Chapter

Late Neo-Proterozoic Tectono-Sedimentary Evolution of the Tarim Block, NW China

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Abstract

The study of the late Neo-Proterozoic tectono-sedimentary evolution of the Tarim Basin is a key to unravel the tectonic setting, the intracontinental rift formation mechanism, and the sedimentary filling processes of this basin. Since in the Tarim Basin, the late Neo-Proterozoic to early Cambrian sedimentary successions were preserved, this basin represents an excellent site in order to study the Precambrian geology. Based on the outcrop data collected in the peripheral areas of the Tarim Basin, coupled with the intra-basinal drill sites and seismic data previously published, the late Neo-proterozoic tectono-sedimentary evolution of the Tarim Basin has been investigated. These data show that there were two individual blocks before the Cryogenian Period, namely, the north Tarim Block and the south Tarim Block. In the early Neo-Proterozoic (ca. 800 Ma), the amalgamation of two blocks resulted in the formation of the unified basement. During the late Neo-Proterozoic, the Tarim Block was in an extensional setting as a result of the Rodinia supercontinent breakup and then evolved into an intracontinental rift basin. The tectono-sedimentary evolution of the basin may be divided into three stages: the rifting stage (780–700 Ma), the rifting to depression transitional stage (660–600 Ma), and the post-rift depression stage (580–540 Ma). In the rifting stage, intracontinental rifts (i.e., the Awati Rift, the North Manjar Rift, and the South Manjar Rift) were formed, in which coarse-grained clastic sediments were deposited, generally accompanied by a massive volcanic activity due to an intensive stretching. In the rifting-depression transitional stage and in the post-rift depression stage, the paleogeography was characterized by uplifts to the south and depressions to the north. Three types of depositional association (i.e., clastic depositional association, clastic-carbonate mixed depositional association, and carbonate depositional association) were formed. The distribution of the lower Cambrian source rock was genetically related to the tectono-sedimentary evolution during the late Neo-Proterozoic. The lower Cambrian source rock was a stable deposit in the northern Tarim Basin, where the late Ediacaran carbonate was deposited, thinning out toward the central uplift. It was distributed throughout the entire Mangar region in the east and may be missing in the Magaiti and the southwestern Tarim Basin.

Keywords: Tarim Block, late Neo-Proterozoic, tectono-sedimentary evolution, intracontinental rift, lower Cambrian source rock

1. Introduction

The Neo-Proterozoic to early Cambrian was a significant period of geological history. Several global geological events occurred in this time interval, for example, the assembly and breakup of the Rodinia supercontinent, the Snowball Earth, and the global sea-level rise and anoxic events [1–13]. The Tarim Basin is a large superimposed basin that underwent multiple phases of tectonic deformation from the Precambrian to the Cenozoic [14]. The late Neo-Proterozoic sedimentary succession was preserved in the peripheral areas of the Tarim Basin, which recorded convergence breakup cycles of the Rodinia supercontinent, multi-glacial events, multiphase volcanism, and evolution of continental rift [15–25]. The study of the late Neo-Proterozoic tectono-sedimentary evolution of the Tarim Basin is a key to unravel the tectonic setting, the continental rift formation mechanisms, and the sedimentary filling processes.

Additionally, being the largest petroliferous basin in northwest (NW) China, the lower Cambrian source rock was a focus of scientific debate [17, 18, 26–28]. In recent years, the results of oil and source rock correlation and the exploration discovery of primary oil and gas in the Cambrian subsalt dolomite reservoirs have shown that the lower Cambrian Yurtusi Formation is the most important source rocks in Tarim Basin [26, 29]. However, there are few stratigraphic data about the lower Cambrian source rock. Due to its small thickness and the deep burial, it is difficult to identify and trace the seismic horizons corresponding with the lower Cambrian source rocks on the seismic sections. Therefore, there are a lot of controversies over the distribution of the lower Cambrian source rocks, especially in the western sectors of the Tarim Basin [17, 18, 26–28]. These issues directly affect the evaluation and the selection of the target areas of deep oil and gas exploration. An accurate prediction of the distribution of the lower Cambrian source rock is essential for the deep oil and gas exploration in the Tarim Basin. The late Neo-Proterozoic tectono-sedimentary evolution of the Tarim Basin was reconstructed based on a comprehensive analysis of a large number of field outcrop data, drilling data, and high-resolution seismic profiles. Moreover, we have discussed how the early basin tectonic background influenced the sedimentary characteristics during the early Cambrian period, with a view to provide new ideas for the distribution of the lower Cambrian source rock.

2. Geological setting

The Tarim Block has an ancient crystallization basement and was separated from the Rodinia supercontinent during the late Neo-Proterozoic. The Tarim Basin, covering an area of approximately 56×10^4 km^2, was the stable area of the Tarim Block (**Figure 1**). As one of the three major continental blocks in China, the Tarim Block experienced several stages of tectonic evolution since its formation, having both similarities and dissimilarities to the North and South China Blocks [30]. The continental crust evolution of trondhjemite, tonalite, and granodiorite (TTG) during the late Neoarchean [31–34] and two orogenic events at the end of the Paleo-Proterozoic and the late Meso-Proterozoic to early Neo-Proterozoic, respectively, occurred. During the early period of the Neo-Proterozoic (ca. 900 Ma), the Tarim Block, that was a part of the Rodinia supercontinent, collided with the Australian Plate [4, 35–39]. Since ca. 800 Ma, the Tarim Block was separated from the Australian Plate, as a result of the breakup of the Rodinia supercontinent, resulting in the late Neo-Proterozoic cover deposits [1, 2]. During the extensional phase, an intense continental rifting, magmatic events, and sedimentary processes subsequently occurred, both in the interior and periphery of the Tarim Block, ranging in age from Cryogenian to Ediacaran [1–13, 15–22, 30, 40, 41].

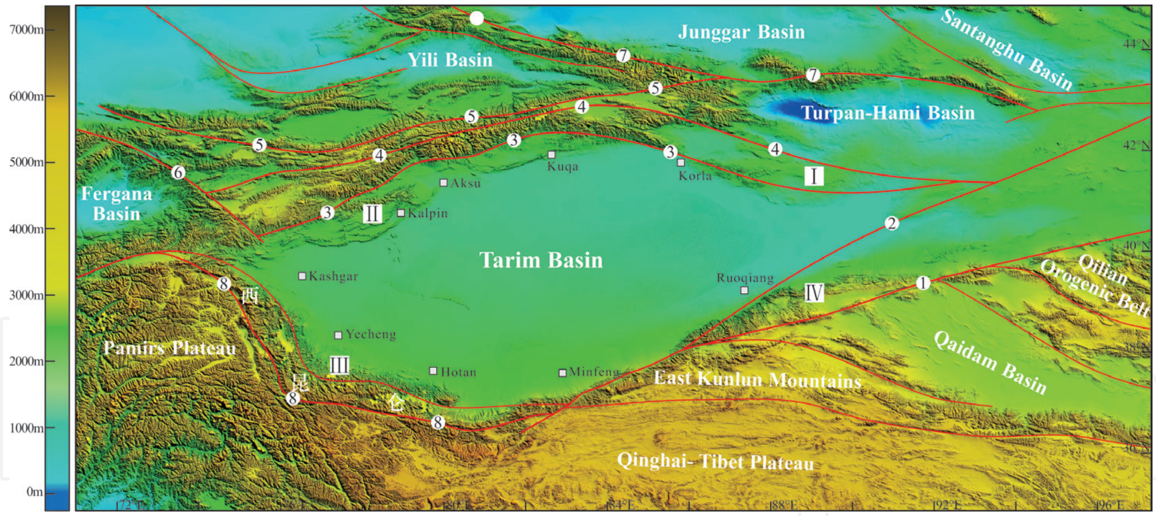

Figure 1.
Tectonic characteristics of the Tarim Basin and its peripheral areas. I-Kuruktag Quruqtagh uplift belt; II-Kalpin uplift belt; III-Tiekelike uplift belt; and IV-Altun uplift belt. 1-Altun strike-slip fault; 2-Xingxingxia strike-slip fault; 3-North Tarim fault; 4-south marginal fault of the central Tianshan; 5-Nikolaev-Nalat fault belt; 6-Talass-Fergana strike-slip fault; 7-north Tianshan suture belt; and 8-Kangxiwar fault belt.

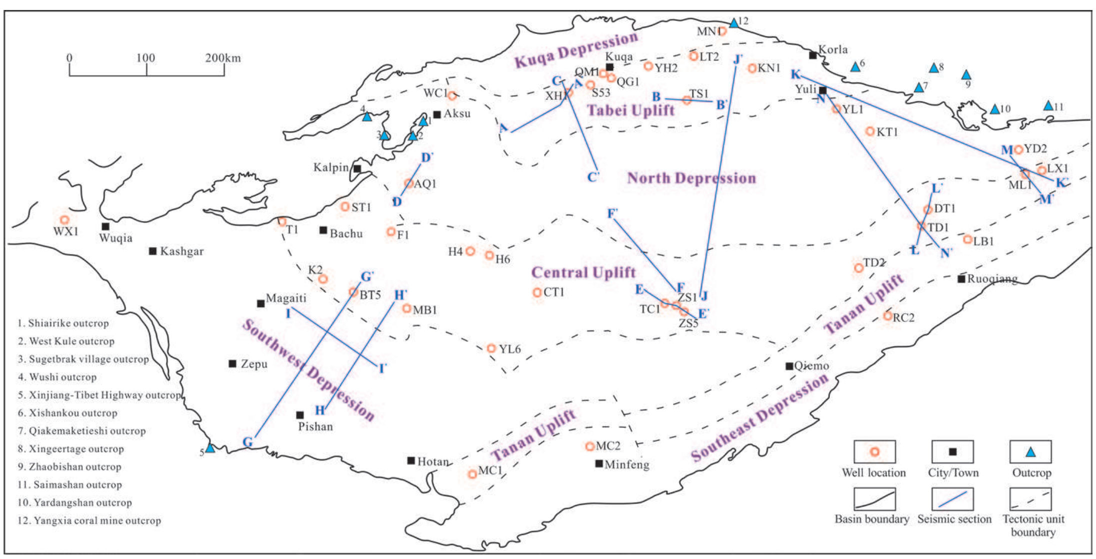

Figure 2.
Tectonic units division and key well locations in the Tarim Basin.

Currently, four uplift belts, that is, Quruqtagh in the northeast, Kalpin in the northwest, Tiekelike in the southwest, and Altun in the southeast (SE), are distributed on the margin of the Tarim Basin, while the hinterland of the basin is covered by desert areas (**Figure 1**). Based on the top of the basement and the regional characteristic of large-scale faults, the Tarim Basin was divided into seven first-order tectonic units, with three structural uplifts and four depressions, that is, the Kuqa Depression, the Tabei Uplift, the North Depression, the Central Uplift (Bachu Uplift, Tazhong Uplift, and Gucheng Uplift), the Southwest Depression, Tanan Uplift, and the Southeast Depression (**Figure 2**) [24].

3. The late Neo-Proterozoic sedimentary distribution

The hinterland of the Tarim Basin was covered by desert. The Neo-Proterozoic outcrops were distributed along the basin margin, mainly in the Aksu-Kalpin area in the northwestern margin, the Quruqtagh area in the northeastern margin, and the Tiekelike area in the southwestern margin, while they are lacking in the Altun area in the southeastern margin of the basin. Within the basin, several wells (including well XH1, well WC1, well QG1, well LT1, well YL1, well DT1, well TD1, and well TD2,) were drilled into the late Neo-Proterozoic strata and some other wells (including well ST1, well T1, well F1, well H4, well BT5, well MB1, well CT1, well TC1, well ZS1, well MC1, and well YD2,) were drilled into the Precambrian basement or into volcanic rocks (**Figure 2**).

3.1 Periphery of the basin

3.1.1 The northeastern margin

The Neo-Proterozoic outcrops in the northeastern margin of Tarim Basin were mainly located in the Quruqtagh area. The Quruqtagh area was separated into northern and southern regions by the Xingdi fault and preserved intact Neo-Proterozoic sedimentary successions.

The Cryogenian sequence was subdivided into the Baiyisi Formation, the Zhaobishan Formation, the Altungol Formation, and the Tereeken Formation from the bottom to the top (**Figures 3** and **4**). In the northern Quruqtagh region, the Baiyisi Formation comprised of diamictites in its lower part and was overlain by volcanic rocks. The Zhaobishan Formation was composed of sandstones, siltstones, and shales in the northern region and was lacking in the southern region. In the northern region, the Altungol Formation developed diamictites in the lower part and consisted of siltstones, sandstones, and volcanic rocks in its upper part. In the southern region, the Altungol Formation was dominated by diamictites and covered by cap dolomite with negative $\delta^{13}C$ values [42]. In the northern region, the Tereeken Formation consisted of diamictites separated by several layers of siltstones, mudstones, and volcanic rocks and was covered by a 10-m thick cap dolomites, characterized by negative $\delta^{13}C$ values [42]. In the southern region, a shallowing upward sequence crops out, which is composed of shales, siltstones, sandstones interlayered with carbonates (**Figure 4**).

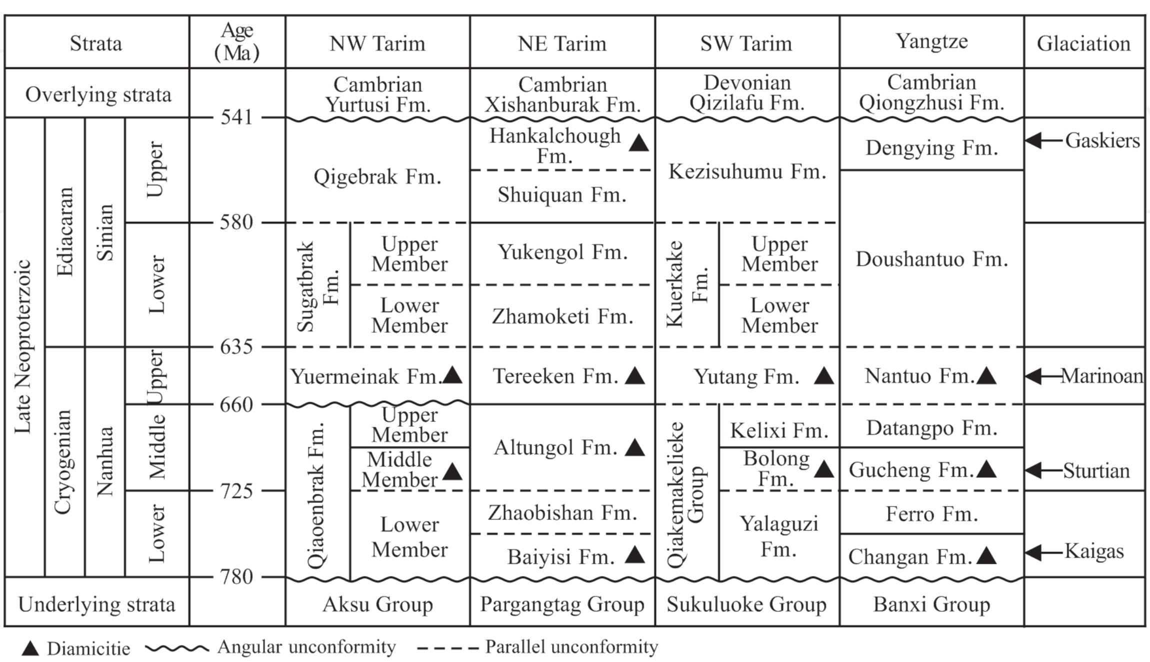

Figure 3.
Stratigraphic classification and correlation of Cryogenian-Ediacaran in the Tarim Basin.

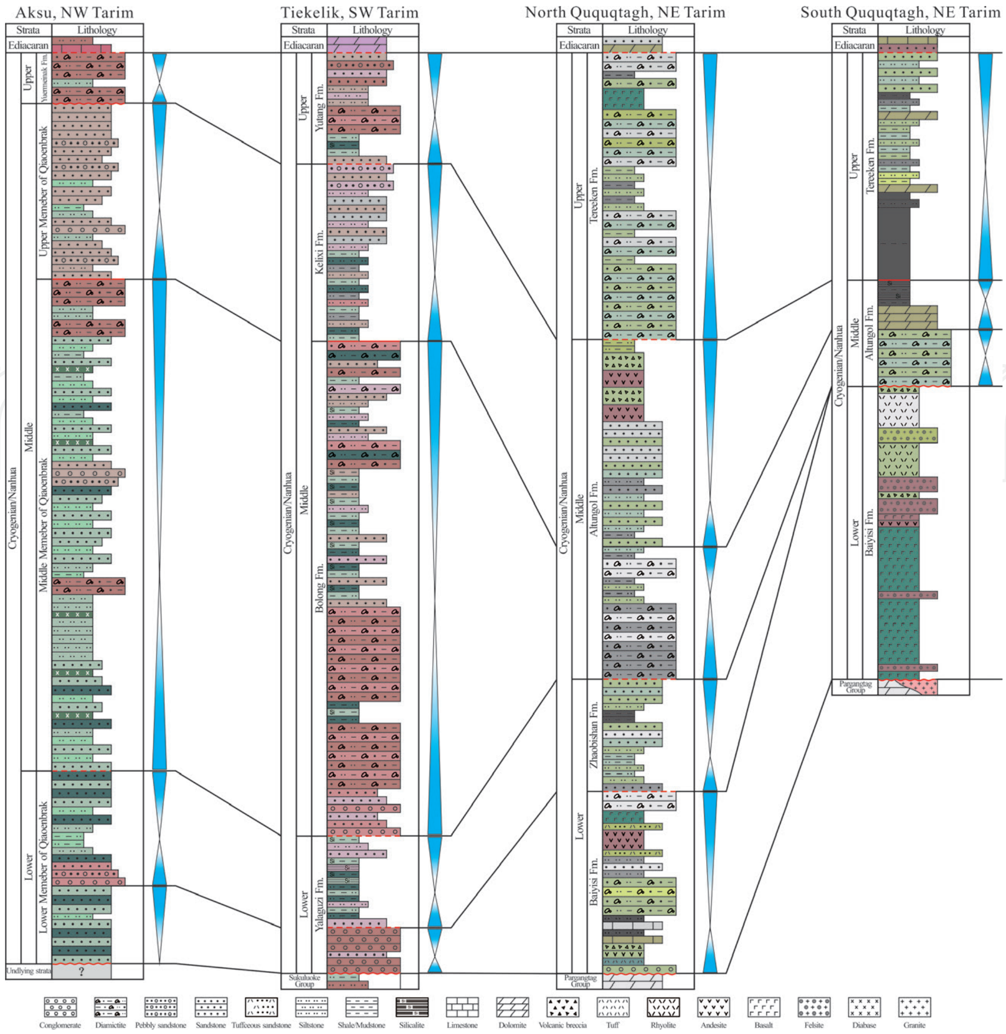

Figure 4.
Stratigraphic correlation of Cryogenian in periphery of the Tarim Basin.

The Ediacaran sequence was disconformably underlain by the Cryogenian strata and was unconformably overlain by the Cambrian Xishanbulake Formation (**Figure 5e**). It was subdivided into the Zhamoketi Formation, the Yukengol Formation, the Shuiquan Formation, and the Hankalchough Formation from the bottom to the top (**Figures 3** and **6**).

In the northern region, the Zhamoketi Formation were comprised mainly of fine-grained clastic deposits and volcanic rocks developed on the figures. The Yukengol Formation was composed of shales, siltstones interlayered with carbonates (**Figures 5e** and **6**). In the southern region, the Zhamoketi Formation and Yukengol Formation have similar sedimentary characteristics, which are mainly sandstones and siltstones (**Figures 5e** and **6**). There are weak differences between the southern and northern regions in the upper Ediacaran and the carbonate deposition gradually increased. The Shuiquan Formation was principally composed of carbonate rocks with a positive $\delta^{13}C$ ratio (**Figures 5g** and **6**) [42]. The youngest Hankalchough Formation in the top part of Ediacaran was comprised of diamictites and cap dolomites, characterized by negative $\delta^{13}C$ values in both northern and southern regions (**Figure 6**) [42].

3.1.2 The northwestern margin

The Neo-Proterozoic outcrops in the northwestern margin of the basin were mainly distributed in the Aksu-Wushi area. The Neo-Proterozoic units are

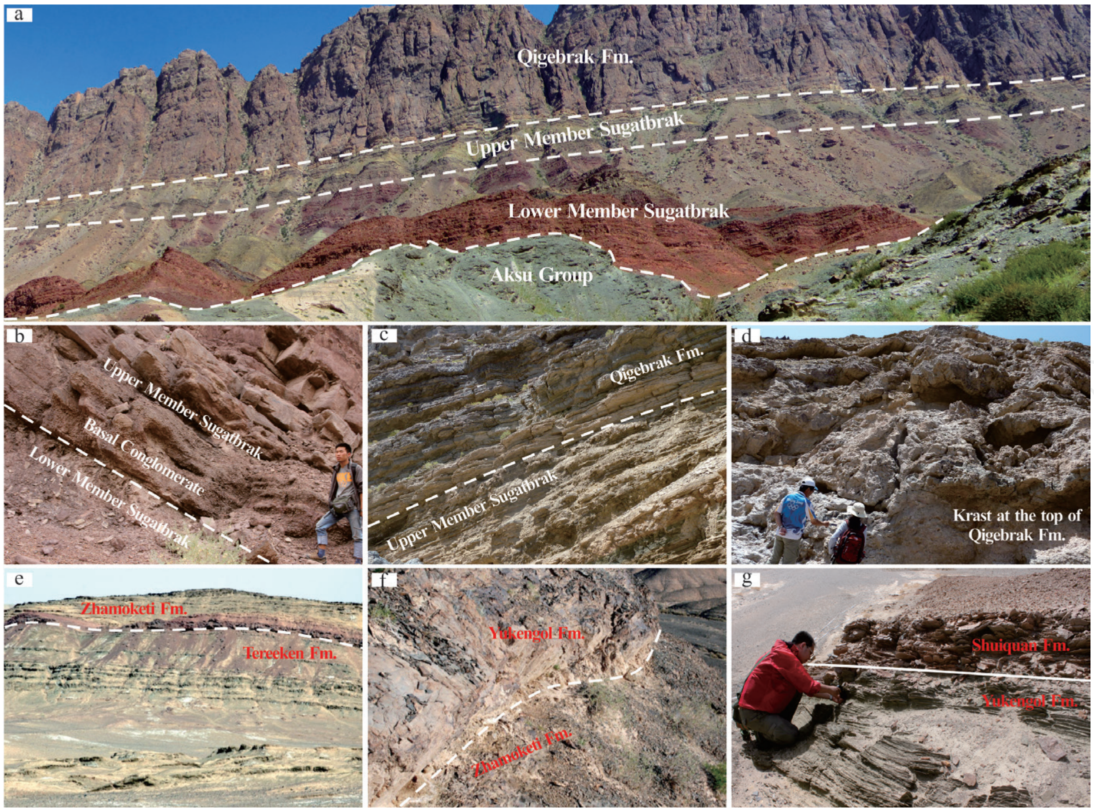

Figure 5.
Characteristics of the Cryogenian-Ediacaran sequence boundary in periphery of the Tarim Basin.

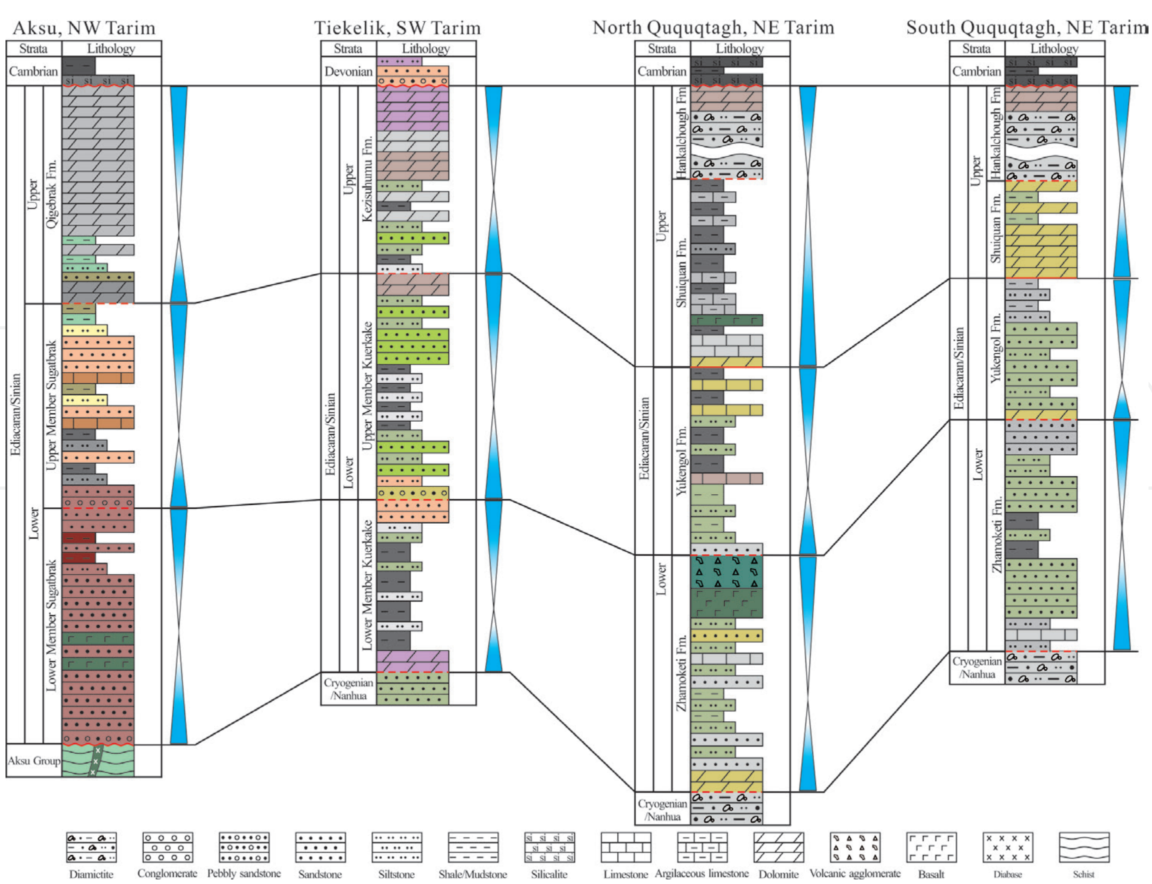

Figure 6.
Stratigraphic correlation of Ediacaran in periphery of the Tarim Basin.

composed of the metamorphic Aksu Group and the unmetamorphosed Cryogenian and Ediacaran sequences. The Aksu Group was mainly comprised of pelitic, psammtie, and mafic schists, which underwent green-schist to blue-schist facies metamorphism (**Figure 5a**) [42–44]. In addition, a series of NW-trending mafic dykes intruded the Aksu Group, with given zircon U-Pb ages of 757 ± 8.9 Ma [5] and 759 ± 7 Ma [45]. The Aksu Group was unconformably overlain by the Cryogenian-Ediacaran sedimentary strata, including the Qiaoenbrak and Yuermeinak Formations of the Cryogenian and the Sugetbrak and Qigebrak Formations of the Ediacaran (**Figures 3**, **4**, and **6**).

The Qiaoenbrak Formation was subdivided into the lower, middle, and upper members (**Figure 4**). The lower member was mainly composed of feldspar sandstones, feldspar-quartz sandstones, and siltstones. The middle member was characterized by thick rhythmic gray-green sandstones and siltstones (**Figure 4**). Several mafic dykes intruded into the middle member, with given zircon U-Pb age of 633 ± 7 Ma. The upper member was mainly calcareous sandstones and coarse-grained feldspars sandstones. There is a clear angular unconformity between the Qiaoenbrak Formation and the overlying Yuermeinak Formation. The Yuermeinak Formation was locally exposed and consisted of thick diamictites and sandstones, which were interpreted as glacial deposits. The Yuermeinak diamictite is generally correlated with the Tereeken diamictite in the northeastern Tarim Basin.

The Sugetbrak Formation was unconformably underlain by the Yuermeinak Formation or the Aksu Group (**Figure 5a**). It consisted of two members. The lower member was composed of red conglomerates and sandstones, which were deposited in an oxidized environment (**Figure 5a** and **b**). The mafic dykes intruded into the lower member, with given zircon U-Pb age of 615 Ma [3]. The upper member was characterized by mixed deposits of fine-grained clastic and carbonate rocks. The Qigebrak Formation was composed of bedded dolomite and stromatolites developed. There is a weathering crust with a thickness of ca. 30–50 m in the uppermost of the Qigebrak Formation, which was unconformably overlain by the Cambrian Yurtusi Formation (**Figure 5d**).

3.1.3 The southwestern margin

The Neo-Proterozoic strata in the southwestern margin of the basin were mainly distributed in the Tiekelike area and the outcrops along the Xinjiang-Tibet Highway were complete. The late Neo-Proterozoic succession has been divided into the Qiakemakelieke Group (including Yalaguzi, Bolong, and Kelixi Formations) and the Yutang Formation of the Cryogenian, Kuerkake, and Kezisuhumu Formations (Ediacaran; **Figures 3**, **4**, and **6**).

The Yalaguzi Formation was composed of conglomerates and unconformably underlain by the Tonian Sukuluoke Group (**Figure 4**). The upper part was composed of gray-green laminated silicalite and siliceous mudstones. The Bolong Formation was mainly composed of two sets of thick diamictites, which were separated by layers of laminated siliceous mudstones, siltstones, and sandstones. The Bolong diamicitie can be generally correlated with the Altungol and Qiaoenbrak diamictites (**Figure 4**). The Kelixi Formation was a shallowing upward sequence. It was composed of mudstones, siltstones, sandstones, and conglomerate-bearing sandstones from the bottom to the top (**Figure 4**) [46]. There was another set of diamicites in the lower part of the Yutang Formation, which was contemporaneous with the Tereeken and Yuermeinak diamictites. The upper part was composed of siltstones and sandstones (**Figure 4**).

The Kuerkake Formation includes two members (**Figure 6**). The lower member was composed of black and dark-gray mudstones intercalated with siltstones, while the upper member consisted of sandstones and siltstones interlayered with dark-gray mudstones. The Kezisuhumu Formation was composed of mudstones, siltstones interlayered with dolomites in its lower part and thick dolomites in the upper part, which was unconformably covered by Devonian or Carboniferous strata.

3.2 The areas within the basin

3.2.1 The northern Tarim Basin (the Tabei area)

In the northern part of Tarim Basin, only well WC1, well XH1, well QG1, and well LT1 have drilled in the Ediacaran strata, while no well drilled in the Cryogenian strata. The Sugetbrak Formation was characterized by fine-grained clastic sediments and limestones, with a thickness of ca. 70–90 m. These features were similar to those in the upper member of Sugetbrak in the Aksu area. The Qigebrak Formation has a thickness of ca. 160–180 m and is composed of dolomites. The well XH1 has drilled phyllite, quartz schist, and granite gneiss beneath the Sugetbrak mudstones. The granite gneiss yielded a zircon U-Pb age of 832 ± 4 Ma [30]. The well WC1 has drilled the chlorite schist and quartz schist with detrital zircon ages clusters at ca. 800 Ma [30, 47]. In the Yangxia section, the sericite quartz schist developed and the detrital zircon ages clusters were at ca. 800 Ma [48]. This metamorphic basement has also been drilled in wells YH2, well LT2, and well MN1. It might be correlated with the Aksu Group in Aksu area accordingly to the detrital zircon ages and to the degree of metamorphism. In addition, Precambrian basement granite (ca. 1.8–1.9 Ga [30, 47, 49]) was revealed in many boreholes. These lithologic and chronological characterisitics suggest that the northern Tarim Basin developed a metamorphic basement which might be corresponded to the Aksu Group, and the Paleo-Proterozoic crystalline basement locally occurred.

As shown on seismic profiles, the Ediacaran strata were distributed stably in the southern area of the Tabei uplift (**Figure 7a**–**c**). Toward the north, the Ediacaran strata were pinched out due to uplifting and denudation during Paleozoic, and hence the Precambrian metamorphic basement was directly covered by Mesozoic strata (**Figure 7c**).

3.2.2 The Bachu-Tazhong area

In the Bachu uplift, only well T1 has drilled the late Neo-Proterozoic strata with a thickness of ca. 200 m. The lithology is composed of mudstones, sandstones, and volcanic rocks, and the underlying andesite (zircon U-Pb age of 755 ± 3 Ma [30]) is intercalated with mudstones. The youngest detrital zircon age of tuffaceous sandstone just below the Cambrian carbonate rocks of well T1 is 707 ± 8 Ma, which was interpreted as the maximum sedimentary age [50]. In addition, some wells (e.g., well ST1, well F1, and well H4) directly drilled in the mafic volcanic rocks just below the Cambrian carbonate rocks (ca. 26–224 m), which were supposed to correspond to the eruption in the period of the late Neo-Proterozoic based on the zircon U-Pb dating [47].

In the northern Bachu uplift, there was no borehole drilled in the Neo-Proterozoic strata. The seismic interpretation has shown that the Cryogenian depositional distribution was controlled by faults and was characterized by intracontinental rift deposition (**Figure 8a**). The Ediacaran strata have stable distribution over the rift sedimentary system (**Figure 8a**).

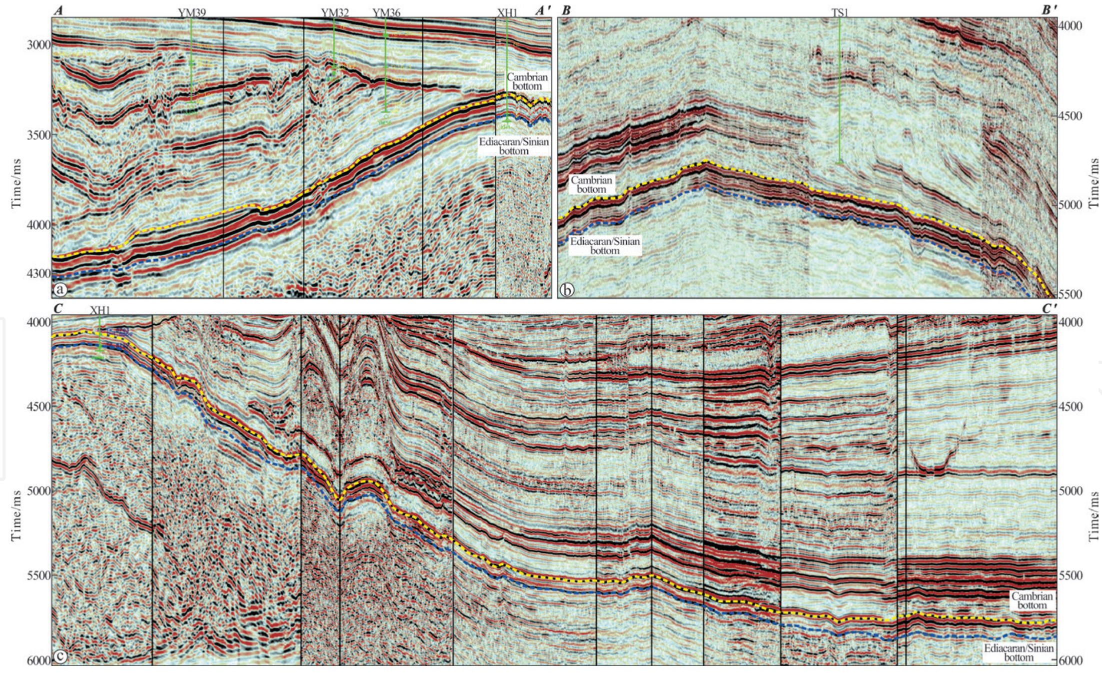

Figure 7.
Seismic reflection characteristics of Cryogenian-Ediacaran in the northern Tarim Basin (profiles location as shown in Figure 2).

In the southern Bachu uplift, well BT5 has revealed a set of breccias below the Cambrian strata. The breccias mainly consisted of basalt/diabase, indicating the deposits were near the source. The well MB1 drilled the granite gneiss (zircon U-Pb age of 1920 ± 14 Ma [50]) just below the Cambrian carbonate rocks. It was suggested that the Paleo-Proterozoic crystalline basement occurred in the Maigaiti area. The well YL6 drilled a set of marble below the middle Cambrian [50], which might be corresponded to the Bochatetage Formation in the Tiekelike area. According to detrital zircon dating, the Bochatetage Formation was deposited in the middle Neo-Proterozoic [11].

In the Tazhong uplift, there was no borehole drilled in the Neo-Proterozoic sedimentary successions. The well ZS1 drilled the olivine-bearing granite (zircon U-Pb ages of 1895 ± 1 Ma [47] and 1915 ± 5 Ma [30]) and well TC1 revealed diorite and granodiorite (zircon U-Pb age of 757 ± 6 Ma [51]) below the Cambrian carbonate rocks. In the northern region of Tazhong uplift, there were obvious seismic reflection characteristics of the Cryogenian intracontinental rift deposition with large thickness and the Ediacaran depression sedimentary successions (**Figure 8c**). However, in the southern area, the late Neo-Proterozoic sedimentary successions were lacking, and the Paleo-Proterozoic crystalline basement was directly overlain by the Cambrian carbonate rocks (**Figure 8b**). The above features implied that the northern part of the Tazhong uplift was a deposition area, while the southern part was the structural high without deposition during the late Neo-Proterozoic.

3.2.3 The eastern Tarim Basin (the Tadong area)

In the Tadong area, several boreholes (e.g., well TD2, well TD1, well DT1, and well YL1) have drilled in the Ediacaran strata. In the Tadong low uplift zone, well TD1, well TD2, and well DT1 drilled in Shuiquan carbonate rocks with a thickness of ca. 28–800 m. The Paleo-Proterozoic granite crystalline basement (zircon U-Pb ages of 1908 ± 9 Ma [51], 1908 ± 9 Ma, and 1908 ± 9 Ma [47]) was revealed in well

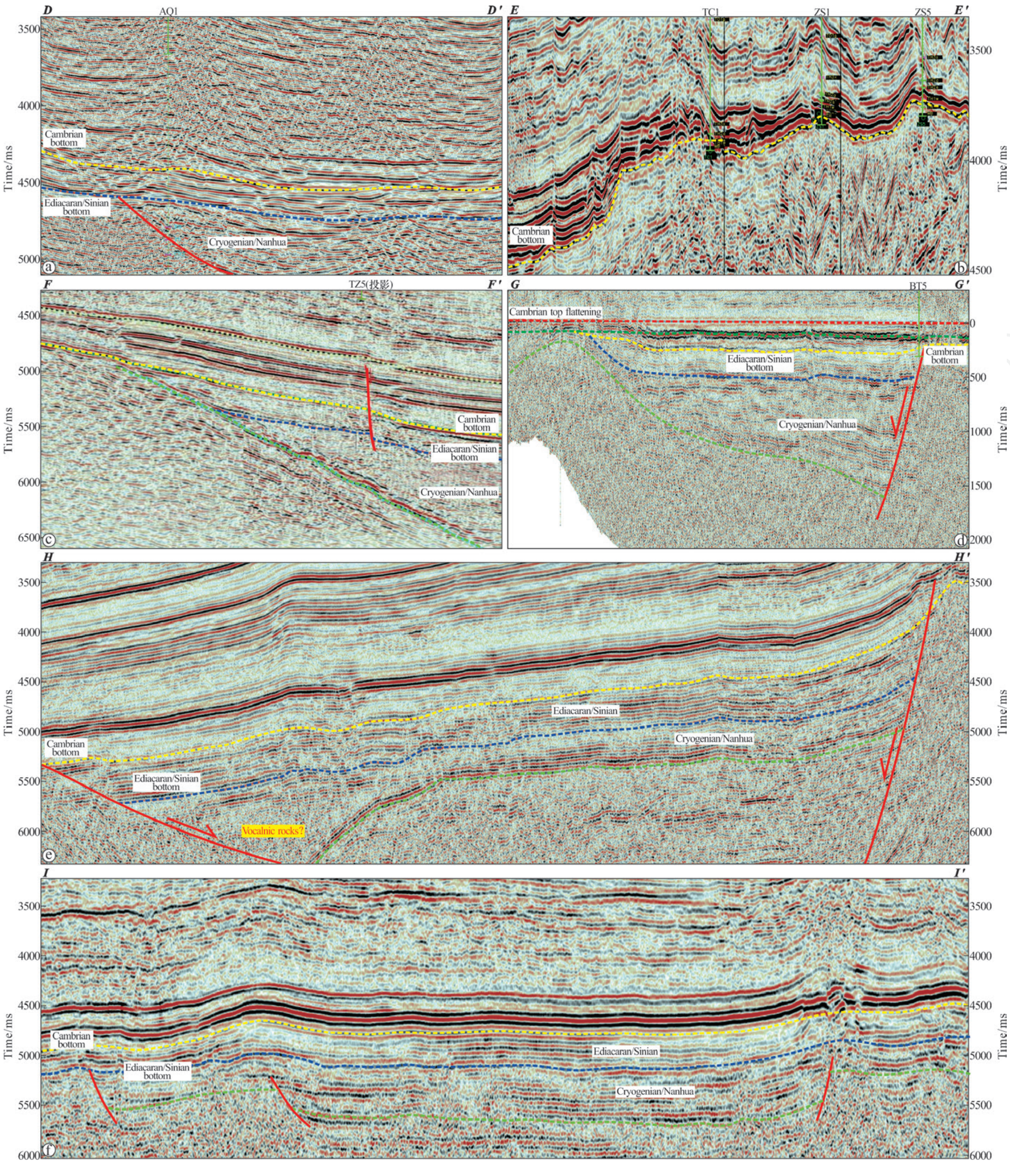

Figure 8.
Seismic reflection characteristics of Cryogenian-Ediacaran in the western Tarim Basin (profiles location as shown in Figure 2).

TD2. The well YD2 drilled the granite (zircon U-Pb ages of 750 ± 7 Ma [47]) and was overlain by the Cambrian black shale. The Ediacaran sedimentary successions including the Zhamoketi, Yukengol, and Shuiquan Formations were drilled by well YL1 in the Manjar sag, which composed of mudstones and siltstones in the lower part as well as micrite and argillaceous limestones intercalated with mudstones in the upper part.

As shown on seismic profiles, the Cryogenian was characteristic of the intracontinental rift deposition with a great thickness variation, which was controlled by faults (**Figure 9a** and **b**). The Ediacaran was the post-rifting depression deposition and stably distributed in the Manjar area (**Figure 9a**, **b**, and **e**). It was implied that the Tadong low uplift was a structural high, which might be the volcanic eruption center or the rift flank, hence it directly deposited the Shuiquan dolomite. The thickness of the Shuiquan dolomite pinched out toward the south (**Figure 9c** and **d**). The Shuiquan dolomite was missed in well YD2, and this might be attributed to denudation due to uplifting at the end of the Ediacaran.

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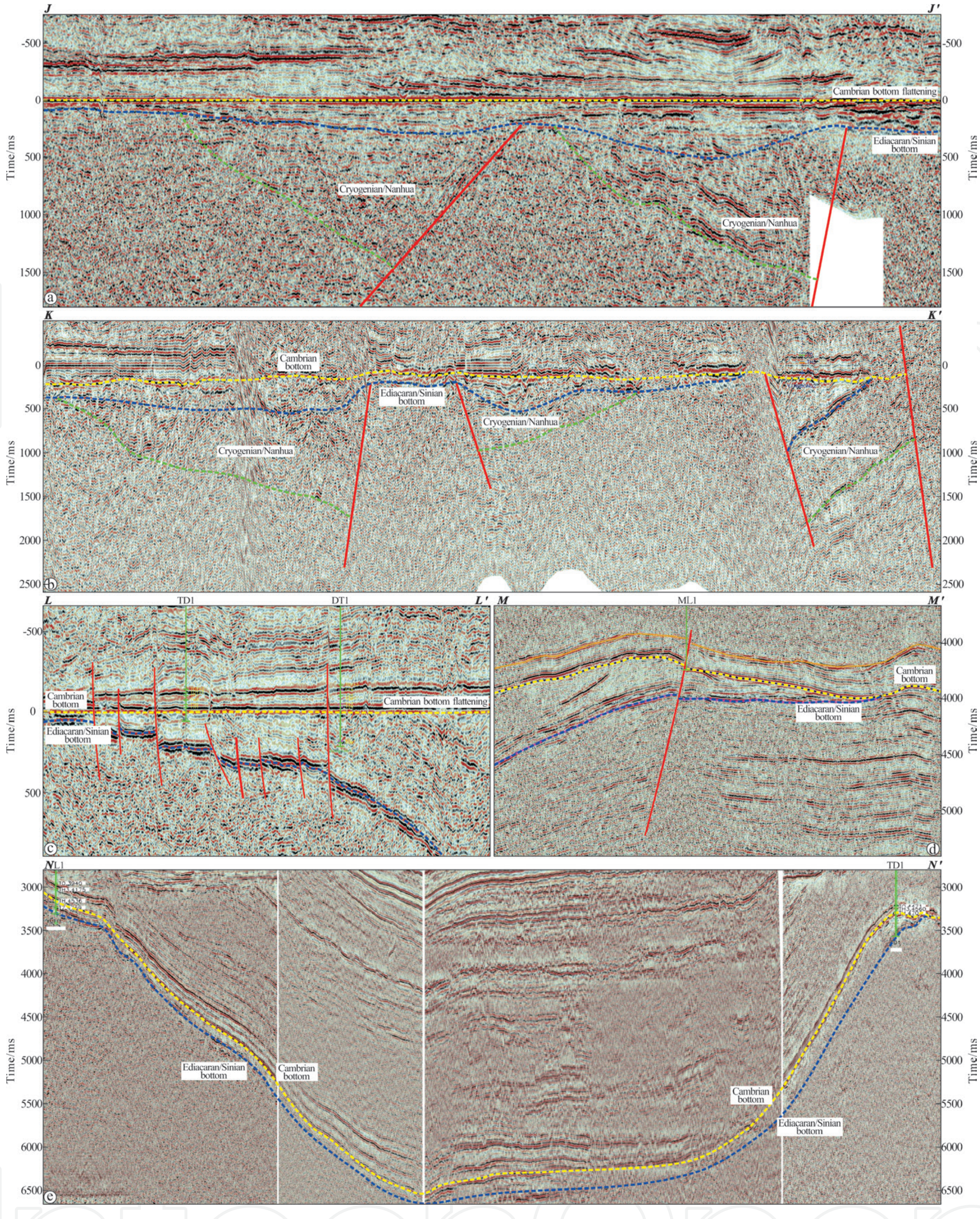

Figure 9.
Seismic reflection characteristics of Cryogenian-Ediacaran in the eastern Tarim Basin (profiles location as shown in Figure 2).

3.2.4 The southwestern to southeastern Tarim Basin

Although no Cryogenian-Ediacaran strata have drilled in the southwestern Tarim Basin due to large buried depth, the distinct seismic reflection signatures could be identified on the seismic section (**Figure 6d**–**f**). The Cryogenian developed intracontinental rift sedimentary successions with a large thickness and the Ediacaran was characteristic of depression sedimentary successions (**Figure 6d**–**f**). The 3D resistivity inversion results displayed that a depth range of 6–15 km exhibited low resistivity in the Magaiti area [52], and the areas of low-resistivity decrease with depth. Thus, it was inferred that the Cryogenian-Ediacaran developed in the southwest (SW) Tarim Basin. The northeast (NE)-SW trending aeromagnetic anomalies belts might indicate the basement difference and were not the identification mark of the Cryogenian-Ediacaran sedimentary successions.

In the southwestern Tarim Basin, no Cryogenian-Ediacaran strata have drilled. The wells MC1 and MC2 drilled in the low green-schist facies metamorphic rocks, with detrital zircon age clusters at ca. 750–850 Ma and 1.8–1.9 Ga [30, 47]. According to the detrital zircon ages, metamorphic grade, and petrological characteristics, it might be equivalent to the Ailiankate Group in the Tiekelike area. The Ailiankate Group was considered as Paleo-Proterozoic, but recent studies revealed it was Neo-Proterozoic [11, 53, 54]. Moreover, no Cryogenian-Ediacaran sedimentary successions were observed in the Altun outcrops, and the Cambrian/Ordovician strata were underlain by the Tonian. Thus, it was concluded that the southeastern Tarim Basin was the uplift area without deposition during the period of Cryogenian-Ediacaran.

4. Discussion

4.1 Tectono-sedimentary evolution

4.1.1 The pre-rifting stage (ca. 880–800 Ma)

Recently, a large number of chronological, geochemical, and geophysical studies on the Precambrian basement were carried out [1–13, 30, 34, 47, 51, 53–62]. These results suggested that there were two individual blocks before the Cryogenian Period, namely, the north Tarim Block and the south Tarim Block (**Figure 10**). The Neo-Proterozoic granitie (ca. 930–910 Ma [60, 63, 64]) was widely distributed in the Altun area, southeastern margin of Tarim Basin. Geochemical analysis indicates that the granite was formed in a collision orogenic tectonic background and interpreted to syn-collision granite [60, 64, 65], which was a result of the Rodinia supercontinent convergence. Thus, it is inferred that the south Tarim Block converged to the northern margin of the Australia Plate and collision orogenesis at ca. 930–910 Ma. This tectonic movement resulted in the formation of extensive

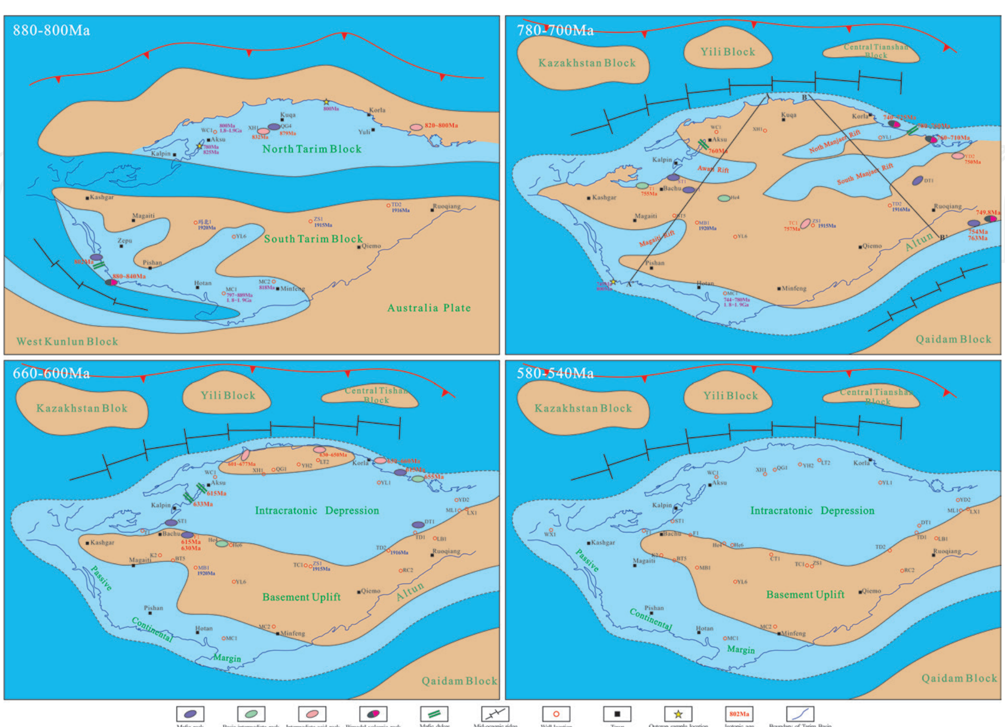

Figure 10.
Tectonic-sedimentary characteristics of the Tarim block during Cryogenian to Ediacaran.

syn-collision granite in the southeastern margin of Tarim Basin. The Sailajiazitage bimodal volcanic rocks were identified in the southwestern margin of Tarim Basin, which were composed of basalts and rhyolites [12]. The geochemical and chronological studies have suggested that these bimodal volcanic rocks formed in the intracontinental rift setting and erupted during the early Neo-Proterozoic (ca. 880–840 Ma) [12, 54, 66].

These different characteristics suggest that the western and eastern parts of south Tarim Block had different tectonic settings during the early Neo-Proterozoic. After the south Tarim Block converged to the northern margin of Australia Plate, the western part of the south Tarim Block was in an extensional tectonic setting and the West Kunlun Ocean gradually opened. The NE-SW trending rifts began to develop at ca. 880 Ma (**Figure 10**) and then deposited the early Neo-Proterozoic successions (Sailajiazitage Group, Bochatetage Formation, Sumalan Formation, and Sukuluoke Formation). This extensional tectonic setting might be last to the end at ca. 800 Ma, which was demonstrated by the ca. 800 Ma basalt and mafic dyke swarms in the Candilik-Xuxugou area [12, 54, 66]. During this period (ca. 880–800 Ma), the Kazakhstan, Yili, and Central Tianshan Blocks were not yet separated from the north Tarim Block (**Figure 10**). Due to subduction of the Tianshan Ocean, a back-arc basin formed and the Aksu Group volcanic-clastic rocks deposited [9, 20]. At ca. 800 Ma, the north and south Tarim Blocks amalgamated together to form the uniform Tarim Block. At the same time, the low green-schist facies metamorphism of the Ailiankate Group in the southwestern margin of Tarim Block and ultra-pressure blue-schist facies metamorphism of the Aksu Group in the northern margin of Tarim Block occurred.

4.1.2 The rifting stage (ca. 780–700 Ma)

In the late Neo-Proterozoic, the Rodinia supercontinent had an initial breakup due to the activity of the super-mantle plume. As a result, the Tarim Block was in an extensional setting and evolved the intracontinental rift basin. Tectono-sedimentary evolution of the basin may be divided into three stages: the rifting stage (780–700 Ma), rifting to depression transitional stage (660–600 Ma), and post-rifting depression stage (580–540 Ma) (**Figures 10**–**12**).

In the periphery of Tarim Block, with the opening of Altyn Ocean, the Qaidam Block was separated from the southeastern edge of Tarim Block and associated intracontinental bimodal volcanic rocks (ca. 760–750 Ma) [60] were developed in the Altun region, while the Altun Block was not separated from the Tarim Block (**Figure 10**) [67]. In the southwestern margin of Tarim Block, the NW-SE trending rifts had been died out by reason of amalgamation of the north and south Tarim Blocks during the early Neo-Proterozoic, and they evolved into the passive continental margin basin during the late Neo-Proterozoic. This tectonic setting continued, at least, till Cambrian, forming the late Neo-Proterozoic to Cambrian unmetamorphosed sedimentary succession. Due to the continuous subduction, the South Tianshan Ocean was opened, and the Kazakhstan, Yili, Central Tianshan, and other blocks were separated from the northern edge of Tarim Block, forming a strong extensional setting in the northern margin of the present Tarim Basin (**Figure 10**). Large-scale rift-related bimodal volcanic rocks (ca. 760–710 Ma) [1–3, 47] distributed in the northeastern margin of the present Tarim Basin, and abundant mafic dykes (ca. 760 Ma) [5, 60] intruded into the Aksu Group in the northwestern margin of the present Tarim Basin.

In the Bachu area, several boreholes have directly drilled the volcanic rocks just below the Cambrian carbonate rocks. The geochemical characteristics suggested that these volcanic rocks erupted in an intracontinental rift setting. In addition,

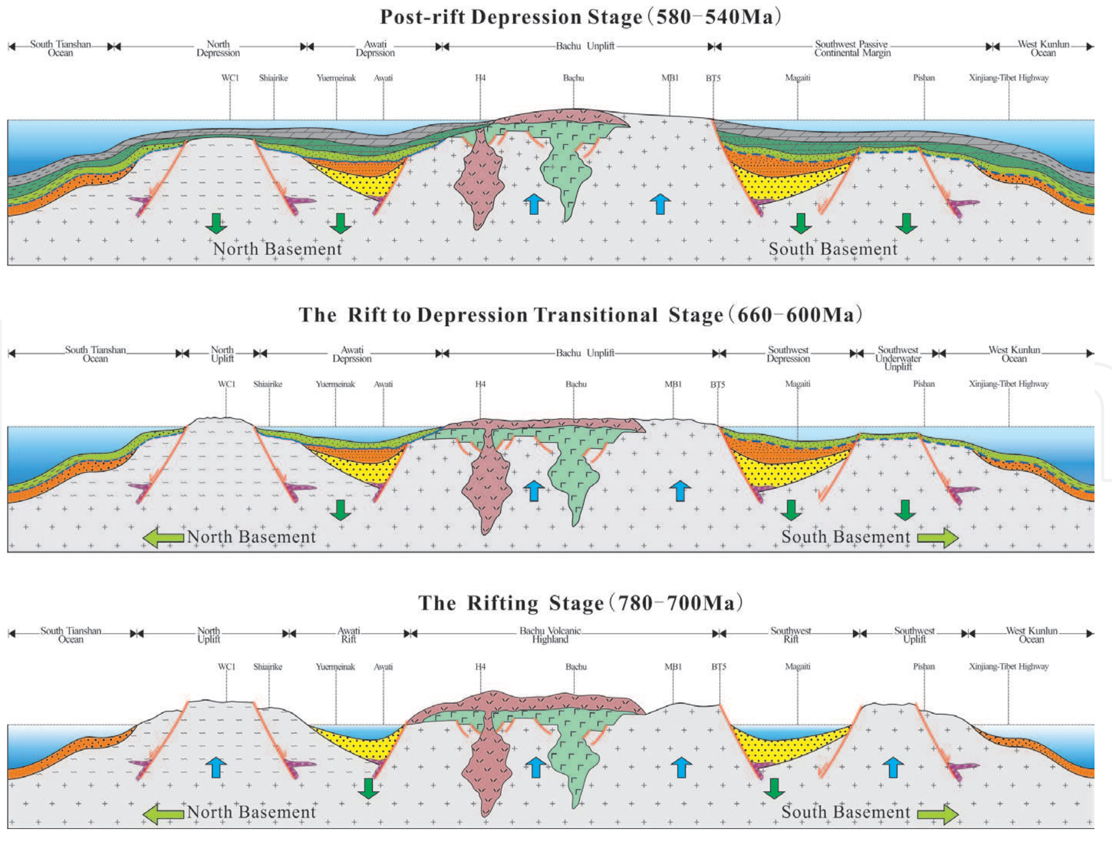

Figure 11.
Tectonic-sedimentary evolution profile of the Cryogenian-Ediacaran in the western Tarim Basin.

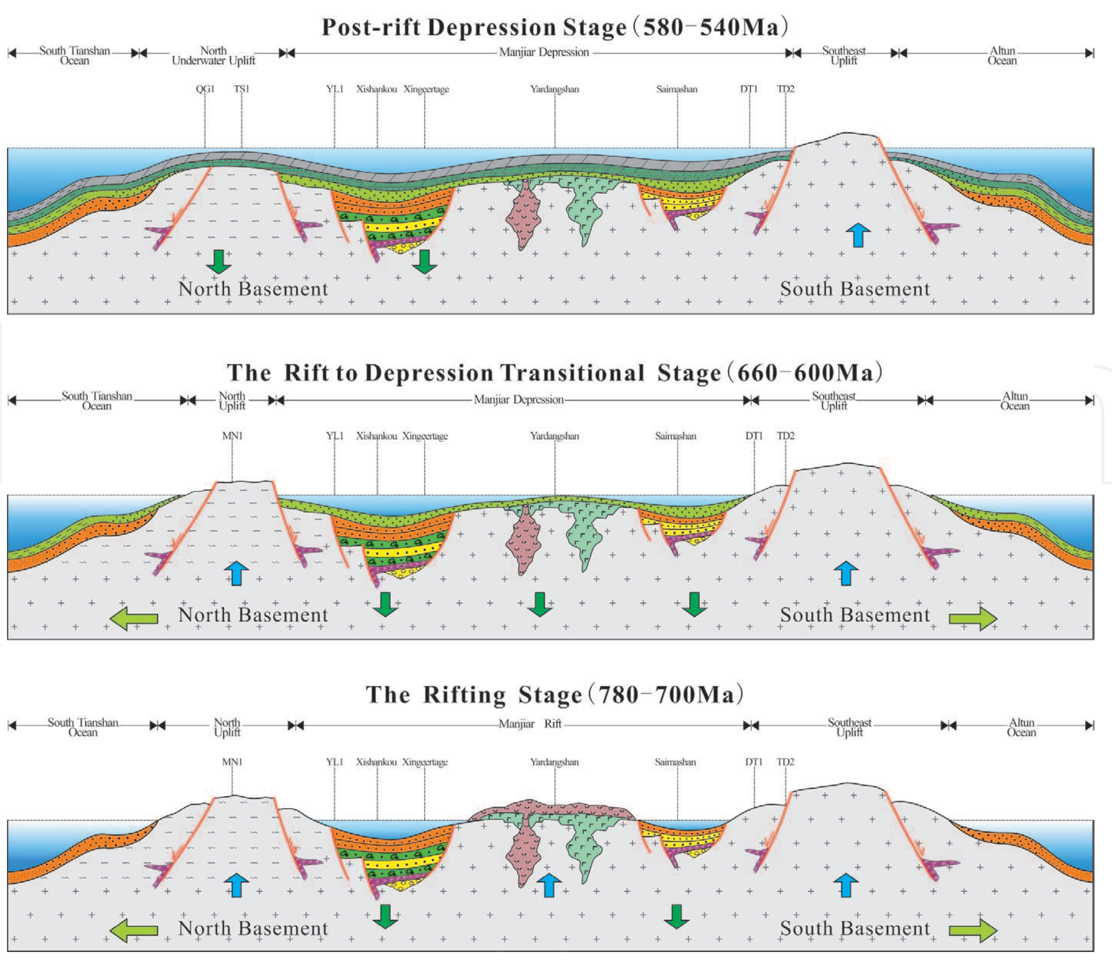

Figure 12.
Tectonic-sedimentary evolution profile of the Cryogenian-Ediacaran in the eastern Tarim Basin.

seismic profiles show obvious characteristics of intracontinental rift in the Awati-Kalpin, Manjar-Kuruktag, and Magaiti areas (**Figures 7–9**).

In summary, the Tarim Block was in a strong extensional setting during the period of ca. 780–700 Ma, and three intracontinental rifts (i.e., the Awati Rift, the North Manjar Rift, and the South Manjar Rift) formed in the northern part of Tarim Block (**Figures 10–12**). Rift shoulders were the uplift area without deposition. The Bachu area was the volcanic eruption center and resulted in the formation highland, which was a provenance denudation zone without deposition (**Figure 11**). The southern part was generally supposed to basement uplift and intracontinental rift developed in the Magaiti area. The southwestern margin was a passive continental margin (**Figures 11** and **12**).

4.1.3 The rifting to depression transitional stage (ca. 660–600 Ma)

At the end of the middle Cryogenian, a tectonic uplifting movement occurred, which resulted in the angular unconformity contract between the Qiaoenbrak Formation and the overlying strata in the Aksu area, and in the parallel unconformity contract between the Altungol Formation and the overlying Tereeken Formation in the Quruqtagh area.

After this phase of tectonic uplifting, the north part evolved into the transformation stage from rifting to depression and still was in an extensional tectonic setting. Episodic magmatic thermal events occurred in the northeast margin, such as rhyolite (ca. 655 Ma) [8] at the top of the Altungol Formation, mafic volcanic and pyroclastic rocks (ca. 635 Ma) [40] at the upper part of the Tereeken Formation, mafic dykes intruded into Zhamoketi Formation (ca. 615 Ma) [2, 8], and large area distribution granite (ca. 660–630 Ma) [13]. In the northwestern margin, ca. 633 Ma and ca. 615 Ma [3] mafic dykes intruded into the Qiaoenbrak Formation and Sugetbrak Formation, respectively.

In the northern part of the Tarim Block, because of continuous stretching and transgression, the isolated rifts gradually interconnected (Awati Rift, North Manjar Rift, and South Manjar Rift), the depositional area continued to expand and the residual paleo-uplift was existed in the Tabei area (**Figures 10–12**). The Bachu-Tazhong-Tadongnan area was still a highland, which was a provenance denudation zone without deposition (**Figure 10**). The seawater was from the South Tianshan Ocean with NE and NW directions of transgression, and the shore sedimentary was in development. In Manjar, grayish green mudstone intercalated with sandstone and siltstone was deposited in the shelf environment.

In the southwestern part of Tarim Block, the intensity of tectonic activity weakened gradually and was mainly post-rifting the thermal subsidence. Pishan palaeohigh was submerged, the continental rift (developed in Magaiti area) connected with the southwest margin and formed a passive continental margin (**Figures 10** and **11**). Influenced by the West Kunlun Ocean, the transgression from the southwest, the shore sedimentary developed in Magaiti and toward southwest shelf to deepwater deposition.

4.1.4 The post-rift depression stage (ca. 580–540 Ma)

During this period, the Tarim Block was in a stable tectonic setting without significant magmatic events and evolved into a post-rift depression stage. The northern part was the intra-cratonic depression basin and was characterized by thermal subsidence. The residual paleo-uplift was gradually flooded by seawater, but the Bachu-Tazhong-Tadongnan uplift still existed (**Figures 10–12**). Due to the decrease of terrigenous clastic and seawater evaporation and concentration, the carbonate content increased. Two deepwater sedimentary environments were developed in the Manjar and the northwest part of the Aksu-Kuqa area, where carbonate rocks and dark mudstone were deposited (**Figure 12**). A tidal-flat environment was developed in the southeastern part of the Manjar to the Kalpin-Awat area and deposited bedded dolomite with abundant stromatolite (**Figure 11**). At the same time, carbonate depositional systems prevailed in the southwestern part of Tarim Block.

At the end of Ediacaran, Tarim Block experienced a tectonic uplifting and the Ediacaran strata suffered from long-term weathering. Hence, a thick weathered crust (ca. 30–50 m) was formed at the top of Qigebrak dolomite, and meanwhile the lower Ediacaran strata were absent or partially absent in the southwestern of Tarim Basin.

4.2 Implication for the distribution of Cambrian source rocks

4.2.1 The lower Cambrian source rock

In the western region of the Tarim Basin, the lower Cambrian source rock developed in the Yurtusi Formation, which composed of silicalites, siliceous shales, and black shales with argillaceous dolomite. In the Aksu area, the Yurtusi source rock was in stable distribution with the thickness of ca. 10–15 m [26]. The total organic carbon (TOC) content was 2–16% [26], up to a maximum 22.39% [28], which is the highest quality marine hydrocarbon source rock in China [26]. In the Tabei uplift, only two boreholes (well XH1 and well LT1) have revealed the Yurtusi Formation whose sedimentary characteristics were similar to the Aksu outcrops. In well XH1, the thickness of the Yurtusi source rock was ca. 33 m, with a TOC of 1.0–9.43% (5.5% on average) [28]. In the Bachu-Tazhong uplift, many boreholes drilled through the Cambrian strata and entered into Precambrian, but no well revealed the Yurtusi source rock. In Magaiti, no well drilled and revealed the Yurtusi source rock. It is probably of large burial depth or was absent in the early Cambrian deposition.

In the eastern region of the Tarim Basin, the lower Cambrian source rock developed in Xishanbrak and Xidashan Formations. In north Quruqtagh, the Xishanbrak Formation developed in siliceous mud rocks with the thickness of ca. 12.5 m and TOC of 1.53%. The Xidashan Formation consisted of black mud rocks whose thickness was ca. 15 m and the TOC was of 1.39–2.17% (1.78% on average). In south Quruqtagh, the Xidashan Formation developed ca. 20 m black mud rocks with a TOC of 0.17–0.92% (0.46% on average). In Manjar area, several boreholes have drilled in the lower Cambrian, but it is difficult to divide between the Xishanbrak Formation and the Xidashan Formation. In well TD1, the thickness of black mud rocks was ca. 55 m with a TOC of 0.70–5.52% (2.3% on average) [27]. In well TD2, the thickness of black mud rocks with limestone was ca. 85 m and the TOC was more than 1%. In well YL1, the lower Cambrian composed of shales and argillaceous limestone, and the thickness was ca. 65 m with a TOC of more than 0.5% (1.56% on average) [27].

4.2.2 The distribution of the lower Cambrian source rock

In recent years, the results of oil and source rock correlation and the exploration discovery of primary oil and gas in the Cambrian subsalt dolomite reservoirs have shown that the lower Cambrian is the most important source rocks in the Tarim Basin [26, 29]. However, there are few stratigraphic data about the lower Cambrian source rock. Due to its small thickness and the deep burial, it is difficult to identify and trace the seismic horizons corresponding with the lower Cambrian source rocks on the seismic sections. Therefore, there are a lot of controversies over the distribution of the lower Cambrian source rocks, especially in the western sectors of the Tarim Basin [17, 18, 26–28].

Based on the oil and gas exploration discovery of Ediacaran-Cambrian in the Sichuan Basin, paleogeography in the late Neo-Proterozoic controlled the distribution of the lower Cambrian source rock [68–70]. Similar to the Sichuan Basin, the sedimentary characteristics of the lower Cambrian were related to the tectono-sedimentary in the late Neo-Proterozoic and uplifting movement at the end of Ediacaran. Based on outcrops and drilling data, in the western of the Tarim Baisn, the Yurtusi source rock existed in an area where the late Ediacaran carbonate deposited. The Yurtusi source rock did not develop in the area where the basement uplift existed in the late Neo-Proterozoic.

Therefore, we suggest that paleogeography in the late Neo-Proterozoic controlled the transgression in the early Cambrian and distribution of the lower Cambrian source rock. During the early Cambrian, the Tarim Basin had the paleogeographical characteristics of uplift in the south and depression in the north. The lower Cambrian source rock was composed of stable deposits in the northern Tarim Basin, where the late Ediacaran carbonate was deposited and thinning out toward the central uplift. It was distributed throughout the entire Manjar region in the east, and its overall thickness was thicker than that in the northern Tarim Basin. The lower Cambrian source rocks may be missing in the Magaiti and the southwestern Tarim Basin.

5. Conclusions

1. During the late Neo-Proterozoic, the Tarim Block was in an extensional setting as a result of the Rodinia supercontinent breakup and then evolved into an intracontinental rift basin. The tectono-sedimentary evolution of the basin may be divided into three stages: the rifting stage (780–700 Ma), the rifting to depression transitional stage (660–600 Ma), and the post-rift depression stage (580–540 Ma).

2. During the different stages of tectonic evolution, there were different paleogeographic characteristics and sedimentary association. In the rifting stage, intracontinental rifts (i.e., the Awati Rift, the North Manjar Rift, and the South Manjar Rift) were formed, in which coarse-grained clastic sediments were deposited, generally accompanied by a massive volcanic activity due to an intensive stretching. In the rifting-depression transitional stage and in the post-rift depression stage, the paleogeography was characterized by uplifts to the south and depressions to the north. Three types of depositional association (i.e., clastic depositional association, clastic-carbonate mixed depositional association, and carbonate depositional association) were formed.

3. The distribution of the lower Cambrian source rock was genetically related to the tectono-sedimentary evolution during the late Neo-Proterozoic. The lower Cambrian source rock was a stable deposit in the northern Tarim Basin, where the late Ediacaran carbonate was deposited, thinning out toward the central uplift. It was distributed throughout the entire Manjar region in the east and may be missing in the Magaiti and the southwestern Tarim Basin.

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