Development Characteristics and Guiding Significance to Oil and Gas Exploration of the Sinian Rift in Tarim Basin of China*

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Search and Discovery Article #10748 (2015)
Posted June 30, 2015

*Adapted from extended abstract prepared in conjunction with oral presentation at AAPG Annual Convention & Exhibition 2015, Denver, Colorado, May 31-June 3, 2015.

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Abstract

The Tarim basin, especially the deep area, is becoming one of the most attractive areas for hydrocarbon exploration in China. The extensional tectonic environment associated with multistage fault activities during the Sinian period controls the development of Sinian rift and depression depositional system, also successively controlling lower Paleozoic depositional systems to a certain extent, which have important significance for the further hydrocarbon exploration within the deep realm in the Tarim basin. Based on previous work, in combination with drilling data and new 3D seismic data, tectonic development characteristics of the Sinian rift in the Tarim basin have been depicted in detail. Analysis shows that the Sinian rift is mainly controlled by the rifting of the ancient Tianshan and Kunlun oceans resulting in the occurrence of three aulacogens (Maigaiti, Manjiaer, and Awati) and three ancient uplifts (Tabei, Bachu-Tazhong and Hetian). Meanwhile, the Sinian depositional system can be subdivided into the former rift depositional system and the latter depression depositional system. Further analysis discloses that the Sinian tectonic movement has great guiding significance for hydrocarbon exploration, which can be interpreted as the following four aspects: 1) The Sinian rift and its successive subsidence directly control the sedimentary distribution of the source rock within Sinian and Yuertusi Formation in the Lower Cambrian. 2) The margins of Sinian successive rift control the distribution of platform margin facies belt and successive palaeo-uplifts control the distribution of platform facies within Lower Cambrian, which can act as favorable reservoirs. 3) Platform margin facies belt developed within both Lower Cambrian and Sinian ancient uplifts control the distribution of gypsum rock in the Middle Cambrian, which can act as important cap-rock. 4) The big structural traps successively develop under the gypsum rock in the Middle Cambrian, which can be favorable hydrocarbon accumulation zones, especially Bachu and Madong.

Introduction

The Sinian Formation in the Tarim basin is the first set of depositional cap-rock developed on the basement of the pre-Sinian metamorphic rock. Its corresponding tectonic setting, stress mechanism and successive activities, to a certain extent, have successive control on the Lower Paleozoic deposits, especially on the Middle and Lower Cambrian deposits, the study of which can make great guiding significance on hydrocarbon exploration.

Based on outcrop and early seismic data, a great deal of previous research on the Sinian Formation has been done from the angle of forming mechanism and controlling setting. However, the development characteristics and significance of the Sinian Formation are still not clear because of the limiting quality and number of data. In recent years, the amount of seismic and well data is increasing and is improving in quality. According to previous studies, integrating outcrop, drilling well data and seismic data, this paper reveals the Sinian Formation developmental characteristics in detail and illustrates the guiding significance on hydrocarbon exploration.

Development Characteristics and New Cognition of the Sinian Rift

Characteristics of Outcrops

The investigation of outcrops suggests that the Sinian Formation mainly exists at the Kuruktag area in the northeastern part of the basin, the Keping-Akesu zone in the northwestern part of the basin, and the piedmont belt of the western Kunlun mountain in the southwestern part of the basin (Lixun and Wanxiang, 1990; Zengyao et al., 2007; Zhenjia, 1990; Xinchang et al., 1998; Qiugen et al., 2004; Shipong et al., 1989). The Sinian Formation in the Kuruktag area can be divided into two parts. The Lower Sinian consists of clastic sediments, interbedded with volcanic rock, tillite and thin-layer limestone approximately 4,350m (14,270ft) thick. The Upper Sinian, including the Zhamoketi, Yukengou, Shuiquan and Hangeerqiaoke members, is about 1,900m (6,233ft) thick, and the middle and base intervals are clastic sediments intercalated with marl. The top interval is tillite intercalated with dolomitic quartzose sandstone, and lenses of argillaceous siltstone. The Sinian Formation in the Keping –Akesu area can be divided into two parts. The lower part, including the Qiaoenbulake and Youermeilake members, is approximately 2,000m (6,562ft) thick composed of marine clastic deposits with a small amount of tuff, limestone, tillite and conglomerate. The upper part, including the Sugaitebulake and Qigebulake members, is 760m (2,493ft) thick composed of offshore sediments intercalated with some basalt and carbonate dominating the Sugaitebulake member, and with carbonate buildups that are rich in magnesium mainly deposited in Qigebulake member. In the Kunlun area, the Sinian Formation, with an average thickness of 2,800m (9,186ft), is divided into two parts. The lower part, the Qiamakelike member, is characterized by red clastic sediments interlayered with tillite and mudstone. The upper part of Kuerkake member, including bottom, middle and top intervals, is varicolored clastic sediments, becoming dolomite and oolitic dolomite toward the top and bottom of this member. The Kezisuku member within the upper part is mainly magnesium carbonate rock interlayered with some clastics.

The analysis of the three outcrops mentioned above reveal that the Sinian Formation is the product of the first transgression after the Traim activity, with obvious differences showing in basinal area. The outcrops were likely deposited during a cratonic periphery rifting stage. In contrast to the drilling result in platform area, we divide the Sinian Formation into two sets of sedimentary systems: a clastic sedimentary system and a carbonate sedimentary system.

Characteristics of Drilling Wells and Seismic Reflections

At present, 16 wells penetrating the Sinian Formation have been drilled in the Traim basin. The comprehensive analysis of wells and seismic data suggests that the Sinian Formation shows three distinct facies (Figure 1). In seismic sections, facies 1 has weak amplitude and moderate continuity with a sheeted pattern, represented by Xinghuo1 which penetrates through the approximately 238m (781ft)-thick dolostone of the Qigebulake Member and 12m (39ft)-thick mudstone of Sugaitebulake Member within the Upper Sinian Formation. Beneath them is the

Presinian basement, interpreted as top dolostone of the Upper Sinian. Facies 2, drilled by Tadong1, which encountered an approximately 91m (299ft)-thick dolostone of the Upper Sinian Formation beneath strata of clastic rock. Tillite and volcanics within the Lower Sinian Formation, although not penetrated, are characterized by wedge-shape reflections, suggesting the Lower Sinian Formation. In addition, facies 3 is characterized by chaotic reflections, penetrated by Zhongshen1. According to the isotopic dating results, the age of rock is approximately 1900Ma, suggesting that those chaotic reflections are not the Sinian succession but the Presinian basement.

Basinal-scale tracking and correlation for the three facies disclose that facies 1 is pervasively distributed in the whole basin. However, the facies 2 is located mainly in the east and west sides of northern depression, southwestern piedmont belt and Maigaiti slope. Facies 3 is concentrated in the northern depression and the Maigaiti slope (Figure 2a).

Distribution Characteristics of the Sinian Formation

Based on the recognition of seismic facies and utilizing well and outcrop data, we can illustrate the distribution of the Sinian Formation in detail. In the northern depression bounded by the Aman area, the Sinian Formation consists of two thick sedimentary areas: the eastern and western parts. The eastern part, Kuman area, is adjacent to the Kulutage outcrop located in northwestern part of the basin. In addition, its sediments thicken from the west to the east. The western part, Awati area, is adjacent to the Keping-Akesu outcrop, with sediments thickening from the east to the west. These two parts are both thinning toward the Aman, Tazhong and Tabei areas. In the southwestern area of the Tarim basin, there are two thick sedimentary areas: the east-west striking banded zone developed along the Maigaiti slope and the zone thickening from the west to the east formed in the Kunlun piedmont.

Formation Mechanism of the Sinian Formation

Previous studies suggest that the Sinian Formation was formed in the rifting stage with intensive rifting in the north and east but weak in the south and west due to regionally extensional tectonic activity (Beijing Geological Publishing House, 1993; Xiaoan et al., 1996). During this period, the northern and southern parts of the Tarim basin are on a passive continental margin, and aulacogens developed in the Kuman area of the northern part of the Tarim Basin. Based on previous studies and the analysis of seismic facies and stratigraphy, taking into account the aeromagnetic data, we made two new interpretations: (1) The Sinian Formation can be divided into two sedimentary stages, including rifting stage and depression stage. In seismic sections, the rifting stage is characterized by wedge-shape reflection, inside formation onlapping on the basement, where clastic rock, tillite and volcanics dominantly developed. The depression stage mainly shows a sheeted reflection pattern with parallel, weak amplitude and moderate continuity. In this stage, dolostone formation, with detachment-unconformity contact with the underlying rifting stage deposits, was mainly developed and has larger range, which is also lithologically distinct from the rifting stage deposits. (2) According to the triple joined point theory, it is believed that the Sinian Formation, affected by the rifting of Yili-Zhongshan block and Kunlun block (Jiqing et al., 1990; Guangya et al., 2007), developed three aulacogens (Manjiaer, Awati and Maigaiti) and three paleo-uplifts (Bachu-Tazhong, Tabei and Hetian) (Figure 3a). Aeromagnetic studies (Chengao, 1995; Guanghui et al., 2012) show that high-value magnetic anomaly, usually corresponding to uplifting zones, is typical of the central uplift zone and the southeastern part of the Tarim basin. However, low-value magnetic anomaly related to subsidence is located mainly in the northern depression and the southwestern part of the Tarim basin (Figure 3b). Thus, aeromagnetic studies obviously match well with our study. In addition, the seismic sections for the Kuman aulacogen reveal that the Sinian Formation shows wedge-shape reflections—thicker from the Tabei and Tazhong paleo-uplifts to the Kuman aulacogen, forming a clear boundary in the plane separating the Kuman aulacogen from the peripheral structures. Toward the south, the Sinian Formation in the Awati aulacogen is evidently bounded by wedge-shape reflections, but the northern boundary cannot be recognized where only some ambiguous wedge-shape reflections can be seen because of the poor quality seismic data there (Figure 3c). On the contrary, the northern and southern boundaries of the Maigaiti aulacogen can be clearly implemented due to the distinct wedge-shape reflections developed in the northern and southern sides as well as the Kunlun piedmont (Figure 3d).

Guiding Significance to Hydrocarbon Exploration

The significant breakthrough obtained in sub-salt dolostone drilled by Zhongshen1 suggests promising prospects of hydrocarbon exploration within the sub-salt realm in the Tarim basin. It is imperative to clarify the distribution of the Cambrian source rock and sub-salt dolostone. Studies show that successive activities in the Sinain Era control the Lower Paleozoic succession to some extent. They directly control distribution of the Sinian source rock, the Yuertusi source rock and Xiaoerbulake reservoir in the Lower Cambrian as well as the Middle Cambrian reservoir, and indirectly affect evolution of the paleo-uplifts and late-stage structures.

Controlling on the Development of Source Rock

The controlling of the Sinian rifting and its successive subsidizing on source rock can be interpreted as the following two aspects: direct control on the Sinian source rock and indirect control on Yuertusi source rock in the Lower Cambrian.

In the Kuluketage area, the Sinian shale in Zhaobishan outcrop totals165.07m (541ft) in thickness, with TOC ranging from 1.56%~3.3% and with recovery TOC ranging from 3.12%~6.6%.The shale in the Yukengou Member has a thickness of 24.79m (81ft), with its TOC amounting to 1.06% and with a recovery TOC of 2.12%. The Teruiaiken Member shale thickness reaches 327m (1,073ft), with TOC amounting to 2.96%. It is obvious that these source rocks can act as good source rock based on the assessment standard and being deposited during the Sinian rifting stage. Thus, the depositional range in the Sinian Era responds to the range of the Sinian source rock.

The Cambrian Yuertusi Member is the first formation deposited on the Sinian succession. It was greatly affected by the Sinian paleo-geomorphology and its successive activities. Well and outcrop data show that the shale of the Yuertusi Member is closely related to the Sinian succession in terms of depositional distribution. For example, the shale of the Yuertusi Member is 33m (108ft) thick in Xinghuo1 that also penetrates the Sinian Formation. In addition, we can find Yuertusi shale in the Keping outcrop where the Sinian Formation exists with a certain thickness. Correspondingly, where the Sinian Formation depletes, the Yuertusi shale is missing, such as the central uplift, He, Tong, Batan, Mabei, Tacan, Zhongshen, etc. Actually, Yuertusi shale is only located in the range of the Sinian rift, emerging facies change toward uplifts (Figure 4).

Controlling on the Reservoirs of the Lower Cambrian

The distribution of platform margin facies in the Lower Cambrian is controlled by successively rifting subsiding. Successive paleo-uplifts decided the distribution of the Lower Cambrian platform where tidal flat and dolomitic flat reservoirs developed.

In the Tabei-Luoxi seismic section, the Sinian rifting margins in the Tabei and Luoxi areas prevail platform margin facies of the Cambrian, with a good corresponding relationship between each other. We can recognize gentle slope-platform margin facies of the Lower Cambrian from the Sinian rifting margin in the Awati area. Figure 5b suggests that the Lower Cambrian formations get thinner from the Aman zone to the Awati depression, with seismic reflections changing from weak-amplitudes, chaotic reflections to strong amplitudes, and sheeted reflections. In addition, progradational reflection configurations developed within the Lower Cambrian is similar to those recognized in the Lower Cambrian platform margins of the Gucheng area, which has been verified by drilling wells (Figure 6). Further studies reveal that platform margin facies are consistent with the Sinian rifting margins in terms of distribution and are mainly distributed in a circle along boundaries of the Kuman rift margin and the Awati rift margin. We believe that the Sinian rifting margins were geomorphic units with higher elevation, relative low water depth, and were suitable for formation of platform margin reef-bank facies in the Cambrian. The water depth increased basinward and the facies changed from platform margin to slope facies and basin facies.

The Hetian paleo-continent, a successive paleo-continent, was formed by the Sinian rifting. Lithofacies and paleogeographic studies (Zengzhao et al., 2006; Wei et al., 2001) show that the Hetian area developed from gentle slope, paleo-continent, limited platform, opening platform, platform margin, slope, and deepwater basin facies from the south to the north during the Early Cambrian. The south side of the paleo-continent is characterized by the sedimentary pattern of gentle slope (Figure 6), but the sedimentary pattern developed in the north side is similar to the Wilson model with limited platform, opening platform, platform margin, slope, basin facies successively deposited from shallow water to deep water. The limited platform developed in north side can be subdivided into mixed tidal flat subfacies and limited evaporative dolomite flat subfacies. Kang, Batan, Mabei, Fang, He and Zhongshen disclose that the reservoirs of dolomite developed in the Lower Cambrian and can be compartmentalized into three types: type I, type II, and type III. Among them, the reservoirs of type I and type II, as the most promising sub-salt exploration fields, account for 25%~73%.

Controlling on the Caprock of the Middle Cambrian

The controlling of the Sinian rifting and its successive activities on the depositional succession of the Middle Cambrian can be illustrated with two illustrations. First, successive rift margins of the Sinian control platform margin development of the Middle and Lower Cambrian. Specifically, the Gucheng- Lunxi platform margin controlled the gypsum and evaporates sedimentation, especially in the area to the west of the Gucheng platform. What we can see from the seismic sections traversing the Gucheng platform margin facies is that platform margin facies of the Middle and Lower Cambrian aggrades and migrate basinward because of multi-stage large-scale regression events, resulting in the forming of limited environment of the platform margins with evaporite intercalated with limestone and dolomite developed (Figure 7). Second, the Sinian successive paleo-uplifts controlled the sedimentary facies of the Middle Cambrian. Due to the influence of the Hetian paleo-uplift, the Tabei uplift of the Sinian, as well as regression events, the Tarim basin was characterized by the sedimentary pattern that from south to north of gentle slope, evaporative platform, platform margin, slope and basin facies during the Middle Cambrian. Algal dolomite (Yongquan et al., 2008), and argillaceous dolomite developed to the north of the Tabei uplift, evaporative salt to the south of the Tabei uplift, argillaceous dolomite of tidal flat to the north of the Hetian paleo-uplift, gypsum and salt to the south of the Hetian paleo-uplift.

Controlling on the Paleo-Uplifts and Late Structures

Tectonic evolution studies of the paleo-uplifts and the present structural framework suggest that the Tabei uplift and central uplift are the result of inheritance development of the Tabei paleo-uplift and Bachu-Tazhong paleo-uplift formed by Sinian rifting. The northern depression is derived from the Awati-Kuman rift. In fact, paleo-structural frameworks caused by Sinian rifting do not all align perfectly with present structural units. The Hetian paleo-uplift has evolved into the present foredeep belt of the foreland basin in the southwestern part of the Tarim basin because of the Kunlun orogenic movement during the Himalayanian period. Moreover, the Late Caledonian and Early Hercynian faults controlling the northern margin of low uplift in central part of the Tarim basin are formed by inversing of the normal fault belt derived of the early Sinian rifting. In addition, the Tumuxiuke faults that control the northern margin of the Bachu fault-uplift developed from the normal fault belt that formed during the Sinian Era in southern margin of Awati rift.

Guiding Significance to Hydrocarbon Exploration

Comprehensive analysis reveals that Tazhong is the favorable play and the Bachu area is the key exploration play in sub-salt field. This can be illustrated in term of the following: (1) From perspective of source rock-reservoir-caprock assemblage and economic exploration limitations, although three of the facies—Gucheng platform margin facies in the Lower Cambrian, Tabei platform margin facies and Awati platform margin facies—may be favorable in term of reservoir. They still are not explored commercially because of deep buried depth. However, Bachu and Tazhong can be chosen as the favorable exploration zone due to good quality reservoirs of dolomite developed there, superior caprock of gypsum developed within the Middle Cambrian, short distance to or nearly superimposed with the Yuertusi shale in Awati, Kuman and Maigaiti, and shallow burial depth less than 7,500m (24,606 ft). (2) In view of hydrocarbon migration and accumulation, paleo-uplifts and sub-salt structures in Tazhong are favorable directional zones of hydrocarbon migration. Tabei uplift is not favorable for hydrocarbon migration due to severe destruction during the late period. However, Bachu-Madong sub-salt structures are favorable for hydrocarbon accumulation and readjustment because of tilting movements during late stage. In contrast to Gaoshiti-Moxi gas field in Sichuan basin, sub-salt structures in Tazhong are favorable in term of accumulation conditions, and Bachu where many anticlines are perfectly saved to present has the same accumulating conditions with Weiyuan gas field, thus it can be chose as the key exploration area (Figure8a, Figure8b).

Conclusions

1. The Tarim basin was characterized by rifting derived from extensional stress during the Sinian Era, controlled by Tianshan paleo-ocean and Kunlun paleo-ocean, resulting in three aulacogens (Manjiaer, Awati, Maigaiti) and three paleo-uplifts (Bachu-Tazhong, Tabei and Hetian).
2. The Sinian rifting and its successive activities directly controlled Yuertusi shale distribution in the Lower Cambrian, platform margin and platform facies distribution in the Lower Cambrian, and indirectly controlled the caprock development and distribution in the Middle Cambrian and formation of paleo-uplifts as well as the secondary structural belts.

3. Tazhong is the favorable play where inherited big structures develop and Bachu area is the key exploration play in sub-salt realm.

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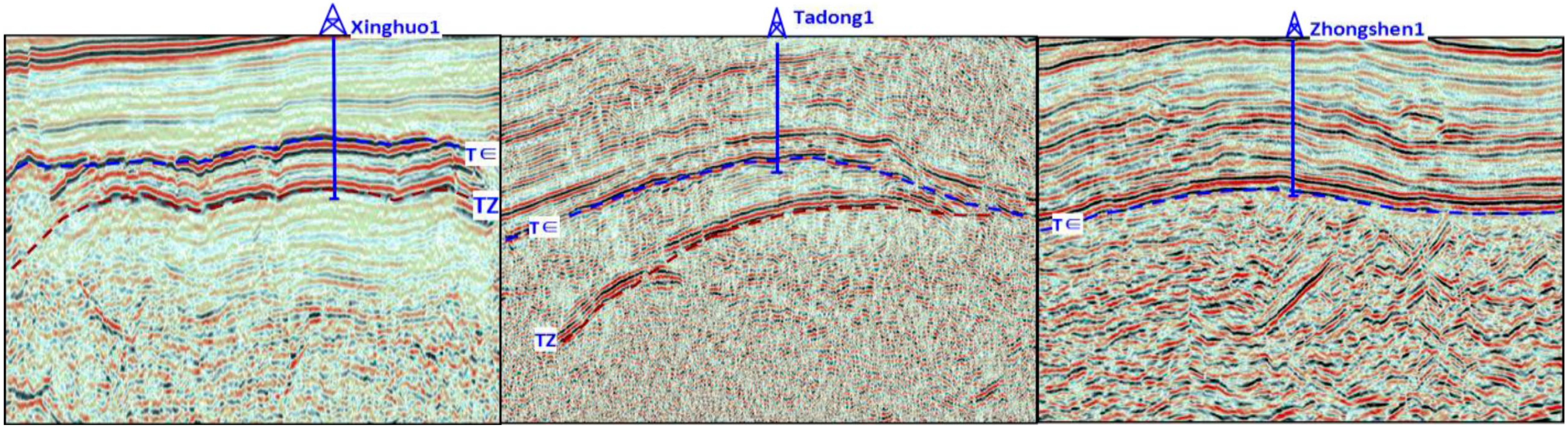

Figure 1. The characteristics of seismic reflection in the Sinian formation.

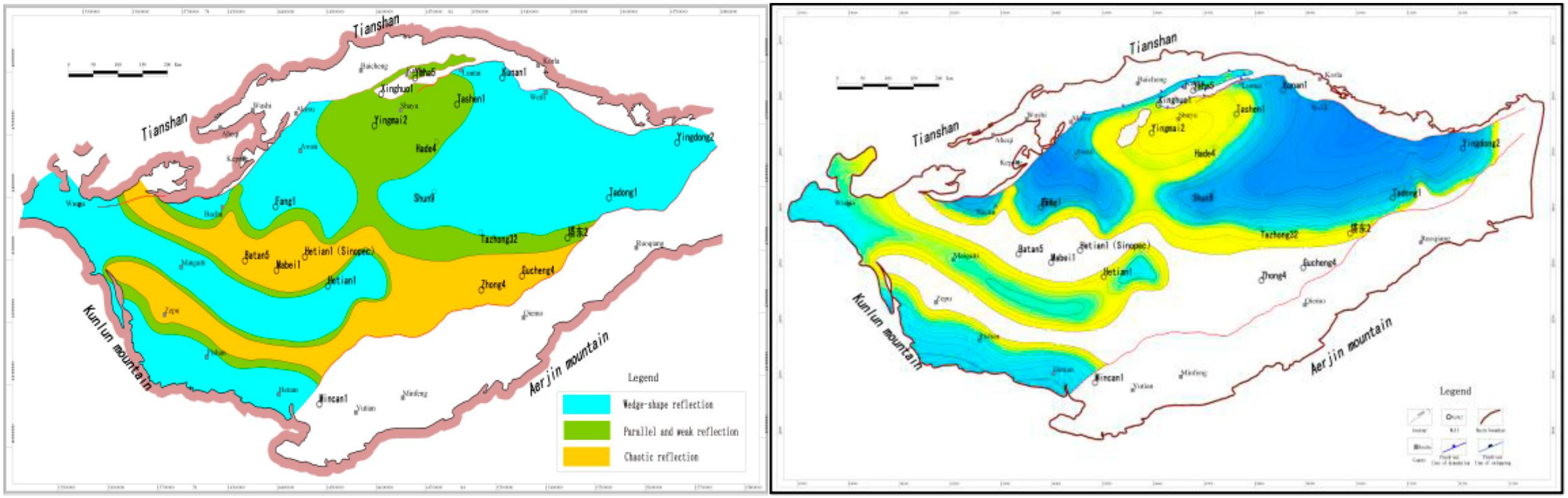

Figure 2. A) Map showing horizontal seismic facies of the Sinian formation in Tarim basin, B) Map showing horizontal residual thickness of the Sinian formation in Tarim basin.

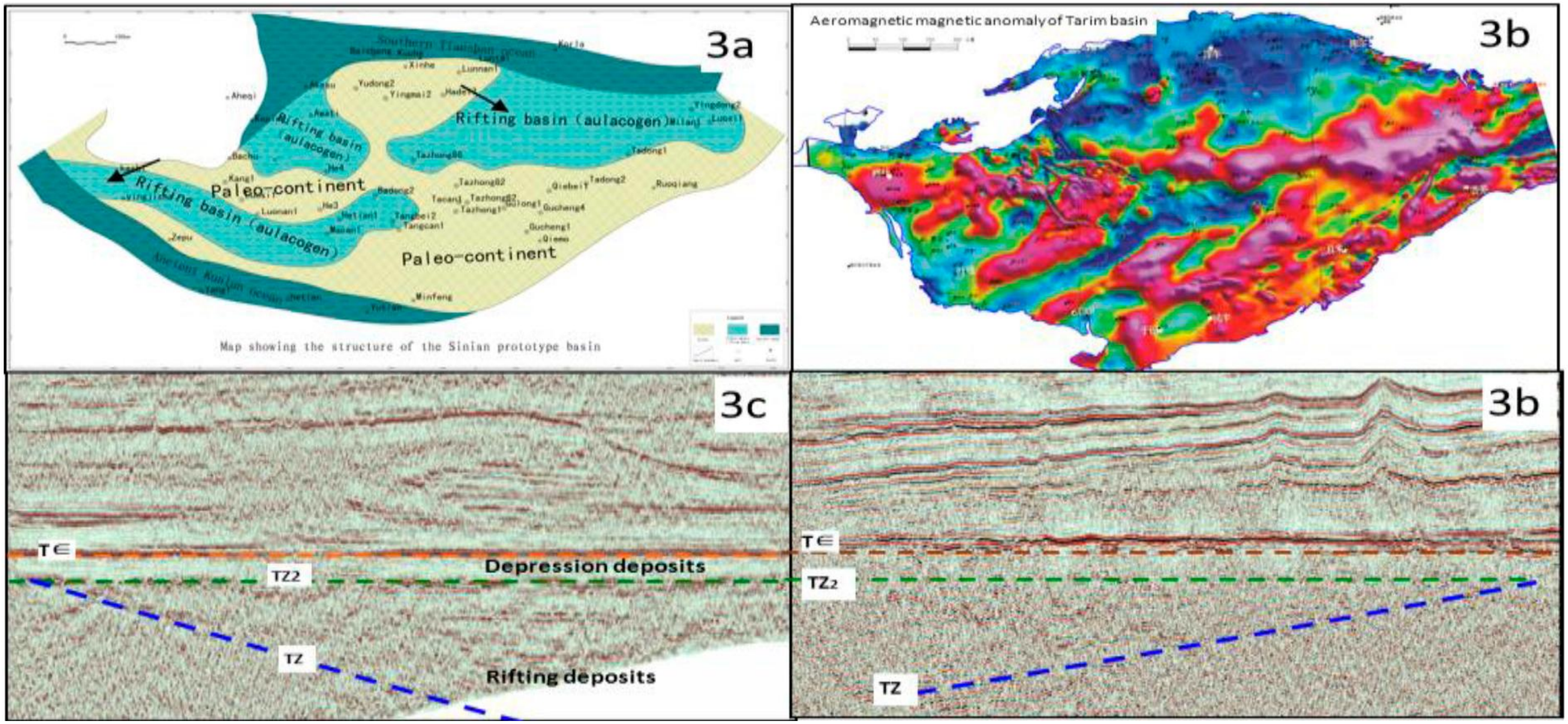

Figure 3. Development characteristics of the Sinian rift valley in Tarim basin.

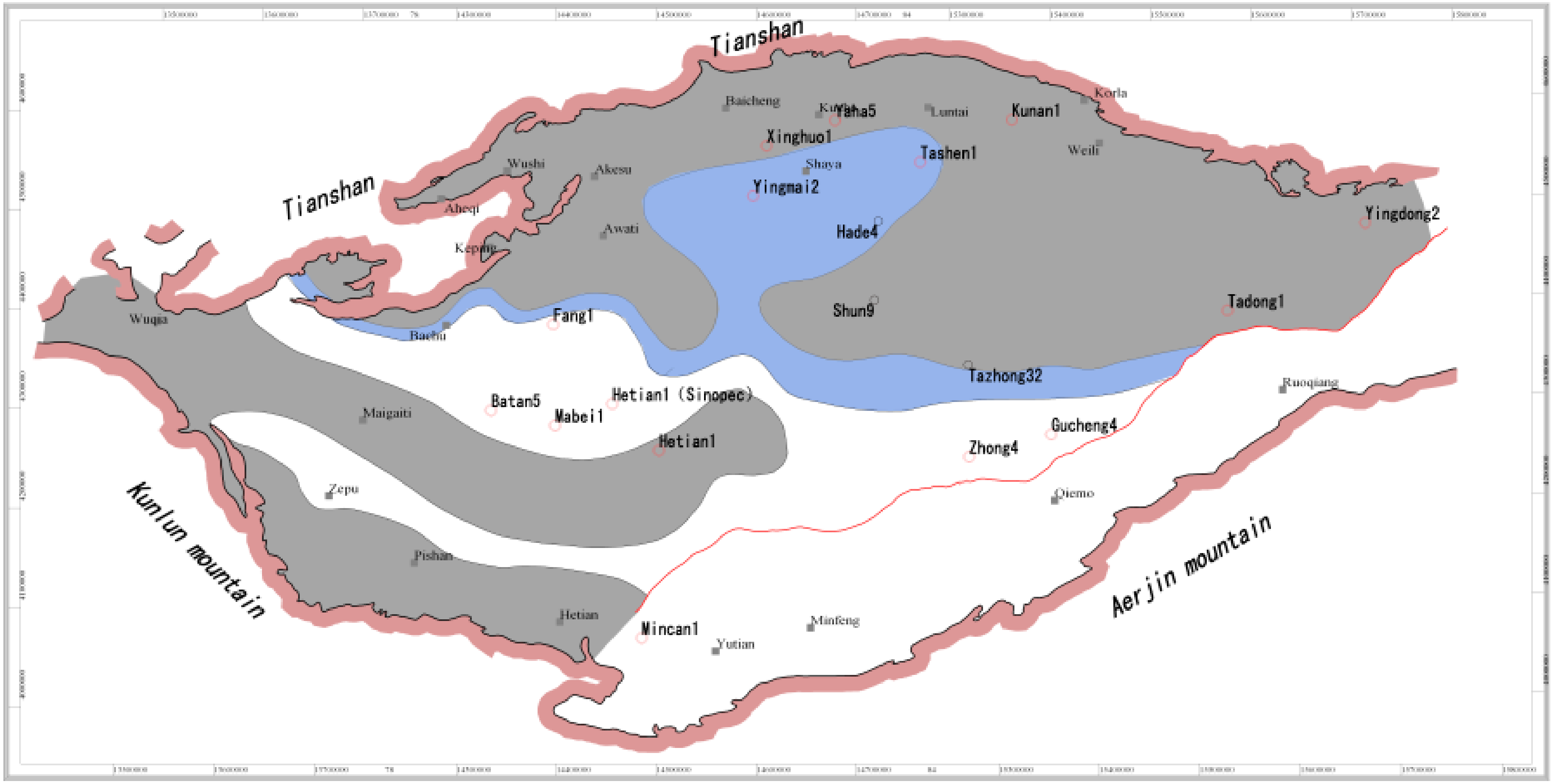

Figure 4. Map showing horizontal distribution of the Cambrian Yuertusi formation in Tarim basin.

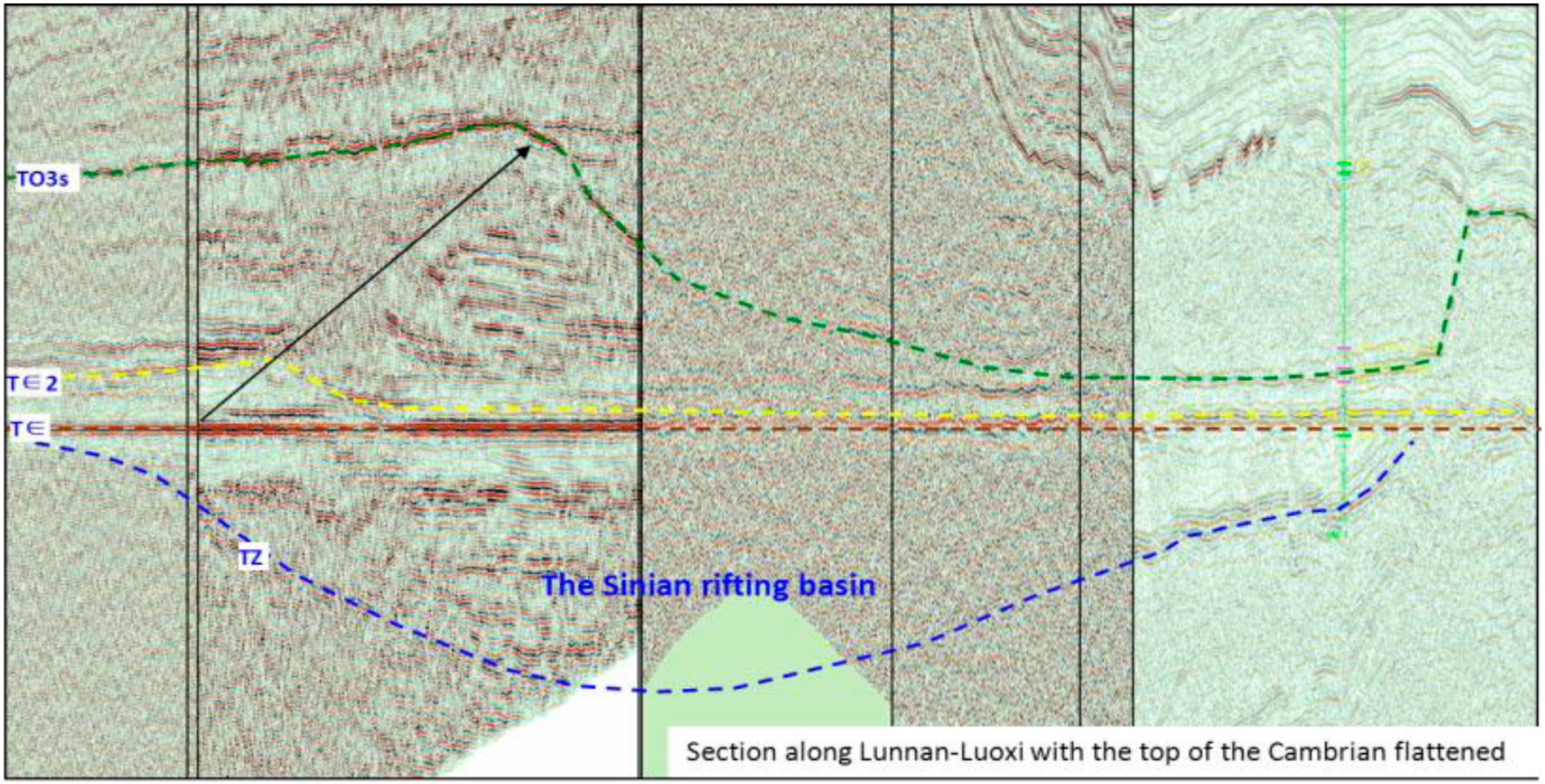

Figure 5. Characteristic section showing controlling of the Sinian rift margin on the Cambrian-Ordovician platform margin facies.

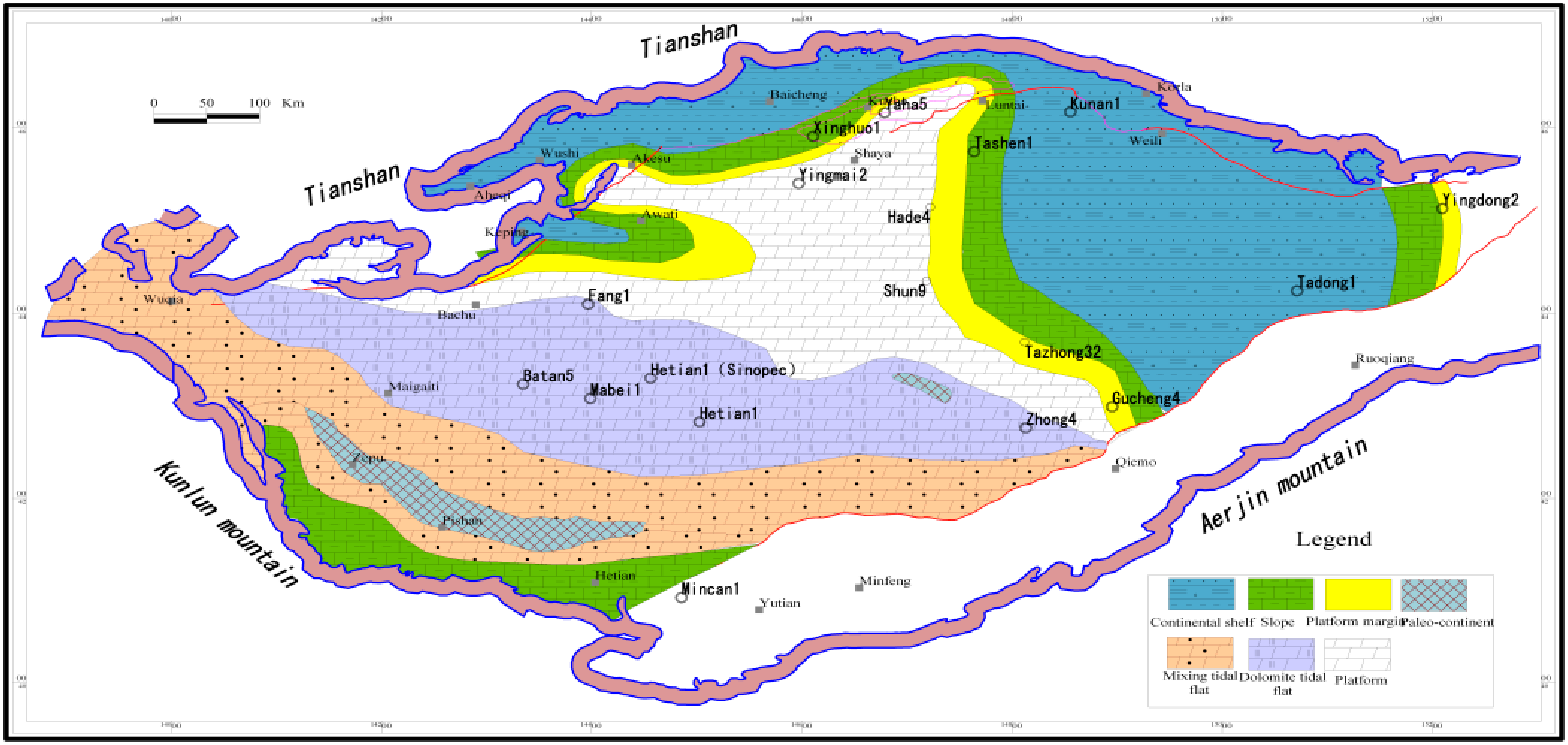

Figure 6. Map showing sedimentary facies distribution of the Lower Cambrian, Tarim basin.

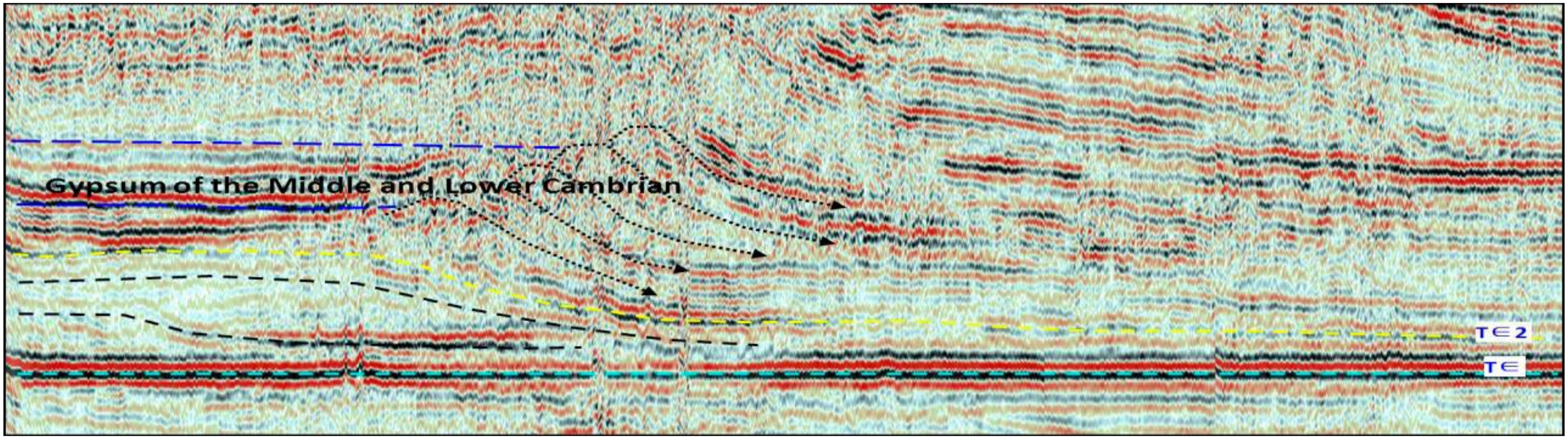

Figure 7. Classical section showing the controlling of the Middle-Lower Cambrian platform margin facies on the Middle Cambrian caprock.

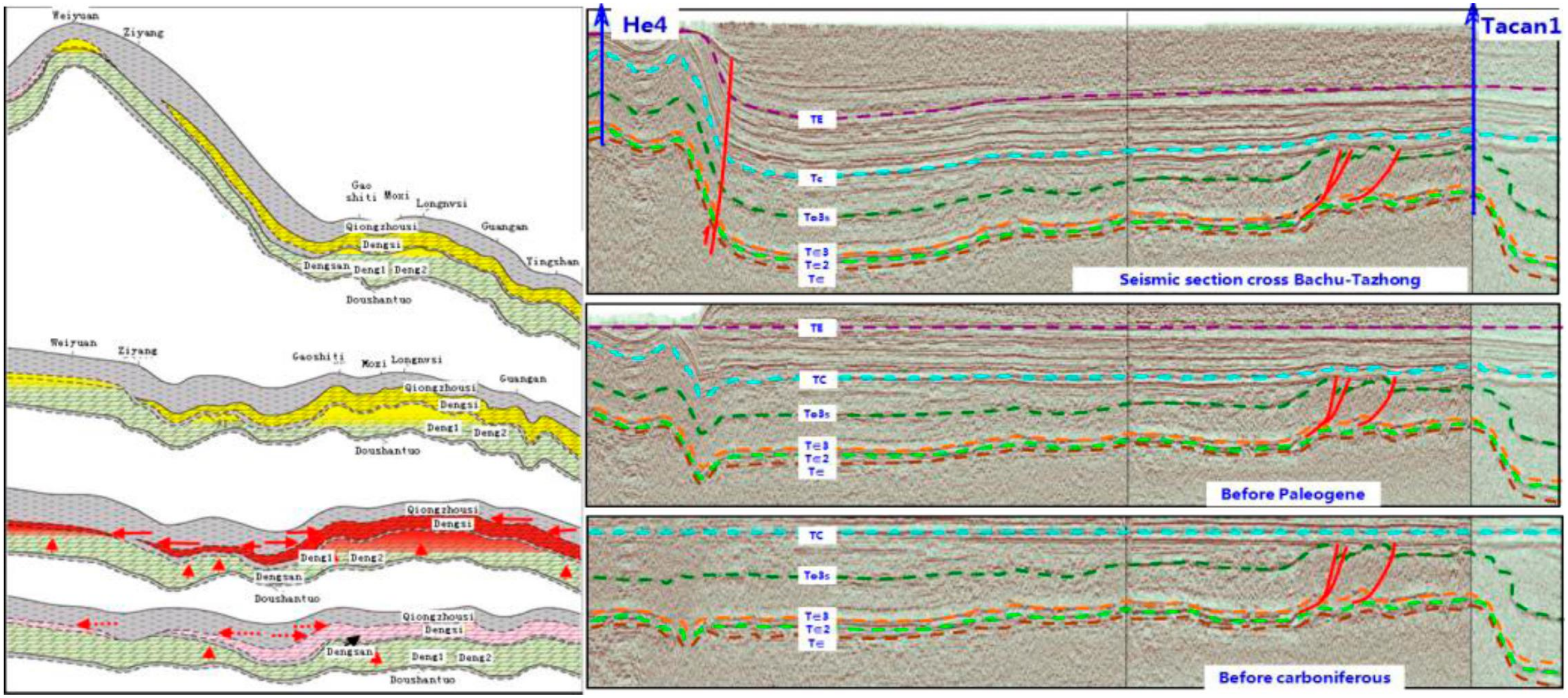

Figure 8. A) Evolution profiles of the Sinian reservoirs in Gaoshiti-Moxi, Sichuan basin, B) Tectonic evolution of the Cambrian subsalt structures in Bachu-Tazhong, Tarim basin.