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Research Article

Control of tectonic differentiation on the formation of large oil and gas fields in craton basins: A case study of Sinian−Triassic of the Sichuan Basin

Wang Zecheng*, Zhao Wenzhi, Hu Suyun, Xu Anna, Jiang Qingchun, Jiang Hua, Huang Shipeng, Li Qiufen

PetroChina Petroleum Exploration and Development Research Institute, Beijing 100083, China

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Abstract

Craton basins are the main sites where marine carbonate oil and gas reservoirs develop in China. However, the previous studies scarcely focused on the controlling effects of tectonic differentiation on the formation of large oil and gas fields in the ancient craton basins. In such circumstances, it is difficult to evaluate and select the favorable zones for exploring carbonate oil and gas. In this paper, based on the research results of the Sinian−Triassic prototype basin and lithofacies paleogeography of the Sichuan Basin, the tectonic differentiation pattern of craton basins and its controls on the accumulation elements and the distribution of hydrocarbons were analyzed with reference to the concept that structures control the sedimentation and distribution of oil and gas. The study reveals the results in three aspects. First, the intra-cratonic graben controls the high-quality source rocks and the hydrocarbon generation center, which forms good source-reservoir assemblage with the high-quality reservoir in the platform margin at the flank, showing excellent near-source accumulation conditions. Second, the three types of paleo-uplifts (i.e. differential denudation, syn-sedimentary, and folding) and the deep-large faults developed in the craton are favorable for the formation and distribution of large-scale carbonate reservoirs. Third, the superimposed areas with tectonic differentiation in multiple periods and multiple types are favorable for forming large oil and gas fields. It is concluded that the marine carbonate rocks show a huge oil and gas exploration potential in the Sichuan Basin. Attention should be paid to the new exploration targets of natural gas, such as the Sinian Dengying Fm. in the platform margin at the east flank of Deyang−Anyue graben, the Lower Cambrian Longwangmiao Fm. on the slope of paleo-uplift in central Sichuan Basin, and the Middle Permian Maokou Fm. in central−west Sichuan Basin, where oil and gas accumulation conditions are favorable.

Keywords: Sichuan Basin; Tectonic differentiation; Intra-craton graben; Syn-sedimentary paleo-uplift; Differential denudation paleo-uplift; Carbonate; Sinian−Triassic; New exploration target

Craton basins in China are usually small and highly active [1]. After multi-cyclic tectonic movements, most of the peri-cratonic basins were involved in subduction zones or orogenic belts and then strongly altered and destroyed. The present better-preserved parts are mainly craton basins [2], where marine carbonate oil and gas are accumulated. After decades of exploration, many large carbonate oil and gas fields have been successively discovered in Sichuan, Tarim, Ordos, and other basins, showing a favorable oil and gas exploration potential.

In the past ten years, many scholars conducted primary studies on the ancient carbonate oil and gas geology in China. They proposed some new viewpoints on the favorable conditions for forming large oil and gas fields from different perspectives. For examples, the “theory of late hydrocarbon generation of dispersed liquid hydrocarbons” [3] reveals that high-over mature source rocks still have a favorable gas generation potential; the theory of “source−cap rocks control the

* Corresponding author.
E-mail address: wangzecheng@petrochina.com.cn (Wang ZC).
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distribution of oil and gas reservoirs" [4] emphasizes the controlling effect of source rocks and cap rocks on oil and gas accumulation; the theory of "bedding karst" and "interlayer karst" [5] reveals that carbonate inner system also can develop karst reservoirs; the theory of "coupling hydrocarbon accumulation of four types of hydrocarbon centers" [6] emphasizes that the coupling of hydrocarbon generation center, gas generation center, gas storage center and gas preservation center controls large gas fields; the theory of "four-palaeos controlling the formation of marine carbonate reservoirs" [7] indicates that the time and space configuration of four-palaeos (i.e. paleo-rift, paleo-bioherm beach complex, paleo-trap, and paleo-uplift) controlled the formation of the giant Anyue gas field. However, deep oil and gas in ancient marine formations of craton basins are still less explored and insufficiently understood. Particularly, there are not systematic studies on the controlling effect of tectonic differentiation on the formation and distribution of large marine oil and gas fields in ancient craton basins. It is difficult to evaluate and select the favorable zones for exploring carbonate oil and gas with low exploration degrees.

Taking the Sichuan Basin as an example, this paper discusses the controlling effect of tectonic differentiation on the accumulation elements and the distribution of hydrocarbons in carbonate rocks, based on the research on prototype basins during Sinian−Triassic periods, so as to point out favorable oil and gas exploration targets.

1. Tectonic differentiation in craton basins

1.1. The concept of tectonic differentiation

Differentiation is a natural and common geological process, such as magmatic differentiation, sedimentary differentiation and regional differentiation, etc. Differentiation finally leads to regular variations of geological elements in spatial distribution.

The term "tectonic differentiation" has appeared in some documents, but there is no exact definition for it yet. Chen Guoda et al. [8] proposed that there is historic-dynamic tectonic differentiation in east and west of central Asia continental crust-body, and emphasized that the difference in dynamic mechanism of thermal energy vergence in intra-continental mantles dominated tectonic differentiation. Zhang Yongsheng et al. [9] put forward that tectonic differentiation controlled by the syn-sedimentary faults during deposition periods controlled the potassium-bearing sag in the Lower Ordovician Majiagou Fm. in the North Shaanxi salt basin. Tang Liangjie et al. [10,11] emphasized the controlling effect of tectonic differentiation (such as tectonic deformation, tectonic evolution and faulting activity) on hydrocarbon accumulation. Thus it can be seen that tectonic differentiation is common in geological bodies with various scales, and has an important influence on tectonic patterns, sedimentary and hydrocarbon accumulation.

In this paper, tectonic differentiation in craton basins refers to the differential tectonic deformation and its regular changes occurred due to tectonic stress, pre-existing structure and dynamic mechanism of thermal energy vergence in mantles etc. It presents as block faulting activity, uplifting, erosion and multiphase activation of basement faults in craton basins, forming tectonic units (intra-cratonic graben, paleo-uplift, paleo-depression and deep-large fault belt, etc.), with apparent controlling effect on stratigraphic sequence, sedimentation, lithofacies paleogeography and hydrocarbon accumulation elements.

The previous studies on the controlling effect of paleo-structures on forming large marine carbonate oil and gas fields focused more on the stability, sedimentary differentiation of carbonate rocks, and the effect of paleo-uplifts (especially the fold-type paleo-uplifts) on hydrocarbon accumulation in craton basins. More and more studies indicate that the tectonic stability of craton basins is relative, and moderate tectonic differentiation has great influence on the formation and distribution of high-quality hydrocarbon accumulation elements in marine craton basins. Therefore, the major controlling factors for the formation and distribution of hydrocarbon accumulation elements should be analyzed comprehensively from the prospective of dynamic evolution and through prototype basin reconstruction and paleo-structure framework restoration. For this purpose, the authors present the concept of tectonic differentiation in craton basins.

1.2. Types of tectonic differentiation

Based on the studies of the deep structures in the Sichuan, Tarim and Ordos basins, the tectonic differentiation in craton basins is divided into three types, i.e. tectonic differentiation in an extensional environment, tectonic differentiation in a compressional environment, and linear faulted tectonic belts with multiphase activities (Fig. 1).

1.2.1. Tectonic differentiation in an extensional environment

There are two patterns: intra-continental rifts and intra-cratonic graben.

Before formation, cratonic basins generally experienced the development stage of intra-continental rifts, with filling formations up to thousands of meters to more than ten thousand meters, featured by volcanic activities during the initial rifting period. The formation of intra-continental rifts was related to continental breakup. For example, in the tectonic dynamic setting of the Rodinia supercontinental breakup, the South China Rift System developed in the upper Yangtze Craton [12,13]; the Early Proterozoic rift in North China craton formed after the Columbia supercontinental breakup [14,15].

Intra-cratonic grabens refer to the local graben formed in cratonic basins of regional extensional tectonics. They are characterized by small scale, faulted during the early period and depressed during the late period, and no apparent volcanic activities. These grabens are filled with formations up to hundreds of meters to over 1000 m, without apparent responses in geophysical profiles (gravity, magnetic and electricity data etc.). Typical examples include the Late