PETROLEUM EXPLORATION AND DEVELOPMENT
Volume 44, Issue 1, February 2017
Online English edition of the Chinese language journal

Available online at www.sciencedirect.com
ScienceDirect

Cite this article as: PETROL. EXPLOR. DEVELOP., 2017, 44(1): 32–39.

RESEARCH PAPER

Significance of source rock heterogeneities: A case study of Mesoproterozoic Xiamaling Formation shale in North China

WANG Xiaomei[1, 2, *], ZHANG Shuichang[1, 2], WANG Huajian[1, 2], SU Jin[1, 2], HE Kun[1, 2], WANG Yu[1, 2], WANG Xiaoqi[2]

1. Key Laboratory of Petroleum Geochemistry, China National Petroleum Corporation, Beijing 100083, China;
2. PetroChina Research Institute of Petroleum Exploration & Development, Beijing 100083, China

Abstract: Taking Mesoproterozoic Xiamaling Formation, Northern China as an example, the heterogeneities of source rock in different scales and hydrocarbon microscopic occurrence are studied based on observation of outcrops and observation with microscopy, and geochemical analysis. The large scale heterogeneities of source rocks are considered to be controlled by the plate movement and paleo-latitude location, while the micro-scale might be controlled by climate changes driven by the astronomical orbit. The constant existence of heterogeneities includes the differences of organic matter, debris sources and porosities. The heterogeneities of source rock should be seriously treated during the evaluation of oil and gas resources, especially the unconventional oil and gas. This kind of heterogeneous source rocks provides excellent source-reservoir assemblage of oil and gas generation, expulsion and accumulation, and new reference indexes for the economic evaluation of unconventional oil and gas. Therefore, quantitative study of the heterogeneity of source rock is of great significance for investigating formation mechanism and resource estimation of unconventional oil and gas.

Key words: shale; source rock; heterogeneity; organic laminae; source-reservoir assemblage; unconventional oil and gas resources evaluation; Mesoproterozoic; Xiamaling Formation

Introduction

In more than one hundred years since the birth of petroleum industry, sources rocks have become the second circle of academic and industrial focus. The first time was in the 1970s, when the theory of “kerogen generating hydrocarbon” was first put forward by Tissot et al., in this theory, the argillaceous rocks and shale, rich in organic matters, are regarded as hydrocarbon sources[1], and so comes the petroleum exploration concept of “hydrocarbon sources controlling hydrocarbon accumulation”. The second time was in the 1990s, triggered by the technological breakthrough made by the Americans in the exploration of unconventional petroleum accumulations, and this time the theory that argillaceous rocks and shale could act as reservoirs was advanced[2–3], subsequently, a new understanding of "source-reservoir in one" have been reached. In over a decade, major oil and gas fields have been found in the deep strata and ancient marine strata around the world[4–7], making us wonder what’s the formation limit, depth limit and potential limit of hydrocarbon exploration once again. Therefore, explorationists and scientists set their eyes on source rock once again, and they tried to find out the factors controlling the organic matter enrichment, formation of source rock, and source-reservoir types from the biogeochemical process experienced by the source rocks, and the perspective of “atmosphere-continent-ocean interaction”[8–11].

In recent years, some researchers have found that high quality source rocks are generally laminated organic-matter-rich shale and organic-matter-poor siliceous rock and carbonate, for example, the Mesoproterozoic Xiamaling Formation in North China[11], the Permian Dalong Formation in South China[12], the Early Jurassic Blue Lias Formation in the southeastern England[13], and the worldwide Cretaceous Campanian organic-matter-rich shale[14]. Further research shows that the heterogeneity of source rocks, rather than chaotic, has some explicit regularity. The sedimentary records reveal that the source rocks have regular patterns in spatial distribution and developing time. The spatial distribution pattern of source rocks is attributed to the Wilson Cycle of tectonic move-

Received date: 04 Jul. 2016; **Revised date:** 19 Dec. 2016.
*** Corresponding author.** E-mail: wxm01@petrochina.com.cn
Foundation item: Supported by the Key Fund of National Natural Science Foundation of China (41530317); the China National Science and Technology Major Project (2016ZX05004); the Scientific Research and Technological Development Project of China National 565 Petroleum Corporation (CNPC 2016A-0204).

ment[15], also influenced by the ancient latitude and geographic location[11]; whereas the developing time span of source rocks is considered to be controlled by the climatic cycle driven by the orbital force[11]. Wagner et al. studied the Cretaceous source rocks on both sides of the Atlantic, and found out that source rock heterogeneity was clearly influenced by ancient climatic changes and the Milankovitch Cycles[9,14,16]. Recent research on the Xiamaling Formation demonstrates that the Mesoproterozoic source rocks are also influenced by the Milankovitch Cycles[11]. The source rock heterogeneity has different time scales: the large cycle is of 1–10 million years, shown as source rock development in different geologic ages; the medium cycle is of 10–100 thousand years, shown as interbeds of organic-matter-rich shale and organic-matter-poor sediments; and the small cycle is less than a thousand year in time span, shown as the alteration of organic-matter-rich layer and clastic layer observed under microscope. Thus, the macroscopic cyclicity and heterogeneity of source rock is clearly related with the tectonic movements of the lithosphere, the orbital force, and the ancient latitude, whereas the microscopic heterogeneity of organic matter layer development is related with the periodic changes of climate. The sedimentary record of recent 0.64 million years reveals that the ancient climatic change, which controls the primary productivity of both the continent and the ocean, is of monsoon type. The climatic change is actually composed of several cycles of different time scales, including smaller cycles of several decades, and larger cycles of several hundred years to several thousand years, which are influenced by solar radiation and ocean current[11]. Thus, the macroscopic and microscopic heterogeneity of source rocks are probably influenced by the inherent forces of the Earth itself. It is the above controlling factors of different time scales that eventually give rise to the source rock heterogeneity of different scales.

The above researches provide us a new way to evaluate source rock heterogeneity and cyclicity quantitatively, surpassing early qualitative source rock assessment from a few parameters such as primary productivity, preservation conditions, and sedimentary rate[17]. But few researches have been carried out on the quantification and hydrocarbon accumulation significance of source rock heterogeneity of different time scales, especially in the unconventional hydrocarbon exploration. Taking the Mesoproterozoic Xiamaling Formation of North China as an example, the source rock heterogeneity and its significance in hydrocarbon accumulation have been discussed from the perspective of organic petrology, geochemistry, and hydrocarbon migration in this paper.

1. Heterogeneity of the Xiamaling Formation shale

The Xiamaling Formation is mainly distributed in the Yanliao Depression in North China (Fig. 1). The age of tuff and bentonite samples were determined by high-precision zircon data are (1 384.4±1.4) Ma and (1 392.2±1.0) Ma respectively, showing the Xiamaling Formation is of the Mesoproterozoic age, and it is thus estimated that the ancient sedimentary rate then was approximately (6.6±1.4) mm/ky[11]. The Xiamaling Formation, deposited in the Xiahuayuan area, Zhangjiakou, is in unconformable contact with the Jurassic Strata above, and Tieling Formation below, 470 m in thickness, and low in maturity (with a EasyRo of 0.6%), and the cumulative thickness of organic-matter-rich shale with total organic carbon content of more than 1% is over 200 m. The middle to lower part of the Xiamaling Formation encompass interbeds of siliceous rock and black shale, in which the black page-like shale has the highest TOC of 24%, chloroform asphalt content of over 8 800 μg/g, and oil content of over 10%, reaching the standard of oil shale[19].

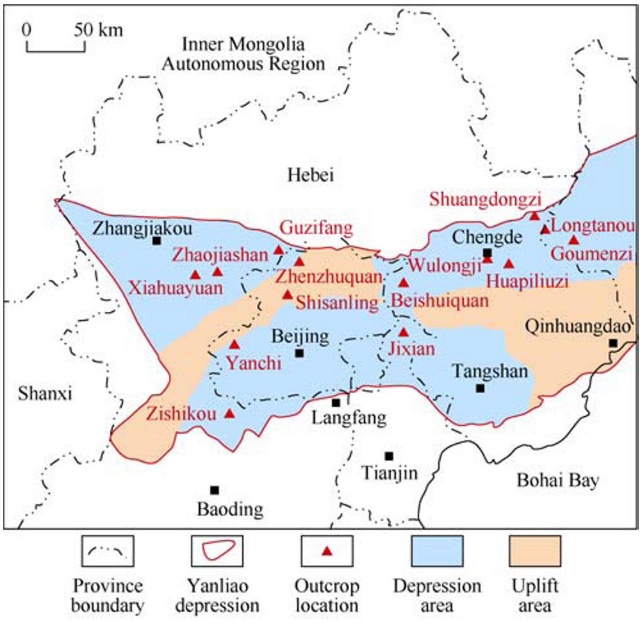

Fig. 1. Outcrop distribution of Xiamaling Formation in North China (Modified from literature [18]).

1.1. Characteristics of the outcrop

This set of low-maturity source rock in the Xiamaling Formation shows distinct heterogeneity on the outcrops, includeing sedimentary cycles of two different time scales. On the large time scale, Unit 1 is composed of alternations of organic-matter-poor layers and organic-matter-rich layers from top of the formation to the base; Unit 2 is rich in organic matter; Unit 3 is composed of alternations of organic-matter-poor layers and organic-matter-rich layers; and Unit 4 is poor in organic matter. Thus, the 350 m sedimentary strata of Xiamaling Formation is divided into four units (Fig. 2). On the small time scale, each unit displays rhythmic sedimentary characteristics of minor difference. Unit 1 (0–75 m) is mainly composed of alternations of black and green shale, and green silty mudstone and marl. Unit 2 (75–242 m) is mainly composed of alternations of black shale and thin-layer gray shale or green mudstone. Unit 3 (242–305 m) is mainly composed of alternations of black shale and siliceous rock or green mudstone. Unit 4 (305–350 m) is mainly composed of red mudstone and