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页岩气藏开发基础

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内 容 提 要

本书以四川盆地长宁—威远地区龙马溪组页岩为主要研究对象，系统地介绍了页岩储层微观孔喉结构特征、非常规页岩储集空间分类方法、页岩有机地球化学特征、页岩吸附能力及考虑多组分吸附的页岩气储量计算方法等，并建立了考虑多重赋存和运移机制的页岩气运移动力学模型，形成了较为完善的页岩气藏不稳定渗流理论。本书是我国在页岩气勘探开发领域的新的研究成果。

本书可作为高等院校相关专业师生的教学用书，也可作为从事页岩气研究的勘探开发人员及其他从事非常规油气资源研究的科技人员的参考用书。

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序(Ⅰ)

油气资源作为一种战略资源,在世界各国的国民经济发展中占据重要的地位,对国际政治、军事、科技、国防安全等方面产生广泛而深远的影响。随着世界经济对能源需求的持续增长,规模大、易探好采的常规能源储量越来越少,全球常规油气资源向非常规油气资源的快速跨越已成为必然选择。作为非常规油气资源的一种,页岩气以其在全世界范围内的巨大储量进入了各国能源战略视野。美国已经成功地实现了对页岩气的商业化大规模开发,对提高国家能源安全、降低对外依存度、缓解天然气供应不足起到了积极作用,使得页岩气藏勘探开发在全球成为了一个新热点。

我国具有丰富的页岩气资源,据估算我国的页岩气技术可采储量居世界首位,具有良好的勘探开发前景。国土资源部发布的《全国页岩气资源潜力调查评价及有利区优选》指出:我国陆域页岩气地质资源潜力为 134.42 万亿立方米,可采资源潜力约为 25.08 万亿立方米。近年来,我国投入了大量的资金和人力在页岩气资源的勘探与开发上,取得了良好的进展。但总体而言,我国在页岩气藏勘探及开发领域都尚处于起步阶段,与北美地区已进入页岩气商业化、规模化开采的国家相比仍有很大差距。

《页岩气藏开发基础》一书是张烈辉、郭晶晶和唐洪明等同志在国家杰出青年科学基金"油气藏渗流力学"(编号:51125019)和相关研究项目的基础上撰写完成的,这也是我国第一部针对页岩气藏开发相关基础研究的专著。该著作以四川盆地南部下古生界志留系龙马溪组页岩为主要研究对象,系统地介绍了页岩储层的岩石学、有机地球化学、物性和微观孔隙结构特征、页岩吸附能力与含气性评价、页岩气藏储量计算方法等;并基于页岩气的多重流动特征,创新性的形成了一套页岩气藏的不稳定试井和非稳态产能预测理论、方法和技术。尤其是提出的页岩储集空间成因分类方案,利用高压压汞、氮气吸附、核磁共振等多种方法和技术测试页岩物性、微观孔隙结构等研究成果在国内处于领先水平;在国内外首次提出将比表面作为评价页岩有机质保存、储集质量的一个新参数。

该专著不仅具有较高的理论价值，而且具有广阔的应用前景，可供大专院校、科研院所和能源企业从事非常规油气藏勘探与开发的科研人员参阅。该专著的出版将对我国页岩藏的勘探与评价、高效开发与利用起到重要的指导和推动作用。

中国科学院院士： 

2014 年 5 月 19 日

序(Ⅱ)

能源是人类生存和发展的重要物质基础,攸关国计民生和国家安全。随着全球范围内的石油资源逐渐减少,以及全球气候变化和环境污染等问题的日趋严峻,天然气在全球能源和我国能源消费中所占的地位也越来越重要。

随着国家层面加强清洁能源消费占比的政策逐步落实,天然气需求总量势必会大幅增加。虽然我国常规天然气产量逐年稳定增加,但其增速赶不上国内的天然气消费量增速,不能满足国内的消费需求。从我国油气总体发展的战略角度出发,积极寻找非常规天然气后备资源已是当务之急。近年来,美国页岩气勘探开发技术取得全面突破,产量快速上升。世界其他主要页岩气资源大国和地区也开始加快页岩气的勘探开发进程。

我国不同地质历史时期广泛发育的富含有机质的页岩地层,具有优越的页岩气藏形成与富集条件,资源潜力巨大,勘探开发前景广阔。在我国天然气供需缺口不断扩大的背景下,页岩气资源开发的战略意义日益凸显。

我国自20世纪90年代引入现代页岩气概念以来,当今页岩气勘探开发已进入了实质性推进阶段,但其理论基础还很薄弱,很大程度上影响了页岩气的勘探和开发进程。我国页岩气藏地质条件明显有别于北美地区,国外页岩气开发理论和模式不可照搬照用,需要结合中国页岩气田的地质地理特点研发配套的开发理论和技术。我国西南石油大学张烈辉、郭晶晶、唐洪明等教授新撰专著《页岩气藏开发基础》的出版,正是为了达此目的。该专著中论及的、作者科研团队自己建立的一些新理论、新方法以及相应的大量实验数据、图片等都是紧密结合我国页岩气藏实际特点的科研成果。

该专著内容丰富,涵盖了页岩气藏开发的诸多重要基础问题和常用方法技术。其主要内容如下:综述国内外页岩气藏开发现状及开发过程中面临的主要问题(第1章);页岩岩石学及有机地球化学特征(第2章);页岩储层微观孔隙结构特征(第3章);页岩吸附能力及含气性评价(第4章);页岩气藏储量计算(第5章);页岩气藏基本渗流模型及其点源解(第6章);页岩气藏中不同井型的试井理论模型(第7章);页岩气藏中不同井型的产能预测模型(第8章)。

难能可贵的是,该专著的相当部分内容是以作者科研团队自己近些年来的创新性科技成果为基础撰写的。例如,该专著中提及的泥页岩储集空间成因分类方

法，将比表面作为评价泥页岩有机质保存、储集质量的一个重要参数，不同井型条件下页岩气藏渗流理论模型，特别是双孔复合气藏水平井分段多级压裂条件下的页岩气藏渗流理论模型等，是国内外最新的研究成果。这些成果都是以充分的实验数据为依据的、既有很高的学术水平又有实际应用意义的理论和方法，并已以40余篇文章的形式先后发表在国内外著名期刊上。

时值我国国民经济快速发展、天然气需求量大幅度上升之际，该专著的出版必将对我国页岩气资源勘探开发的科学研究、技术开发、规划设计和现场生产起到积极的推动作用。

该专著可供高等院校、科研院所和油气企业从事页岩气勘探开发和非常规油气勘探开发的科研、教学与管理人员，以及研究生和高年级本科生参考阅读。

中国科学院院士：

2014年6月18日

序(Ⅲ)

能源安全作为国家安全的重要组成部分,直接关乎国家利益。近年来,随着我国经济持续快速发展,国内天然气消费需求的增长速度已经超过煤炭和石油,天然气供需矛盾突出。特别是2013年,我国大范围地区持续出现雾霾天气,各地纷纷制定煤改气、油改气计划,更加刺激了天然气需求以超常规速度增长。页岩气作为一种清洁、高效的非常规天然气资源,对缓解我国天然气供需矛盾、调整能源结构和保障国家能源安全具有重要意义。

页岩气的开发已成为全球油气资源勘探开发的一个新亮点,加快页岩气开发已成为世界主要页岩气资源国的共同选择,但目前只有美国和加拿大实现了对页岩气的商业化大规模开发。其中,美国对页岩气的开发起步最早,也是最早成功实现低成本、商业化开采页岩气的国家。美国页岩气的快速发展不仅改变了美国的能源消费结构,也减少了对中东国家石油能源的依赖,同时对全球天然气市场、能源供应格局以及地缘政治都产生了重要的影响。加拿大紧随其后开展了一系列页岩气藏评价、试验工作,目前也已实现了页岩气的商业化开采。近年来,中国也逐渐加大了页岩气藏研究和政策扶持力度,中国对页岩气的开发正在逐步由早期勘探评价阶段向商业化开发阶段迈进。

中国沉积盆地中广泛分布着富含有机质的泥页岩,这些泥页岩厚度大、成熟度高、生烃能力大,具有很好的勘探开发前景。但是,与北美地区相比,中国页岩气在形成、富集、保存条件上都存在一定的差异性。中国页岩气藏埋藏更深、地表条件更加复杂、储层非均质性更强,不能仅靠照搬美国页岩气开发技术理论,而必须建立一套适用于中国页岩气藏实际特点的评价标准和开发理论。尽管北美地区利用压裂技术,尤其是水平井压裂技术、多级压裂水平井技术开发页岩气藏的工程实践较为成功,但对页岩气复杂渗流规律的研究落后于生产实践。

《页岩气藏开发基础》是张烈辉教授主持的国家杰出青年科学基金"油气藏渗流力学"(编号:51125019)项目的研究成果。该著作以四川盆地南部下古生界志留系龙马溪组页岩为主要研究对象,介绍了页岩储层的岩石学、有机地球化学、物性和微观孔隙结构特征、页岩吸附能力与含气性评价、页岩气藏储量计算方法等;建立了描述页岩气赋存和运移的动力学模型,形成了较为完善的页岩气藏中复杂多级压裂水平井不稳定渗流理论。作者发表在《Journal of Hydrology》、《Journal

of Petroleum Science and Engineering》、《Transport In Porous Media》等国际著名刊物上的文章表明，作者建立的多级压裂水平井试井理论有其独特的学术价值和实用价值。该模型不仅系统考虑了吸附—解吸、扩散、渗流以及任意压裂缝条数的影响，还考虑了裂缝与水平井间的任意夹角，储层应力敏感等因素的影响，非常新颖，有很多创新性认识。

该专著是以作者所在科研团队所获取的实际岩心资料、室内测试分析及实验成果、理论推导和模拟等为基础所编写的，结论依据充足，理论推导严谨，是我国在页岩气开发领域新的研究成果，该专著的出版会对我国页岩气藏的合理开发和开采有重要的意义。

中国工程院院士： 周守为

2014 年 5 月 23 日

Preface(Ⅳ)

In the past few decades, the petroleum industry has faced increasing challenges because of rapidly growing demand of energy from oil and natural gas, while at the same time fewer, new conventional oil and gas reservoirs have been found worldwide. Consequently, unconventional oil and gas resources from tight sand and shale reservoirs have received great attention in the past decade around the world, because of their large reserves discovered worldwide as well as technical advances in developing these resources. As a result of improved horizontal drilling and multi-stage hydraulic fracturing technologies, significant progress has been made toward commercial oil and gas production from such unconventional petroleum reservoirs, as demonstrated in the US. However, current understandings and technologies needed for effective development of unconventional reservoirs are far behind the industry needs. Even with the significant progress made in producing natural gas from low-permeability shale and tight gas reservoirs in the past decade, gas recovery remains very low (estimated at 10%～30% of GIP). Gas production or flow in such extremely low permeability formations is further complicated by many co-existing processes, such as severe heterogeneity, large Klinkenberg effect, nonlinear or non-Darcy flow behavior, adsorption/desorption, and strong interactions between fluid (gas and water) molecules and solid materials within tiny pores as well as micro- and macro- fractures of shale and tight formations. Currently, there is little in fundamental understandings on how these complicated flow behaviors impact gas flow and the ultimate gas recovery in such reservoirs.

Shale formation is characterized by extremely low permeability from subnanodarcys to microdarcys and is different for different shale types, even under the similar porosity, stress, or pore pressure condition. The permeability of deep organic-lean mudrocks ranges from smaller than to tens of nanodarcys, while permeability values in organic-rich gas shales from subnanodarcys to tens of microdarcys. The Klinkenberg effect or gas-slippage effect has been practically ignored

in conventional gas reservoir studies, except when analyzing pressure responses or flow near gas production wells at very low pressure. This is because of larger pore size and relatively high pressure existing in those conventional gas reservoirs. In shale gas reservoirs, however, the Klinkenberg or slippage effect is expected to be significant, because of the nano-size pores of such rock, even under high pressure condition.

Unconventional reservoir flow dynamics are characterized by highly nonlinear behavior of multiphase flow in extremely low-permeability rock, coupled by many co-existing physical processes, e. g. , non-Darcy flow at high or low flow rates. Because of complicated flow behavior, strong interaction between fluid and rock as well as multi-scaled heterogeneity, the traditional Darcy-law-and-REV-based model may not be generally applicable for describing flow phenomena in unconventional gas reservoirs. Past studies point out that non-laminar/non-Darcy flow concept of high-velocity may turn out to be important in shale gas production.

Natural gas in shale gas formations is present both as a free gas phase and as adsorbed gas on solids in pores. In these reservoirs, gas or methane molecules are adsorbed mainly to the carbon-rich components, i. e. kerogen. The adsorbed gas represents a significant percentage of total gas reserves (20%～80%) as well as recovery rates, which cannot be ignored in any model or modeling analysis for development. In shale gas formations, studies have found that methane molecules are adsorbed mainly to the carbon-rich components, i. e. kerogen, correlated with total organic content (TOC) in shales, as a function of reservoir pressure.

In conventional oil or gas reservoirs, the effect of geomechanics on rock deformation and permeability is generally small and has been mostly ignored in practice. However, in unconventional shale formations with nano-size pores or nano-size micro-fractures, such geomechanics effects can be significantly large and may have a significant impact on both fracture and matrix permeability, which has to be considered in general. Studies show that permeability in the Marcellus Shale is pressure dependent and decreases with an increase in confining of pore pressure. The degree of permeability reduction with confining pressure is generally significantly higher in shales than that in consolidated sandstone or carbonate.

Considering the current tremendous activities in development of shale gas resources in China and around the world, this book is very timely and it provides a comprehensive summary of shale gas resources, resource evaluation, geological characteristics, micro pore structure, and physical processes. More importantly,

the book derives several gas flow models and present many practical solutions for well pressure-transient testing analysis. Furthermore, the "triple-porosity" model is proposed to investigate pressure transient dynamics of multiple-fractured horizontal wells. Considering multi-scaled pore types and multiple storage mechanisms, the model conceptualizes shale gas reservoirs as triple porous media and takes into account multiple flow mechanisms, which can better describe actual gas flow characteristics in shale gas reservoirs. In addition, this book discusses the state-of-the-art of the technologies that can be used in quantitative investigation for effective development of shale gas reservoirs. In particular, many approaches and technologies presented in the book are based on the studies of the authors' own work, therefore, this book provides an excellent reference and theoretical background as well as many useful analysis tools to petroleum reservoir engineers, geologists, graduate students, and other scientists in their efforts to study and develop shale gas reservoirs.

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Preface(Ⅴ)

Shale gas is a kind of biogenic and/or thermogenic unconventional natural gas that is preserved in organic-rich shale in absorption or free gas status. Shale gas resources are very abundant all over the world and have a greater potential of development than conventional gas. According to statistic data, current shale gas resources are about 456 trillion cubic meters globally, mainly distributed in North America, Middle Asia, China, Middle East, North Africa, Latin America and Russia. So far, shale gas has been successfully put into commercial development in U. S. and Canada. In 2012, shale gas production counted for nearly 40% of gas production in U. S. whose gas production has exceeded Russia and become the biggest gas production country for four years.

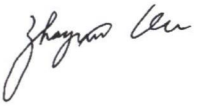
Successful shale gas development in U. S. started a revolution of its development in the world. As a new field of global oil and gas exploration and development, shale gas is attracting more and more attention. In 2013, gas import to China reached 53 billion cubic meters, counting for more than 30% of gas consumption in the country. Gas demand in China pushes more exploration and development of unconventional gas, such as shale gas. Shale gas formations of different geologic periods have been widely developed in China. The predicted shale gas resources in the Cambrian Qiong Zhu-si formation and the Silurian Long Ma-xi formation are competitive to conventional gas resources in Sichuan Basin. The amount of shale gas resources determines its prosperous exploration and development prospect in China. In October 2009, MOLAR initiated the first shale gas exploration project in Qijiang, Chongqing, which was the milestone of the start of shale gas exploration and development in China following U. S. and Canada. In recent years, shale gas exploration and development techniques have been greatly improved. However, Chinese petroleum engineers are still at an early stage of developing and utilizing this kind of unconventional resources, and there are some catch-ups to do with North America.

As unconventional gas, shale gas has different storage space, status and mi-

gration mechanisms from conventional petroleum gas, which means that the existing appraisal and prediction theories and methods for conventional gas are not practical for shale gas plays. Development of applicable basic theories and methods for shale gas plays according to their micro pore structure features, occurrence models and migration mechanisms is critical to the success of shale gas development.

Shale Gas Development Basis written by Liehui Zhang, Jingjing Guo, Hongming Tang, et. al. is a monograph of basic theories for unconventional shale gas reservoirs. It comprehensively and systematically introduces geochemical characteristics, storage space, micro-pore and throat structure, OGIP calculation methods and reservoir flowing theories of shale gas based on laboratory results and theoretical studies. This monograph covers relevant basic theories of shale gas development, and is an informative reference. Particularly on the complex flowing mechanisms of multi-stage fractured horizontal wells, the authors studied and analyzed multiple flow regimes of shale gas in multiple spaces, considered the effects of gas absorption, desorption, diffusion and viscous flow, and creatively proposed a theoretical flow model for horizontal wells with multi-stage fractures considering a coupling of hydraulic and natural fractures and multiple flowing mechanisms. This model is at present the most comprehensive and systematic model for multi-stage fractured horizontal wells in shale gas plays, and has attracted great interests and attention.

Overall, this monograph is an excellent reference with a high theoretic level and practical value, containing the latest research results for shale gas development. It is a good reference for people working on unconventional oil and gas play exploration and development.



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Preface(Ⅵ)

Shale gas has been the hottest unconventional exploration targets in North America during the last 10 years. The key factors for the success of shale gas plays are related to the advance of technologies of multistage hydraulic fracking in horizontal wells. The exploration and production of shale gas in the United States have increased substantially, which have fundamentally reshaped the structure of globe energy reserve and supply. In 2000, shale gas provided only 1% of U. S. natural gas production. However, it was over 20% by 2010. It is predicted that by 2035, 46% of U. S. natural gas supply will come from shale gas.

The exploration and production of shale gas have since expanded to the rest of the world and dramatically increased worldwide energy supply. China and central Asia is estimated to have the world's largest shale gas reserves. In order to tap into this vast shale gas resource, there is an urgent need to understand and evaluate the nature and characteristics of shale gas because our previous knowledge on conventional oil/gas cannot simply be copied to the shale gas plays. As we know today, shale mineralogy, strata architecture and fabric variations strongly influence porosity and permeability and have a major control on the "fracability" of shale-dominated rocks. Although there are a number of publications on various topic related to shale gas exploration and development in recent years in North America, these publications are scattered in different English journals that might not be readily available to or understood by the people who are working on frontline of shale gas projects in China. The timely publication of this book will provide much needed information to guide the exploration and development of shale gas in China.

This book provides a comprehensive and systematic coverage on every major important topic related to the exploration and development of shale gas. It contains a summary of the current status on shale gas plays and its major challenges in Chapter 1. It provides detailed information on lithological characteristic of shale and its organic geochemical attributes in Chapter 2. In Chapter 3 and Chap-

ter 4, it summarizes applications and limitations of different methods to characterize micro porosity and porosity distribution of shale, including low-temperature N_2 isotherm analyses; high pressure mercury capillary analyses and NMR analyses. Based on the authours' research in the Sichuan Basin, it provides the original analyses of factors that may influence the adsorbed gas in the shale reservoirs and proposes to use surface area as a new parameter for reserve and flow calculation. It presents, for the first time, the authors' original contribution to a new and improved calculation for shale gas reserve based on isothermal analyses of absorbed gas in Chapter 5. It introduces a new shale gas flow model based on multi-state of shale gas and multi-flow of shale gas in Chapter 6. It provides original testing models and productivity forecasting models that are specifically designed for different shale gas wells under disequilibrium or unsteady conditions in Chapter 7 and Chapter 8.

This book contains most recent theoretical breakthrough and field practice of shale gas plays from overseas. In addition, it is illustrated with ample examples of field experience and case studies that are/were carried out by the authors in China. I definitely recommend this book, as an authoritative account to shale gas exploration and development to petroleum geologists and petroleum engineers, who are working on shale gas projects in China. Academics, professionals and research scientists should also find this book of considerable value as a comprehensive and fully integrated treatment of shale gas exploration and development. In addition, this book can serve as an excellent text book for graduate courses in academic institutions for the courses that are related to shale gas.

I have the privilege to know the primary author, Professor Zhang Liehui, for a number of years. Professor Zhang is a well known expert in exploration and production in unconventional reservoirs with more than 200 publications and 6 books. His contributions in this field have been widely recognized in China as illustrated by a number of major national awards that Professor Zhang received in the last few years, including Changjiang Scholar awarded by the Ministry of Education of China, recipient of National Science Foundation for Distinguished Young Scholars of China, the second prize of National Science and Technology Progress Award. Yet, Professor Zhang is always very low-key, humble and modest person. He is always easily approachable by his colleagues and his students. I was also fortunately to have the second author, Dr. Guo Jingjing, as a visiting PhD student in my research Lab at University of Regina from 2012-2013. Dr. Guo is a