree of commitment is such that the accumulation is not expected to be developed and placed on production within a reasonable time frame. While 5 years is recommended as a benchmark, a longer time frame could be applied where, for example, development of economic projects are deferred at the option of the producer for, among other things, market-related reasons, or to meet contractual or strategic objectives. Discovered subcommercial projects are classified as Contingent Resources. 如果对一个项目未承诺油气聚集体在合理时间框架内预期开发投产，则该项目属于次商业的；一般建议以五年期限为基准，但有些情形下也可以适用较长的期限，例如生产者出于市场原因，或为实现合同或战略目标，选择推迟经济项目的开发；已发现的次商业的项目划分为条件资源量。
Submarginal Contingent Resources 次边际条件资源量	2007- 2.1.3.3	2.1	Known (discovered) accumulations for which evaluation of development project(s) indicated they would not meet economic criteria, even considering reasonably expected improvements in conditions. 指开发项目评估表明，即使合理预期评估条件改善后项目仍不能满足经济条件的已知（已发现）油气聚集体的资源量。
Sweet Natural Gas 无硫天然气（甜气）	2001- 3.3	none —no occurrences 未出现	Sweet Natural Gas is a natural gas that contains no sulfur or sulfur compounds at all, or in such small quantities that no processing is necessary for their removal in order that the gas may be sold. 无硫天然气指不含或者含极少量硫和硫化物，在销售前不需要去硫处理的天然气。
Synthetic Crude Oil (SCO) 合成原油	2001- A12, A13	8.2	A mixture of hydrocarbons derived by upgrading (i.e., chemically altering) natural bitumen from oil sands, kerogen from oil shales, or processing of other substances such as natural gas or coal. SCO may contain sulfur or other nonhydrocarbon compounds and has many similarities to crude oil. 通过天然沥青（来源于油砂）和干酪根（来源于油页岩）改质（即化学改变），或者通过处理天然气或煤炭等其他物质得到的烃混合物；合成原油可能含硫或其他非烃混合物，与原油有很多的相似之处。
Taxes 税负	2001- 9.4.2	7.15, 8.1, 10.14	Obligatory contributions to the public funds, levied on persons, property, or income by governmental authority. 指政府部门对个人、财产或收入强制征收的用作公共资金的义务费用。
Technical Uncertainty 技术不确定性	2007- 2.2	2.1, 4.1	Indication of the varying degrees of uncertainty in estimates of recoverable quantities influenced by range of potential in-place hydrocarbon resources within the reservoir and the range of the recovery efficiency of the recovery project being applied. 表明油气藏内受潜在油气原地资源量范围和项目采收率范围影响的可采估算量的不确定性程度。

Term 术语	Reference* 参考文献 *	Used in These Guidelines 本指南引述情况	Definition 定义
Total Petroleum Initially-In-Place 石油总原始原地量	2007- 1.1	2.2	Total Petroleum Initially-In-Place is generally accepted to be all those estimated quantities of petroleum contained in the subsurface, as well as those quantities already produced. This was defined previously by the WPC as “ Petroleum in-place ” and has been termed “ Resource Base ” by others. Also termed “ Original in-Place ” or “ Hydrocarbon Endowment. ” 石油总原始原地量通常包括地下含有的全部石油估算量以及已经采出的量；世界石油大会从前将其定义为“ 石油原地量 ”，也有其他人士称其为“ 资源基础 ”；此外，也称“ 原始原地量 ”或“ 油气禀赋 ”。
Uncertainty 不确定性	2007- 2.2 2001- 2.5	2.50, 3.17, 4.28, 5.30, 6.20, 7.8, 8.18, 9.1	The range of possible outcomes in a series of estimates. For recoverable resource assessments, the range of uncertainty reflects a reasonable range of estimated potentially recoverable quantities for an individual accumulation or a project. (See also Probability.) 一系列可能的评估结果估算值的范围；对于可采资源量的评估，不确定性范围反映单个油气聚集体或项目的潜在可采估算量的合理范围（参见术语“ 概率 ”）。
Unconventional Resources 非常规资源	2007- 2.4	1.1, 8.6	Petroleum accumulations that are pervasive throughout a large area and that are not significantly affected by hydrodynamic influences (also referred to as “ continuous-type deposits ”). Examples include coalbed methane (CBM), basin-centered gas, shale gas, gas hydrate, natural bitumen (tar sands), and oil shale deposits. Typically, such accumulations require specialized extraction technology (e.g., dewatering of CBM, massive fracturing programs for shalegas, steam and/or solvents to mobilize bitumen for in-situ recovery, and in some cases, mining activities). Moreover, the extracted petroleum may require significant processing prior to sale (e.g., bitumen upgraders). 非常规资源是指大面积广泛分布、不受水动力效应明显影响的油气聚集体（也称为“ 连续型沉积 ”）；如煤层气（CBM）、盆地中心气、页岩气、天然气水合物、天然沥青 (焦油砂）和油页岩沉积；通常，这些油气聚集体需要专门的开采技术（例如，排水开采煤层气、大规模压裂开采页岩气、蒸汽和 / 或溶剂驱原位开采沥青，以及在某些情况下进行露天挖掘等）；此外，采出的石油在销售前还可能需要进行大量的处理（例如沥青改质）。

Term 术语	Reference* 参考文献 *	Used in These Guidelines 本指南引述情况	Definition 定义
Undeveloped Reserves 未开发储量	2001- 2.1.3.1 and Table 2 2001- 2.1.3.1 和表 2	2.4, 6.1, 8.2	Undeveloped Reserves are quantities expected to be recovered through future investments: (1) from new wells on undrilled acreage in known accumulations, (2) from deepening existing wells to a different (but known) reservoir, (3) from infill wells that will increase recovery, or (4) where a relatively large expenditure (e.g., when compared to the cost of drilling a new well) is required to (a) recomplete an existing well or (b) install production or transportation facilities for primary or improved recovery projects. 未开发储量是指预期可通过未来投资采出的石油数量：（1）从已知油气聚集体未钻井区域所钻新井；（2）从加深现有井到另一不同的（已知）油气藏；（3）从可增加可采量的加密井；（4）需要较大成本（如钻一口新井的成本）用于①一口现有井的重新完井或②为一次采油或提高采收率项目安装生产或运输设施。
Unitization 联合作业		None - no occurrences 未出现	Process whereby owners group adjoining properties and divide reserves, production, costs, and other factors according to their respective entitlement to petroleum quantities to be recovered from the shared reservoir(s). 指所有者们联合开发毗邻的合同区资产，并根据各自在共享油气藏中石油可采量的份额来分割储量、产量、成本和其他要素的过程。
Unproved Reserves 未证实储量	2001- 5.1.1	none -no occurrences 未出现	Unproved Reserves are based on geoscience and/or engineering data similar to that used in estimates of Proved Reserves, but technical or other uncertainties preclude such reserves being classified as Proved. Unproved Reserves may be further categorized as Probable Reserves and Possible Reserves. 未证实储量是根据类似于证实储量估算中所用的地球科学和工程数据得到的，但由于技术或其他方面存在的不确定性，使其不能划分为证实储量；未证实储量可进一步分级为概算储量和可能储量。
Unrecoverable Resources 不可采资源量	2007- 1.1	8.1	That portion of Discovered or Undiscovered Petroleum Initially-In-Place quantities that are estimated, as of a given date, not to be recoverable. A portion of these quantities may become recoverable in the future as commercial circumstances change, technological developments occur, or additional data are acquired. 指在给定日期估算的已发现或未发现石油原始原地量中不能被开采的那部分数量；将来，由于商业环境变化和技术发展或者获得更多资料后不可采量中的一部分可能转化成为可采量。

Term 术语	Reference* 参考文献 *	Used in These Guidelines 本指南引述情况	Definition 定义
Upgrader 改质设施	2007- 2.4	9.2	A general term applied to processing plants that convert extra-heavy crude oil and natural bitumen into lighter crude and less viscous synthetic crude oil (SCO). While the detailed process varies, the underlying concept is to remove carbon through coking or to increase hydrogen by hydrogenation processes using catalysts. 一种应用于将超重原油和天然沥青转化为轻质原油和低黏度合成原油（SCO）的处理加工厂的通用术语；尽管具体处理过程不尽相同，但基本原理都是通过焦化除碳，或者通过催化剂加氢过程增加氢的含量。
Well Abandonment 井的废弃		4.3, 7.3	The permanent plugging of a dry hole, an injection well, an exploration well or a well that no longer produces petroleum or is no longer capable of producing petroleum profitably. Several steps are involved in the abandonment of a well: permission for abandonment and procedural requirements are secured from official agencies; the casing is removed and salvaged if possible; and one or more cement plugs and/or mud are placed in the borehole to prevent migration of fluids between the different formations penetrated by the borehole. In some cases, wells may be temporarily abandoned where operations are suspended for extended periods pending future conversions to other applications suchas reservoir monitoring, enhanced recovery, etc. 指对干井、注入井、探井、不再生产石油的井或不再盈利生产的井进行永久性封堵；井的废弃要经过下列几个步骤：从政府机构获得废弃许可及程序要求；若可能，要移除和打捞套管；要在井筒中注入一段或多段水泥塞和/或钻井液，防止井筒钻开的不同层位间发生窜流。某些情况下，在长时间停止作业时，井可以临时报废，以备将来转成监测和提高采收率等其它用途。
Wet Gas 湿气	2001- 3.2 2007- 3.2.3	4.2, 8.1, 9.3	Wet (Rich) gas is natural gas from which no liquids have been removed prior to the reference point. The wet gas is accounted for in resource assessments, and there is no separate accounting for contained liquids. It should be recognized that this is a resource assessment definition and not a phase behavior definition. 湿（富）气是在参照点之前没有去除任何液体的天然气；在资源评估中，湿气量要记帐，但不单独登记湿气中所含的液量；应注意这是资源评估的定义，而不是相态定义。

Term 术语	Reference* 参考文献 *	Used in These Guidelines 本指南引述情况	Definition 定义
Working Gas Volume 工作气量		none —no occurrences 未出现	With respect to underground natural gas storage, Working Gas Volume (WGV) is the volume of gas in storage above the designed level of cushion gas that can be withdrawn/injected with the installed subsurface and surface facilities (wells, flow lines, etc.) subject to legal and technical limitations (pressures, velocities, etc.). Depending on local site conditions. 对于地下天然气储气库，工作气量（WGV）就是储气库内超过所设计垫底气量的气体数量；工作气量可以在法律和技术限制（压力、速度等）范围内通过地下和地面设施（井、放喷管线等）进行采出 / 注入；根据当地现场条件（注入 / 回收速度、使用时间等），工作气量可实现每年一次以上的循环。
Working Interest 工作权益	2001- 9	7.1, 9.3, 10.4	A company ’ s equity interest in a project before reduction for royalties or productionshare owed to others under the applicable fiscal terms. 指根据适用的财税条款，公司在扣除矿费或其他各方的份额产量之前所拥有的项目权益。

致　谢

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SPE Oil and Gas Reserves Committee

1. PRMS Application Guidelines in English Version

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Reference Terms	参考术语	Kerry Scott	Kerry Scott

*With key contributions from the following SEG Oil and Gas Reserves Committee members: Patrick Connolly, Henk-Jaap Kloosterman, James Robertson, Bruce Shang, Raphic ven der Weiden, and Robert Withers.

The authors of the individual chapters have relied on their expertise regarding appropriate guidance and application examples in relation to PRMS. The views expressed in this document do not necessarily represent the views of the employers of any of the authors, nor of any organizations with which they may be associated. All chapters have been peer reviewed and the complete document has been endorsed by the sponsoring organizations of PRMS.

Applications Document Committees

Delores Hinkle and Jeff Tenzer, Chairpersons of the OGRC during development and review of these guidelines, provided required support throughout the process. The following Applications Document Subcommittee members laid the foundations during the first two years: Satinder Purewal (Chair), Delores Hinkle, Bernard Seiller, Stuart Filler, Stefan Choquette, Yasin Senturk, Phil Chan, James Pearson. The contributions of the following committees are also gratefully acknowledged.

*SEG石油天然气储量委员会的主要贡献人员包括：Patrick Connolly，Henk-Jaap Kloosterman，James Robertson，Bruce Shang，Raphic ven der Weiden和Robert Withers。

各章节作者是指导PRMS应用及提供应用示例的专家。其在本文件中表达的观点不代表其雇主的观点，也不代表任何相关组织的观点。所有章节都经过同行审阅，最终文稿得到了PRMS发起组织的背书。

应用指南文件编制委员会

在编制和审阅本指南期间，OGRC主席Delores Hinkle和Jeff Tenzer在整个过程中提供了必要的支持。应用指南分委员会的以下成员在头两年为工作奠定了基础：Satinder Purewal（主席）、Delores Hinkle、Bernard Seiller、Stuart Filler、Stefan Choquette、Yasin Senturk、Phil Chan和James Pearson。也感谢以下委员会成员的贡献：

Committee 委员会		Members (* denotes Committee Chair) 成员（* 负责人，向储委会主席汇报）
Managing Steering Committee	管理指导委员会	Satinder Purewal *(SPE), Stefan Choquette (SPE), David Gold (SPEE), Ken Mallon (AAPG)
Editing Committee—Chapter 1	第 1 章编辑委员会	Jeff Tenzer* (SPE), Delores Hinkle (SPE)
Editing Committee—Chapter 2	第 2 章编辑委员会	Ron Harrell*(SPEE), John Lee (SPE), Anibal Martinez (WPC)
Editing Committee—Chapter 3	第 3 章编辑委员会	John Ritter*(AAPG), Robert Withers (SEG), Dominique Marion (SPE), Tom Scott (SPE), Bruce Shang (SEG)
Editing Committee—Chapter 4	第 4 章编辑委员会	John Etherington*(AAPG), Mike Adams (SPE), David Gold (SPEE)
Editing Committee—Chapter 5	第 5 章编辑委员会	Rawdon Seager*(SPE), Satinder Purewal (SPE), Glenn McMaster (AAPG), Jack Schuenemayer (AAPG)
Editing Committee—Chapter 6	第 6 章编辑委员会	Rawdon Seager*(SPE), Satinder Purewal (SPE), Jeff Brown (AAPG), Jack Schuenemayer (AAPG)
Editing Committee—Chapter 7	第 7 章编辑委员会	John Etherington* (AAPG), Mike Adams (SPE), Stefan Choquette (SPE), Stuart Filler (SPEE)
Editing Committee—Chapter 8	第 8 章编辑委员会	Phil Chan*(SPE), Guy Sistrunk (SPE), Tom Scott (SPE), Creties Jenkins (AAPG), Paul LaPointe (AAPG)
Editing Committee—Chapter 9	第 9 章编辑委员会	Wolfgang Schollnberger*(AAPG), David Gold (SPEE), Jeff Tenzer (SPE), Satinder Purewal
Editing Committee—Chapter 10	第 10 章编辑委员会	Elliott Young*(SPE), Stuart Filler (SPEE)
Editing Committee —Reference Terms	参考术语编辑委员会	Kerry Scott*(SPE), Jeff Brown (AAPG)

In addition, Holly Hargadine and other SPE staff contributions are acknowledged for providing continuous support throughout the process of developing this document. Without SPE staff support, this project would not have been possible to bring to fruition.

Applications Document Review Process Summary (2009–11)

A review process for these Guidelines was formally adopted at the October 2009 SPE Oil and Gas Reserves Committee (OGRC) meeting. Chapter Editing Committees were formed for each chapter, with expert members procured from all the stakeholder societies. Clear mandates and timelines were established for finalization and review of the chapters. Each Chapter Editing Committee worked with the chapter author(s) to incorporate comments and endorse the revised chapter. A Steering Committee, chaired by Satinder Purewal, oversaw the process.

When each Chapter Editing Committee completed and endorsed its chapter, the Chairman sent the chapter to the Steering Committee Chairman, who circulated it for comment within the Steering Committee. Any comments from the Steering Committee were incorporated with consultation of the Chapter Editing Committee. All

此外，感谢 Holly Hargadine 和其他 SPE 工作人员的贡献，其在指南编制的整个过程中提供了持续不懈的支持。如果没有 SPE 工作人员的支持，这个项目就不可能实现。

应用指南审阅过程小结（2009-11）

2009 年 10 月 SPE 油气储量委员会（OGRC）会议正式采纳本指南的审阅流程。每章均设置了编辑委员会，其成员是从所有相关协会中遴选，并确定了各章节完成和审阅的具体任务和时间表。每章的编辑委员会负责与章节作者合作，吸纳审阅意见，并确认修订后的章节。Satinder Purewal 担任主席的管理指导委员会对该过程进行了监督。

当每个章节的编辑委员会完成并确认该章节后，由编辑委员会主席将该章节发送给指导委员会主席，由其组织指导委员会进行审阅。指导委员会的任何意见都与章节编辑委员会进行了磋商

chapters were completed in draft form and posted on an online site accessible to all reviewers and authors. Final edits were made and incorporated into one document, which was edited by SPE staff for consistency, language, and clarity. This document was posted on the SPE website from 15 December 2010 to 15 March 2011 for industry review and comment. Prominent notice of the posting appeared on the home page at www.spe.org.

All comments received by SPE were circulated to the Chapter Editing Committees and the Steering Committee. The comments were discussed at the April 2011 OGRC meeting. Each Chapter Editing Committee worked with the author(s) for inclusion of relevant comments. Finalized chapters, endorsed by the Chapter Editing Committees and by the OGRC were combined into a single document. The Reference Terms were updated to ensure consistent references to the text, as several chapters (e.g., Chaps. 3 and 8) had changed since the draft was published on the SPE website in December.

The final document was sent to the SPE Board of Directors for review and approved on 26 June 2011. Approval from the endorsing societies (AAPG, SPEE, SEG, and WPC) was obtained 19 October 2011. The document was published on the SPE website on 1 November 2011.

2. PRMS Application Guidelines in English-Chinese Version

Recognizing the wide acceptance and applications of PRMS in global petroleum industry, the SPE Oil and Gas Reserves Committee (OGRC) decided to translate the PRMS Application Guidelines (2011) into other main languages, including Chinese and Russian, to maintain the quality and integrity of the document as well as for the convenience of users who are more comfortable with their native languages.

This is a significant, multidisciplinary, complicated and creative task with a huge workload. Like any other work in the society, it must rely on many qualified professionals serving as volunteers to accomplish. China National Petroleum Corporation (CNPC) and her subsidiaries have provided great support. In a short time, more than 20 volunteers were invited from CNPC, China National Offshore Oil Corporation (CNOOC), China Petrochemical Corporation (Sinopec), and other IOCs respectively and formed the Chinese Translation Subcommittee. The whole task has experienced three rounds of translation, review and integration, which lasted for 5 years. In the later stage of standardization work, the Department of Mineral Resources Protection and Supervision,

汇编。所有章节草案完成后，在网站上进行了张贴，供所有作者和审阅人访问。最终稿由 SPE 工作人员编辑、合并为一个文档，以确保表述一致、语言顺畅和观点清晰。本指南文件于 2010 年 12 月 15 日至 2011 年 3 月 15 日在 SPE 网站上进行了公示，征求行业审阅意见。该重要通知在 SPE 的网站主页 www.spe.org 上进行了告示。

SPE 征集到的所有审阅意见都已分发给章节编辑委员会和指导委员会。2011 年 4 月的 OGRC 会议对这些意见进行了讨论。每个章节编辑委员会与作者合作，进一步汲取了行业意见。将章节编辑委员会和 OGRC 批准的最终章节合并，形成了完整的指南文件。由于草案自 2010 年 12 月在 SPE 网站上发布以来，有几个章节（例如，第 3 章和第 8 章）发生了变化，因此更新了参考术语，以确保在文本中的引用一致。

最终文件提交 SPE 董事会审阅，并于 2011 年 6 月 26 日得到批准。2011 年 10 月 19 日获得了其他学会（AAPG、SPEE、SEG 和 WPC）的背书。该指南文件已于 2011 年 11 月 1 日在 SPE 网站上发布。

2. PRMS 应用指南英中版

鉴于 PRMS 已在全球石油行业得到广泛接受和应用，SPE 油气储量委员会 (OGRC) 决定将《PRMS 应用指南 (2011)》翻译为包括中文和俄文在内的其他主要语言，确保翻译质量和忠实原文，并方便那些更熟悉本国语言的用户。

这是一项十分重要、涉及多学科、复杂且具有创新性的工作任务，工作量庞大。与学会其他工作一样，仍需要依靠许多资深的专家作为志愿者来完成。该项工作得到了中国石油天然气集团公司及其下属机构的大力支持。在很短时间内，20 余名分别来自中国石油天然气集团公司、中国海洋石油集团公司、中国石油化工集团公司和其他国际油公司的行业专家应邀作为志愿者组建了中文翻译分委会。整个编译工作经历了三轮译、审、校，历时 5 年。在后期的术语审阅与标准化工作中，中国自然资源部矿产资源保护监督司给予了大力

the Ministry of Natural Resources of China played an important guiding role on this task.

All translated chapters have been reviewed by international professionals assigned by the SPE OGRC, and the complete document has been endorsed by the sponsoring organizations of PRMS.

Chinese Translation Subcommittee

This English-Chinese translation document represents the collaboration achievement of an international joint taskforce of more than 20 experienced reserves evaluation professionals who were involved in the translating, editing, review, and standardization work of this document. Major contributors to the translation are:

支持和帮助，并发挥了重要的指导作用。

所有翻译章节都已经过 SPE 储量委员会指定的全球同行专家审阅，并得到了 PRMS 发起组织的认可与背书。

中文翻译分委会

本英中译本是一个国际联合工作组的合作成果，有 20 多位资深储量评估专家成员参与了翻译、编辑、审阅与标准化等工作。

主要贡献者包括：

Chapter, 章		Translator(s), 编译者	
Chapter 1	第 1 章	Hua YANG (CNPC), Tony WONG (SPEE)	杨桦 (中石油)、黄奇生 (SPEE)
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Chapter 3	第 3 章	Yu YE (CNPC), Erheng LI (MNR)	叶禹 (中石油)、李二恒（自然资源部）
Chapter 4	第 4 章	Hua YANG (CNPC), Kai LUO (CNPC), Qianyao LI (CNPC)	杨桦 (中石油)、 罗凯（中石油）、李茜瑶（中石油）
Chapter 5	第 5 章	Mingjun XIA (CNPC), Shanbo SHENG (CNPC)	夏明军 (中石油)、盛善波（中石油）
Chapter 6	第 6 章	Yanjing YI (CNPC), Haibo ZHANG (MNR)	衣艳静 (中石油)
Chapter 7	第 7 章	Ruie YUAN (CNPC), Zhiyu LI (CNPC)	原瑞娥 (中石油)、李之宇（中石油）
Chapter 8	第 8 章	Phillip CHAN (SPE), Jian ZHENG (Sinopec), Mingli GUO (Sinopec), Xinjun SHAO (CNPC)	Phil CHAN (SPE)、郑舰 (中石化)、郭明黎（中石化）、邵新军 (中石油)
Chapter 9	第 9 章	Tao YANG (PetroChina Southwest Oil and Gas Field Company), Yanjing YI (CNPC)	杨涛（中石油西南油气田分公司）、衣艳静 (中石油)
Chapter 10	第 10 章	Yanjing YI (CNPC), Ruie YUAN (CNPC)	衣艳静 (中石油)、原瑞娥 (中石油)
Reference Terms	参考术语	Hua YANG (CNPC), Ruie YUAN (CNPC)、Qingru WANG (CNOOC), Jian ZHENG(Sinopec), Lei WU (CNPC), Yundong HU (GCA)	杨桦 (中石油)、原瑞娥（中石油）、王庆如（中海油）、郑舰（中石化）、吴蕾（中石油）、胡永栋（GCA）

Translation Steering Committee

The Translation Steering Committee have played important leading role on the translation. Members are: Jianhua JU, Feng WANG, Xiandeng YE, Henian LIU, Qingru Wang, Yongle HU, Chunlei QIAO, Lei WU, Jian Zheng, Haizhen MA, Yuwen CHANG and Hua

翻译指导委员会

翻译指导委员会对编译工作发挥了重要引领作用，成员包括：鞠建华、王峰、叶先灯、刘合年、王庆如、胡永乐、乔春磊、吴蕾、郑舰、马海珍、

YANG. Their valuable guidance and contribution are also sincerely acknowledged.

Other Major Contributors

Chairpersons of the SPE OGRC, Rawdon Seager, Dan Diluzio, Bernard Seiller, and Steven McCants provided necessary guidance and monitoring during the development and review of this document.

The Department of Mineral Resources Protection and Supervision, the Ministry of Natural Resources of the People's Republic of China (MNR) have provided vigorous support and important guidance on the translation work, in particular on the standardization of PRMS terminology in Chinese.

Melissa Schultea, Holly Hargadine and other SPE staff have provided continuous efforts and supports throughout the process of developing this document. Their devotion and contribution are also gratefully acknowledged.

Assigned by the SPE OGRC, the following experts have been involved in the reviewing work as well:

Busheng LI, BBVA Compass, nominated by Stephen Gardner;
Phillip CHAN, Author of Chapter 8, nominated by John Lee;
Yundong HU, GCA, nominated by Doug Peacock; and
Yangyang LIU, BP, nominated by Mark Neiberding.

In addition, Zheng HAN, Hong CHEN, Wuhe WANG, Jun TIAN, Yingtao SUN, Yong HU, Junzhang ZHENG and Shishen LI have also provided valuable comments during the review process.

CNPC and her subsidiaries, in particular China National Oil and Gas Exploration and Development Company Ltd. (CNODC), Research Institute of Petroleum Exploration and Development (RIPED), and Petroleum Industry Press (PIP), have provided great supports for the translation work, including sponsoring translation, review, travelling, meeting, and preparation of the document.

The translation of PRMS Application Guidelines is important to disseminate PRMS knowledge and methodology in China, and further promote globally communication and transparency on petroleum resources evaluation and management. The SPE Oil and Gas Reserves Committee (OGRC) gratefully acknowledges again all sponsors and contributors' time, efforts and wisdom.

常毓文和杨桦。谨对他们的悉心指导与贡献表示诚挚感谢。

其他主要贡献者

SPE 油气储量委员会的历届主席，Rawdon Seager、Dan Diluzio、Bernard Seiller 和 Steven McCants 为本文的编制和审阅工作提供了必要的指导与监管。

中国自然资源部矿产资源保护监督司对本指南编译工作给予了大力支持并提供了重要指导意见，尤其是 PRMS 中文术语体系的标准化工作。

Melissa Schultea, Holly Hargadine 和其他 SPE 工作人员在本文的整个编制过程中提供了持续不懈的努力和支持。衷心感谢她（他）们所作出的贡献与奉献。

经 SPE 油气储量委员会选派，还有以下专家参与了本指南的审阅工作：

Busheng LI，康百士银行; Stephen Gardner提名;
Phillip CHAN, 第 8 章作者 ; John Lee 提名 ;
Yundong HU, GCA 公司 ; Doug Peacock 提名 ;
Yangyang LIU, BP 公司 ; Mark Neiberding 提名。

此外，韩征、陈红、王武和、田军、孙英涛、胡勇、郑俊章和李士申等专家也在审阅期间提供了宝贵意见。

中国石油天然气集团公司及其下属机构，特别是中国石油国际勘探开发有限公司（CNODC）、中国石油集团科学技术研究院（RIPED）和石油工业出版社（PIP）对编译工作给予了大力支持，包括翻译、审阅、差旅、会议和文本编辑等。

《PRMS 应用指南》的翻译工作对于在中国宣传 PRMS 理念和方法、进一步促进全球石油资源评估与管理领域的交流力度与透明度十分重要。SPE 油气储量委员会（OGRC）再次衷心感谢所有赞助机构和参译专家们为翻译工作所付出的宝贵时间、精力与智慧。

附录 - 更正与修订

Addendum-Corrections & Modifications

SPE Oil and Gas Reserves Committee

Addendum-Corrections & Modifications

The following corrections and modifications have been made since the original publication of the PRMS Application Guidelines in November 2011:

附录 - 更正与修订

以下是在 2011 年 11 月发布的《PRMS 应用指南》原版基础上所做的更正与修订。

Page 页码	Original Text 原文	Corrected Text 更正后	Date 时间
5, Line 6 第 5 页 , 第 6 行	Chap. 7 covers commercial evaluations, including a discussion on public disclosure and regulatory reporting under existing regulations.	Chap. 7 covers commercial evaluations.	July 2012 2012 年 7 月
66, Line 1 第 66 页 , 第 1 行	…parameters Di and n.	…parameters Di and b.	July 2012 2012 年 7 月
84, Line 18 第 84 页 , 第 18 行	If a reservoir is poorly defined, material balance calculations or analog methods may be used to arrive at an estimate of the range of RFs. Uncertainty ranges in the RF can often be based on a sensitivity analysis. If a reservoir or project is poorly defined, material balance calculations or analog methods may be used to arrive at an estimate of the range of RFs. Uncertainty ranges in the RF can often be based on a sensitivity analysis.	If a reservoir is poorly defined, material balance calculations or analog methods may be used to arrive at an estimate of the range of RFs. Uncertainty ranges in the RF can often be based on a sensitivity analysis.	July 2012 2012 年 7 月
119, Eq. 7.3d 第 119 页 , 公式 7.3d	$DF_t = 1/[MARR]^{(t-0..5)}$	$DF_t = 1/[MARR]^{(t-0.5)}$	July 2012 2012 年 7 月
134, Line 15 第 134 页，第 15 行	basic-centered gas accumulations (BCGA)	basin-centered gas accumulation (BCGA)	July 2012 2012 年 7 月

With the SPE OGRC's guidance, more minor modifications have been made in the English-Chinese version of the PRMS Application Guidelines as well.

在 SPE 油气储量委员会的指导下，《PRMS 应用指南》英中文版进一步做了一些细小的更正。