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Research paper

Kinematics of syn-tectonic unconformities and implications for the tectonic evolution of the Hala'alat Mountains at the northwestern margin of the Junggar Basin, Central Asian Orogenic Belt

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A B S T R A C T

The Hala'alat Mountains are located at the transition between the West Junggar and the Junggar Basin. In this area, rocks are Carboniferous, with younger strata above them that have been identified through well data and high-resolution 3D seismic profiles. Among these strata, seven unconformities are observed and distributed at the bases of: the Permian Jiamuhe Formation, the Permian Fengcheng Formation, the Triassic Baikouquan Formation, the Jurassic Badaowan Formation, the Jurassic Xishanyao Formation, the Cretaceous Tugulu Group and the Paleogene. On the basis of balanced sections, these unconformities are determined to have been formed by erosion of uplifts or rotated fault blocks primarily during the Mesozoic and Cenozoic. In conjunction with the currently understood tectonic background of the surrounding areas, the following conclusions are proposed: the unconformities at the bases of the Permian Jiamuhe and Fengcheng formations are most likely related to the subduction and closure of the Junggar Ocean during the late Carboniferous–early Permian; the unconformities at the bases of the Triassic Baikouquan and Jurassic Badaowan formations are closely related to the late Permian–Triassic Durbut sinistral slip fault; the unconformities at the bases of the middle Jurassic Xishanyao Formation and Cretaceous Tugulu Group may be related to reactivation of the Durbut dextral slip fault in the late Jurassic–early Cretaceous, and the unconformity that gives rise to the widely observed absence of the upper Cretaceous in the northern Junggar Basin may be closely related to large scale uplift. All of these geological phenomena indicate that the West Junggar was not calm in the Mesozoic and Cenozoic and that it experienced at least four periods of tectonic movement.

1. Introduction

An unconformity, a type of inconsistent contact between layers that represents times of denudation or no sediment deposition, is commonly observed in field outcrops and seismic profiles and is important to the study of the origin, evolution and reconstruction of basins. Depending upon the contact relationship between layers, unconformities are classified into four types: nonconformity, unconformity, disconformity and paraconformity (Dunbar and Rodgers, 1957). In addition, many researchers have further classified unconformities on the basis of contact relationship, seismic reflection, sedimentary hiatus and genetic mechanism (Lu, 1980; Pan, 1983; Beer et al., 1990; Yang and Zha, 2007a; Yang et al., 2007b). Riba (1976) raised the concept of syn-tectonic unconformity (progressive and angular syn-tectonic unconformities), in which an angular unconformity develops near an active orogenic belt and progressively becomes conformable in the interior of a basin (Riba, 1976; Anadon et al., 1986). Further research has determined that syn-tectonic unconformities are related to the acceleration, deceleration and denudation of uplifts (Rafini and Mercier, 2002; Chen et al., 2004). Thus, syn-tectonic unconformities are particular tectonic phenomena that formed in the peripheral area of orogenic belts when they were active. Therefore, the syn-tectonic unconformities are important for revealing the orogenic activation history. Following this concept, many

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researchers have studied the relationship between syn-tectonic unconformities and their peripheral orogenic belts worldwide, such as the Tarim Basin (Ghiglione and Ramos, 2005; Jaimes and Freitas, 2006; He et al., 2011; Lin et al., 2012).

The West Junggar is an important tectonic unit of the Central Asian Orogenic Belt (CAOB). It is located in a key tectonic position in the southern Altai, which connect the Kazakhstan orocline in the west to the Altai and East Junggar in the east. Many researchers have previously studied the volcanic rocks, granites, ophiolites (Jiang et al., 2003; Zhang et al., 2006; Geng et al., 2009, 2011; Tang et al., 2010; Zhang et al., 2011a,b; Yang et al., 2012a,b,c; Chen et al., 2013) and outcropping clastic rocks (Wei et al., 2009; Choulet et al., 2012a,b; Tao et al., 2013) to understand the tectonic evolution of the West Junggar in the Paleozoic. However, the research on the evolution of West Junggar in the post-Carboniferous is rarely discussed in previous work because the Mesozoic and Cenozoic outcrops are sparsely distributed in the orogenic belt and are mostly covered by Quaternary deposits in the interior of the sedimentary basin. Choulet et al. (2013) performed paleomagnetic research on the limited outcrop of the Triassic rocks in West Junggar and the rocks in South Junggar and concluded that Junggar became a rigid block which then rotated in the Triassic, and the authors further deduced the revival of West Junggar in the Mesozoic, but convincing geometric and kinematic evidence was lacking. In addition, the adjacent Tian Shan and Altai Mountains were uplifted and formed foreland basins filled with conglomerates during the Mesozoic and Cenozoic (De Grave et al., 2007; Glorie et al., 2012). Therefore, the syn-tectonic unconformities of the foreland basin at the northwest margin of the Junggar Basin are very important to understanding the post-orogenic tectonic evolution of West Junggar in Mesozoic and Cenozoic.

The study area of the Hala'alat Mountains is situated at the conjunction of the northwest margin of the Junggar Basin and West Junggar. Extensive oil and gas exploration has given rise to numerous drilling sites and to detailed high-resolution 3D seismic data collected from the area. Complete syn-tectonic unconformities were constructed from the Permian upward. Characteristics of these syn-tectonic unconformities and kinematic features can help reveal both the formation process of the Hala'alat Mountains and the activation history of the peripheral orogenic belts.

2. Geological setting

The West Junggar is located between the Tian Shan and Altai Orogenic Belts, and lies on the northeastern end of the Kazakhstan orocline of the CAOB. It has NE–SW extension and outcrops as a Paleozoic accretionary complex and volcanic rocks (Şengör et al., 1993; Xiao et al., 2010). It comprises the Sawur and Bozchekul–Chingiz volcanic arcs in the north and the Toli, Mayila and Tangbale blocks in the south (Windley et al., 2007; Chen et al., 2010; Xiao et al., 2010) (Fig. 1). These tectonic units were in the Paleoasian Ocean in the early Paleozoic and formed their structures via subduction, accretion, collision and even reconstruction (Buckman and Aitchison, 2004). In these processes, ophiolites, volcanic rocks and oceanic sediment related to arcs developed in this area (Feng et al., 1989; Zhang and Huang, 1993; Buckman and Aitchison, 2004). A Cambrian island arc ophiolite outcrops at Tangbale (Jian et al., 2005), together with Ordovician and Silurian sedimentary rocks

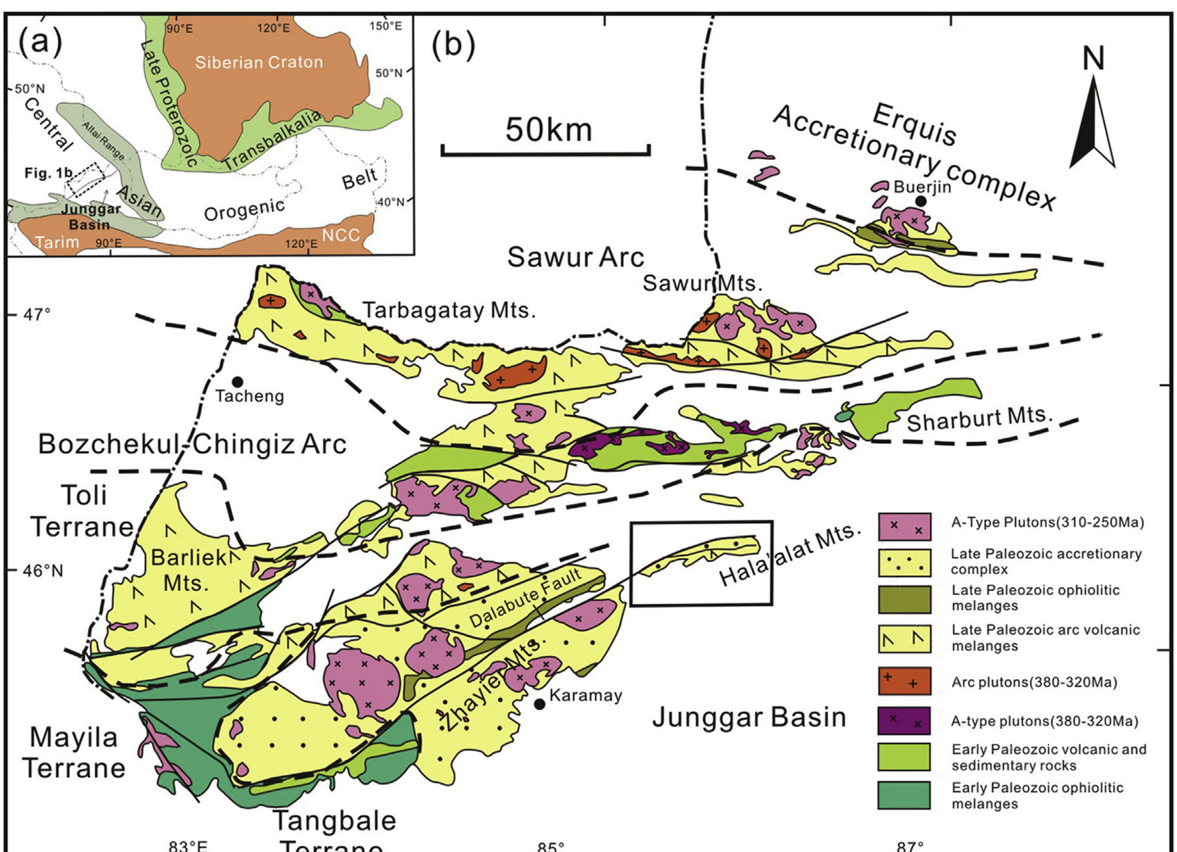

Figure 1. (a) Simplified map of northeastern Eurasia, including the Central Asian, Orogenic Belt and location of Junggar Basin and West Junggar (modified after Jahn et al., 2000). (b) Tectonic map of the West Junggar areas (modified after Tao et al., 2013).

(Feng et al., 1989). A Silurian ophiolite with a supra-subduction zone (SSZ)-signature was discovered at Mayila (Wang et al., 2003), and Devonian and Carboniferous ophiolitic mélanges outcrop on both sides of the Durbut Fault (Zhu et al., 1987; Feng et al., 1989; Xu et al., 2006a). The youngest reported ophiolite at Mayila in West Junggar has a Carboniferous age (Dong and Wang, 1990). Widely distributed ophiolite ages reflect the various closure times of oceanic crust between these blocks. The late Paleozoic magmatic rocks including A-type and I-type plutonic intrusions and high-Mg diorite dykes widely distributed throughout the West Junggar are dated at 320–250 Ma (Chen and Jahn, 2004; Li et al., 2004; Han et al., 2006; Xu et al., 2008; Geng et al., 2009; Yin et al., 2010), and reflect a post-collision tectonic environment (Choulet et al., 2012b).

The Zhayier–Hala'alat Mountains are situated on the western border of the Junggar Basin and are crosscut by the Durbut Fault to the northwest (Fig. 1). These mountains are generally considered as a Carboniferous accretionary complex (Xiao et al., 2008; Geng et al., 2009; Tang et al., 2010; Zhang et al., 2011a; Choulet et al., 2012b) and include turbidites (Jin et al., 1987), tuff (Zhang et al., 2011a), greywacke (Guo et al., 2010; Choulet et al., 2012a,b), and the Durbut and Baijiantan ophiolites, which were split ca. 100 km apart by the Permian Durbut sinistral slip fault (Choulet et al., 2012b). The Durbut ophiolite outcrops to the north of the Durbut Fault and may represent Devonian residual oceanic crust (Zhang and Huang, 1993; Xu et al., 2006a; Gu et al., 2009; Chen et al., 2013) The age of Baijiantan ophiolite is likely Carboniferous (Xu et al., 2006a; Geng et al., 2009; Zhang et al., 2011b). At present, most authors have considered the Zhayier–Hala'alat Mountains as the product of northwestern subduction of the Junggar Ocean (Feng et al., 1989; Buckman and Aitchison, 2004; Xiao et al., 2008; Choulet et al., 2012b). However, Zhang et al. (2011b) reported that the Durbut Ocean had existed and was subducted bilaterally to both the northwest and the southeast. Detrital zircon U–Pb age analysis conducted by Choulet et al. (2012a, b) suggests that the potential source areas of the West Karamay complex are characterized by middle Carboniferous Sawur magmatic arc rocks. Wei (1983) and Wang et al. (1987) studied the fossils in the exposed Carboniferous rocks and reported that the Hala'alat Mountains area was in a shallow marine island arc environment in the Carboniferous. Tao et al. (2013) performed geochemical analysis on the late Carboniferous clastic rocks and concluded that this area was a fore-arc basin in the late Carboniferous and that the Hala'alat Mountains had not yet formed. They also determined that the Sawur and Bozchekul–Chingiz arcs were the main source protoliths for these sedimentary rocks. The Carboniferous or Permian and younger strata drilled in this area reveal that the sedimentary rocks overlying those of the Carboniferous were in a continental environment, reflecting a single cycle from Carboniferous marine environment to Permian and post-Permian non-marine environment.

The basement of the Junggar Basin, which is covered mostly by Mesozoic and Cenozoic sediments, is still a controversial issue. Some researchers have proposed that the Junggar Basin is underlain by a Precambrian continental block (Zhang et al., 1984; Wu, 1986; Li, 2006). On the basis of geological, geochemical, geochronological and geophysical data, it was proposed that the basement of the Junggar Basin may be composed mostly of arcs and accretionary complexes or trapped oceanic crust (Hsu, 1988, 1989; Carroll et al., 1990; Xiao and Tang, 1991; Hu et al., 2000; Chen and Jahn, 2002, 2004). Wang et al. (2002) and Zheng et al. (2007) obtained borehole samples from the northern and middle parts of the Junggar Basin at 493 and 5341 m depths and identified rhyolite and alkali basalt, respectively. The U–Pb ages of these rocks yield 345 and 395 Ma for the rhyolite and alkaline basalt, respectively (Wang et al., 2002; Zheng et al., 2007). Geochemical analysis indicates that the basaltic rock is Nb-enriched, which suggests a possible intra-oceanic island arc without a continental basement (Wang et al., 2002; Zheng et al., 2007). Geological and geophysical investigations along the boundary between the West Junggar and the Junggar Basin show that the surface ophiolitic complex has a deep root both in the West Junggar and the adjacent basement of the Junggar Basin (Xu et al., 2006b). The basement of the Junggar Basin is likely an assembly of island arcs, accretion complex and trapped oceanic crust (Xiao et al., 2008). Moreover, Choulet et al. (2013) reported that Junggar area became a rigid block and rotated in the Triassic.

3. Dataset and methodology

Wave reflection seismic exploration is based on seismic wave reflection at the rock interface received by geophones at the ground surface. The data are digitally recorded and undergo correction, stacking, inverse filtering, migration and imaging processes. Seismic exploration is preferred by oil and gas exploration companies in this region over other geophysical exploration methods due to advantages in its precision and resolution. High-quality 3D seismic data in the Hala'alat Mountains area were collected by the Chinese National Petroleum Corp. in 2004 and the Sino Petrochemical Corp. in 2011. Both groups deployed a 25 m trace interval to pass through the Hala'alat Mountains and the Wuxia Fault Zone of the Junggar Basin with a 6–7 s two-way travel time; the profiles discussed in this paper were extracted from those 3D seismic data. Several drill holes including Wells Fengnan-1, Fenggu-4 and Hashan-1 (Fig. 2a and b) allow a direct correlation to be made between the seismic and geological units. In such cases, acoustic and density logs are used to create synthetic seismograms (unpublished data) that provide a tie between rock units and seismic reflection data, so that the seismic units may be confidently identified in the seismic profiles. High-quality seismic profiles can provide data on abundant geological phenomena such as faults and syn-tectonic unconformities that cannot be identified in the field. Through observation of fault-plane reflections, fault cutoffs and kink band terminations, precise identification of faults in seismic profiles is possible. Syn-tectonic unconformities have important significance in revealing the time and intensity of tectonic activities, and can also be identified through seismic truncation (Fig. 9) and growth strata (Fig. 10).

Balancing and restoration of seismic sections was conducted by stripping off (back-stripping) each sequence and restoring faults and folds by using Move 2009.1 software so that the paleo-topography or depositional surfaces were restored to continuous layers with topography. Faults were restored by using the Incline-Shear algorithm, which assumes that the hanging wall deforms by simple shear and that the footwall remains undeformed by compression. Next, the cross-section was restored by using the flexural-slip unfolding algorithm. After unfolding, the new sequence was back-stripped, and the same procedure was repeated until only the deepest layer remained.

4. Stratigraphy

The lower Carboniferous rocks composed of pyroclastic rocks, intermediate–basic volcanic rocks, sandy conglomerate and tuffaceous sandstone outcrop in the Hala'alat Mountains, whereas Cretaceous and Quaternary rocks outcrop in the piedmont zone, and Jurassic and Quaternary rocks outcrop in the Heshituoluogai Basin (Fig. 2a). A large amount of drilling information indicates that thick Carboniferous, Permian, Triassic and Jurassic layers are buried in the Hala'alat Mountains area (Fig. 4), where only Cretaceous and Quaternary rocks are exposed (Fig. 2b). In the Carboniferous,

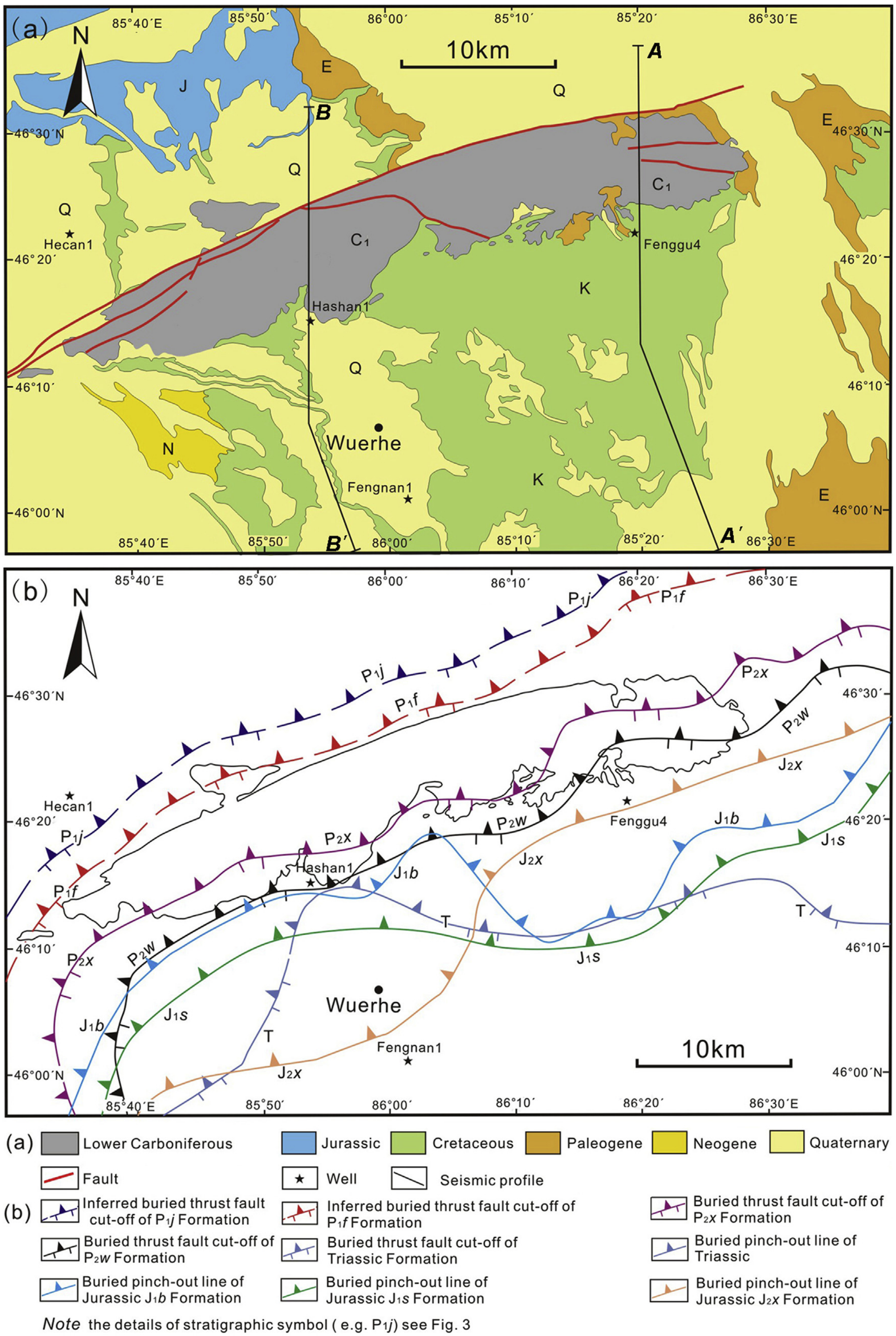

Figure 2. (a) Geological map of the study area showing the pinch-out lines and seismic profiles. (b) Pinch-out lines of buried strata from the Permian Jiamuhe Formation to the Cretaceous.

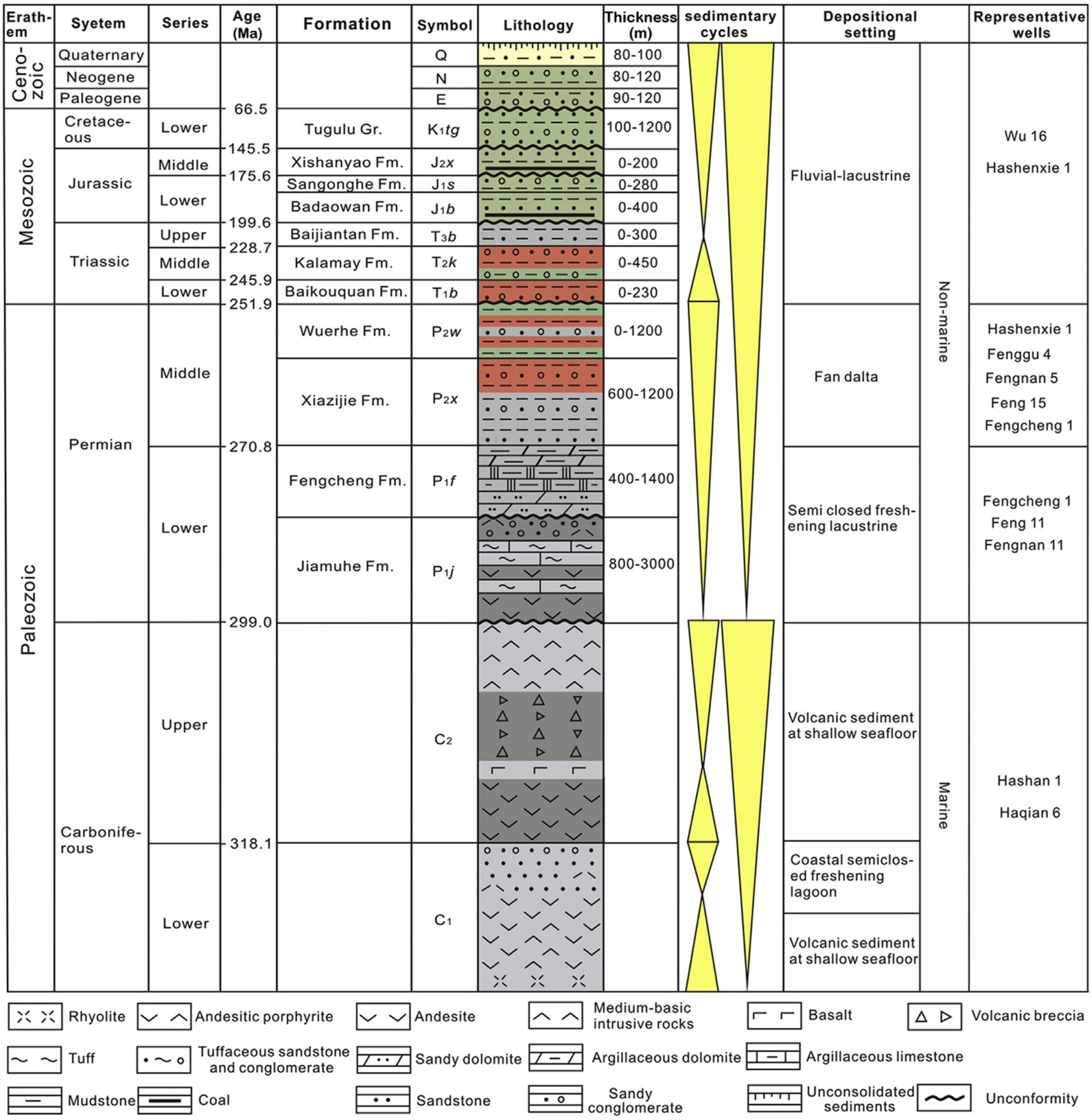

Figure 3. Comprehensive stratigraphic column of the Hala'alat Mountains area.

the Hala'alat Mountains area was in a marine environment, and in the Permian (and subsequently) it has remained in a non-marine environment (Fig. 3). Therefore, the area has experienced a single-cycle evolution from a marine to a non-marine environment (Fig. 3).

The Carboniferous rocks are exposed in the Hala'alat Mountains and have been drilled in the piedmont zone and the Heshituoluogai Basin. The Wells Hashan-1 and Hashan-6 near the mountains penetrate the upper Carboniferous andesite and intermediate–basic volcanic rocks aged at 305 ± 5 and 304 ± 4.5 Ma, respectively (unpublished data from Sino Petrochemical Corp.). Several authors have studied the fossils and depositional components of the Carboniferous rocks and proposed that the Hala'alat Mountains experienced two transgressions from a shallow marine volcanic depositional environment to a semi-closed freshwater lagoon and back to a shallow marine volcanic depositional environment (Wei, 1983; Ma, 1987; Wang et al., 1987). Moreover, thrusts, cleavage and evident weathering denudation surfaces appear in these Carboniferous rocks.

Thick Permian layers developed in this area and have been classified into four formations based on their chronology, as follows: the Jiamuhe (P_1j), Fengcheng (P_1f), Xiazijie (P_2x), Wuerhe (P_2w) formations. The Jiamuhe Formation consists of andesite, tuffaceous sandstone and sandstone, reflecting a transitional marine–continental environment from the Carboniferous to the late Permian. The Fengcheng Formation consists of dolomitic mudstone, shaly limestone and sandy mudstone developed in a semi-closed freshwater lagoon environment. The Xiazijie Formation consists of typical red molasse units, which suggests that the area experienced rapid uplift and denudation, and then rapid deposition. The Wuerhe Formation consists of sandstone and mudstone developed in a fan delta environment.

The sandstone and mudstone in the lacustrine environment developed in the Triassic include the Baikouquan (T_1b), Kalamay (T_2k) and Baijiantan (T_3b) formations, from the base upward. The Baikouquan Formation is composed mainly of red–brown mudstone and sandy conglomerate. The Karamay Formation is composed mainly of celadon and gray sandy conglomerate and red–brown mudstone bearing thin sandstone and conglomerate. The Baijiantan Formation is composed mainly of gray mudstone and sandy mudstone with thin mud siltstone.

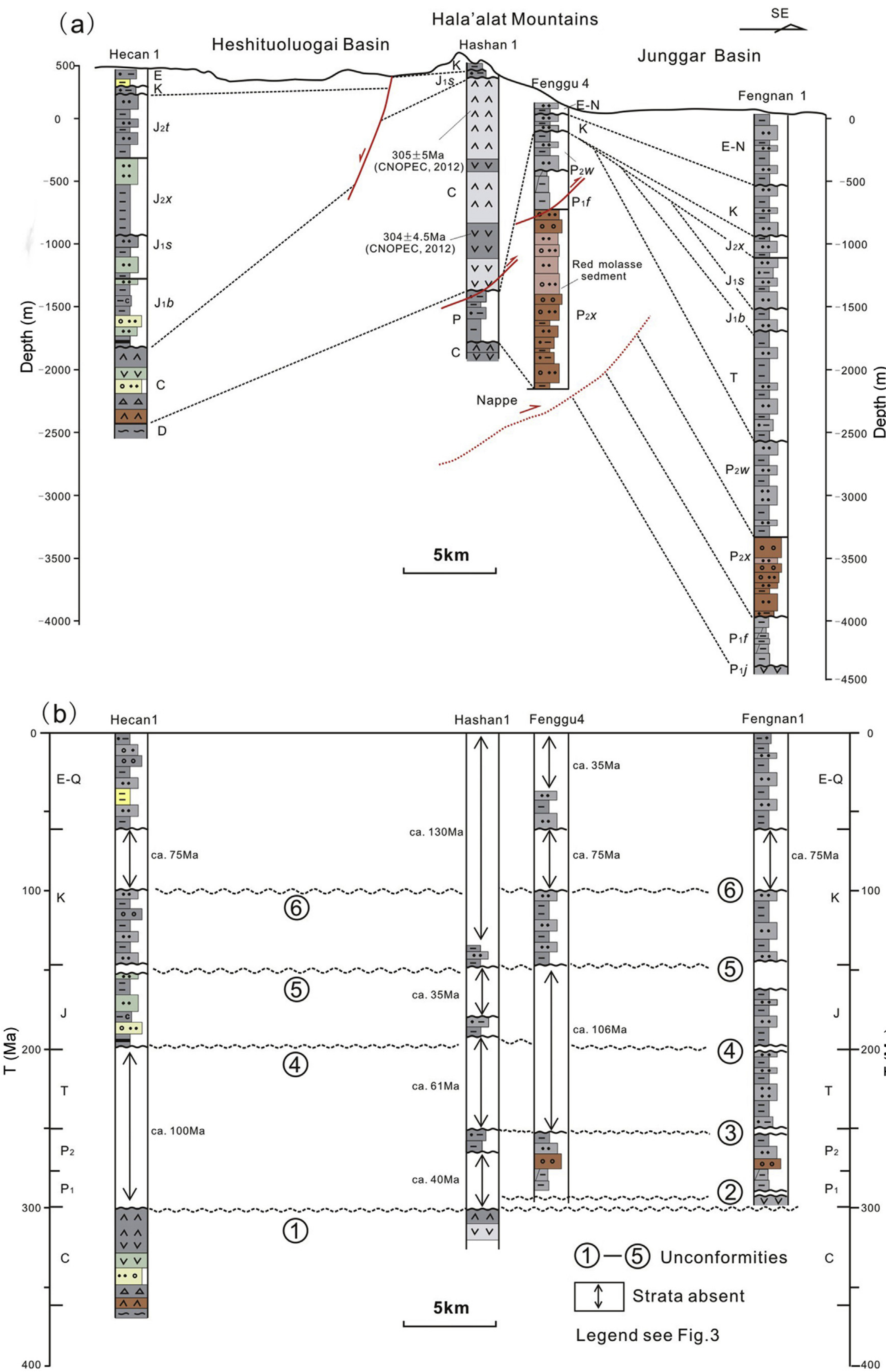

Figure 4. Wells data correlation of the Hala'alat Mountains area in time and depth.

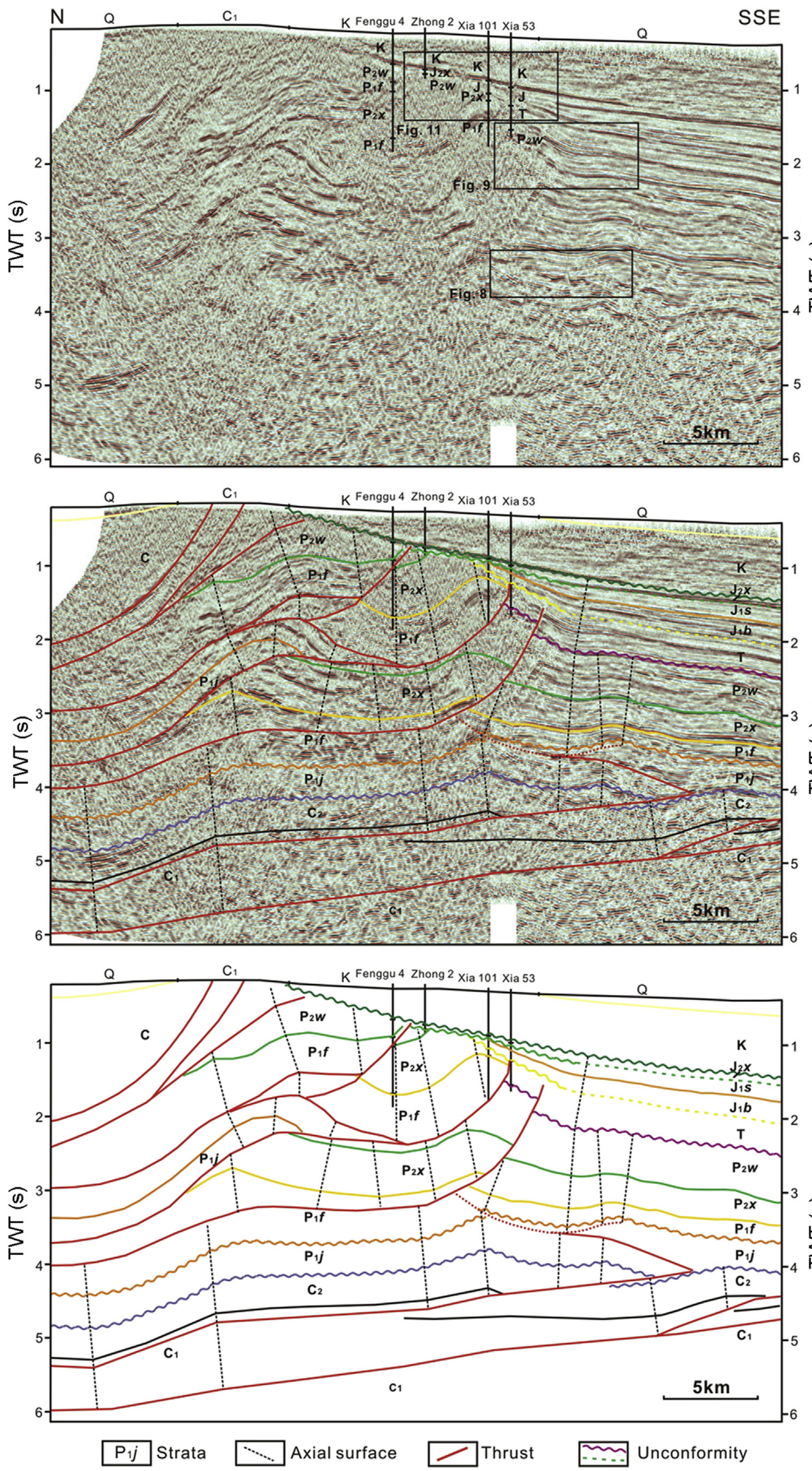

Figure 5. A–A′ unexplained and explained seismic profile in the eastern part of the Hala'alat Mountains area (Details of the stratigraphic symbols are given in Fig. 3; seismic profile locations are given in Fig. 2a).

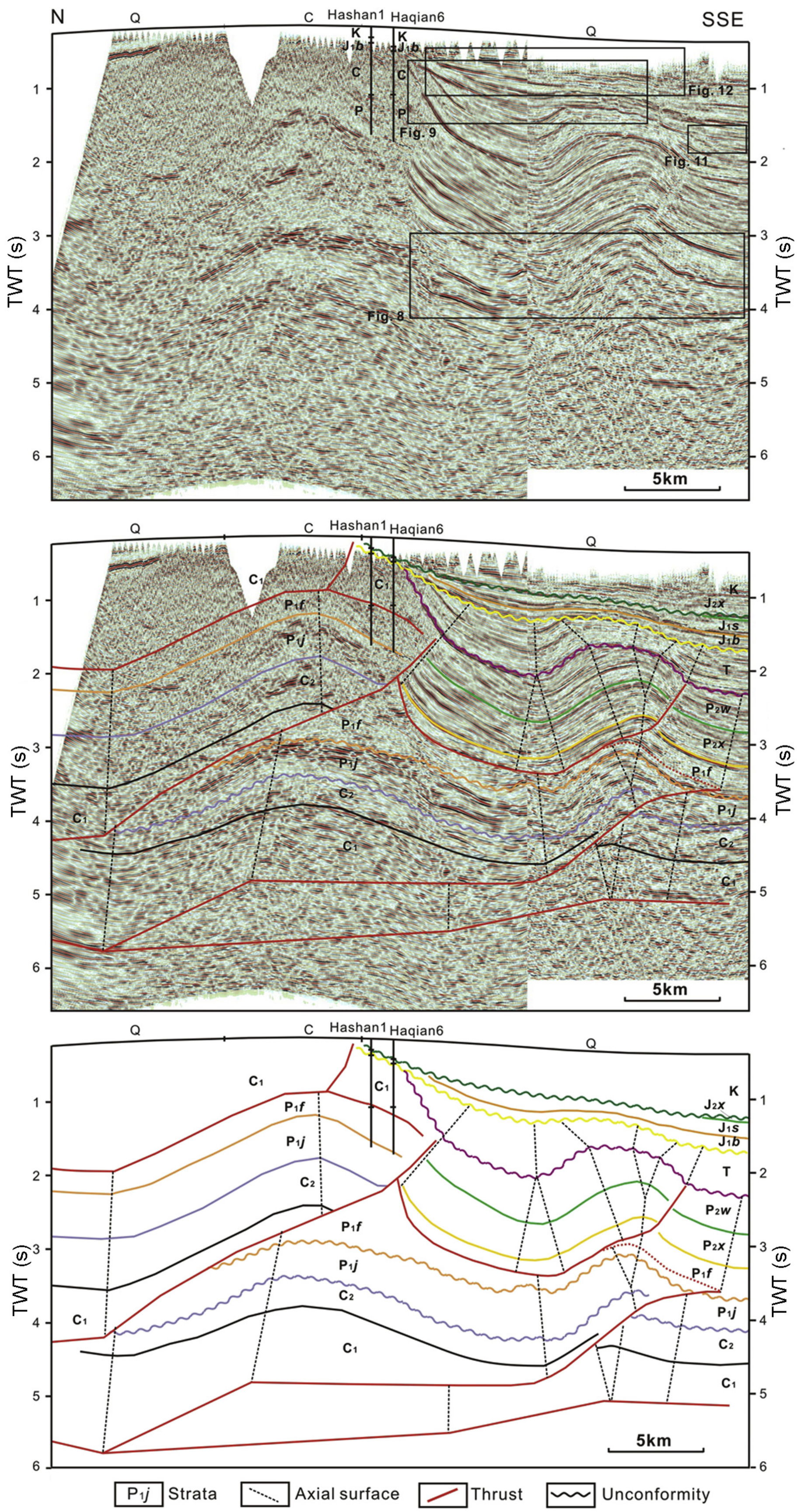

Figure 6. B–B′ unexplained and explained seismic profile in the eastern part of the Hala'alat Mountain area (Details of the stratigraphic symbols are given in Fig. 3; seismic profile locations are given in Fig. 2a).

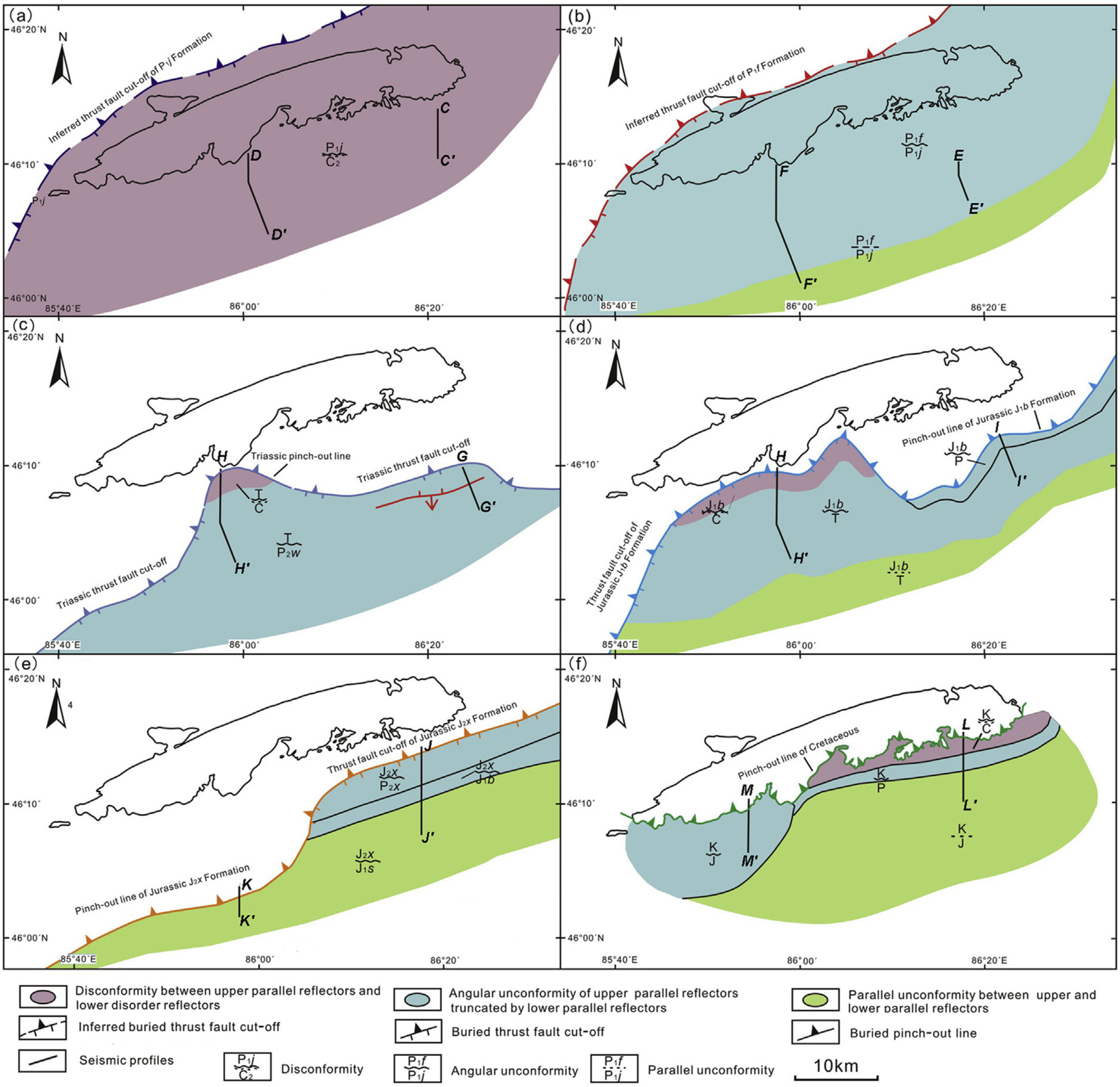

Figure 7. Distribution ranges of the unconformities in the Hala'alat Mountains area.

The Badaowan (J_1b), Sangonghe (J_1s) and Xishanyao (J_2x) formations which developed in the Jurassic thin from south to north. The Badaowan Formation is composed of celadon sand–mudstone in an upward-fining sequence with coal at the base. The Sangonghe Formation is composed of interbedded sandstone and mudstone, and the sedimentary rhythm is not clear. The Xishanyao Formation comprises mudstone and sandstone interbedded in an upward-fining sequence, with a coal bed at its base.

The Cretaceous includes the lower Cretaceous Tugulu Group with an absence of the middle–upper Cretaceous units. The Tugulu Group is composed of thick celadon mudstone and sandy conglomerate of fluvial and lacustrine facies. The Cenozoic outcrops in the Hala'alat Mountains area are composed of sandy mudstone and sandy conglomerate of the Paleogene and Neogene, and unconsolidated Quaternary sediment.

A comparison of typical well data in this area (Fig. 4) reveals that the layers in the piedmont zone develop completely. Drilling in Hala'alat Mountains penetrated only the Carboniferous and Permian, which has been determined as a nappe (Figs. 5 and 6). The Heshituoluogai Basin has no Permian and Triassic sediment, and the Carboniferous is covered directly by Jurassic rocks.

5. Features and distribution of unconformities

The Hala'alat Mountains area underwent the Central Asian Orogenic Movement in the Paleozoic, and subsequent reconstruction. In response to these tectonic events, a large number of unconformities developed in this area (Chen et al., 2000; Cao et al., 2006; Yang and Zha, 2007a; Yang et al., 2007b; Chen et al., 2008). Seven unconformities in the Carboniferous and overlying younger strata—P_1j/C_2, P_1f/P_1j, T/P_2w, J_1b/T, J_2x/J_1s, K/J, E/K—have been observed through high-resolution 3D seismic profiles and drilling data (Figs. 3, 5 and 6).

5.1. Nonconformity between the Permian Jiamuhe Formation and the upper Carboniferous (P_1j/C_2)

This nonconformity extends widely into the Hala'alat Mountains and is cut by a large-scale thrust belt (Fig. 7a). Above this

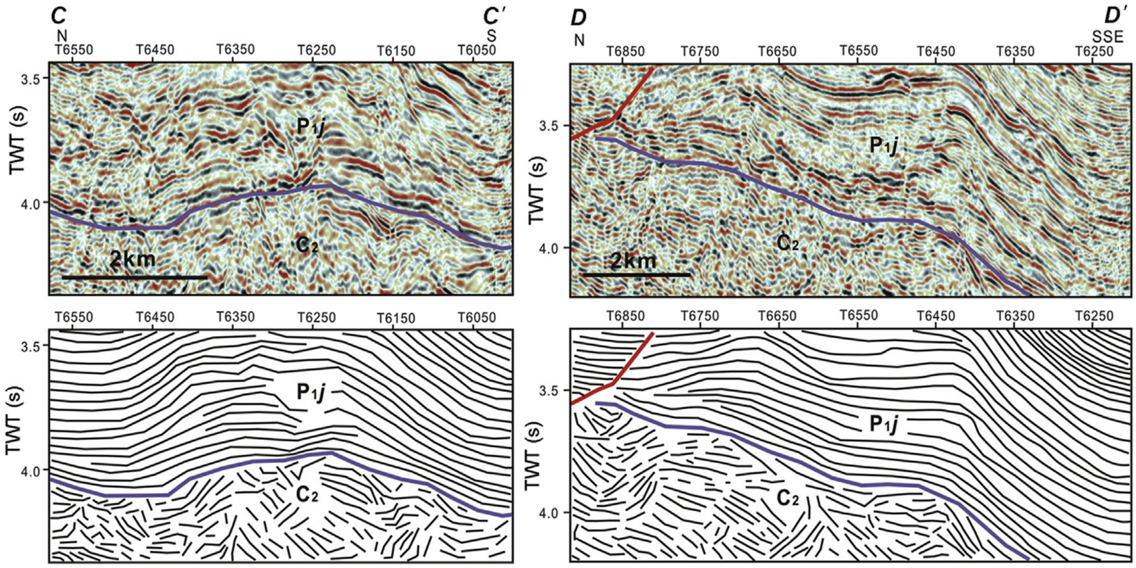

Figure 8. Seismic profiles of the nonconformity between the Carboniferous and Permian Jiamuhe Formation.

nonconformity, rocks are composed mainly of Permian sandy conglomerate and tuffaceous sandstone, and beneath it lie Carboniferous intermediate–basic volcanic rocks and andesite. The lithologies below and above this nonconformity are distinctly different. This phenomenon can be easily observed in seismic profiles because the reflectors above the nonconformity are strong and continuous, while those beneath it are characterized by chaotic reflections (Fig. 8). Although the nonconformity beneath the nappe of the Hala'alat Mountains is not obvious because compaction attenuates reflections, it still can be identified with careful attention. The nonconformity was folded and cut by the thrust, and the occurrence of this nonconformity surface is concordant with the Fengcheng Formation (Figs. 5 and 6).

5.2. Unconformity between the Permian Fengcheng Formation and Jiamuhe Formation (P_1f/P_1j)

The Jiamuhe Formation reflectors are angularly truncated by those of the Fengcheng Formation (Fig. 9) in the Hala'alat Mountains area, and the contact relationship progressively becomes a disconformity eastward in the north slope of the Mahu Depression (Fig. 7b). Its distribution range is similar to the nonconformity of P_1j/C_2 for the entirety of the thrust belt. The main erosion direction is from the Hala'alat Mountains to the interior of the basin. However, in some local areas such as Wuerhe and other uplift zones beneath the nappe, there also exist double-erosion directions (Figs. 5 and 6) in the lower Permian. The thickness in the Jiamuhe Formation and Fengcheng Formation is constant, and the occurrence of both layers is consistent (Figs. 5 and 6).

5.3. Unconformity between the Triassic and pre-Triassic

The distribution range of this unconformity is much smaller than that between the Fengcheng and Jiamuhe formations (Fig. 7c) mainly because the thrust activity was intense, with a displacement of tens of kilometers. In the eastern part of the Hala'alat Mountains area, the upper Permian and Triassic on the hanging wall of the thrust were absent (Fig. 5) because these layers were uplifted by the thrust and were then denuded. However, the Upper Permian rocks on the footwall were rotated and denuded to form this unconformity before being progressively developed into a disconformity in the interior of the basin (Fig. 7c). In the western part of the Hala'alat

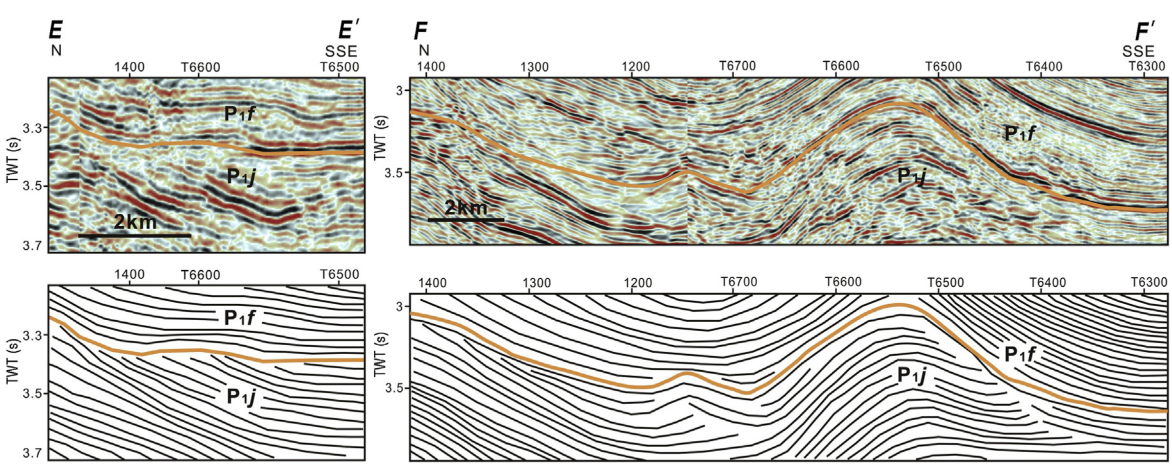

Figure 9. Seismic profiles of the unconformity between the Permian Jiamuhe Formation and Fengcheng Formation.

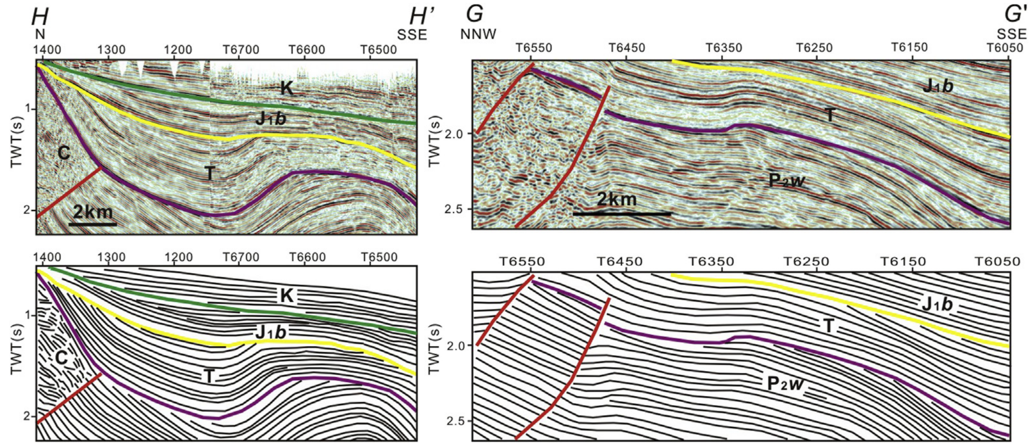

Figure 10. Seismic profiles of the unconformity at the base of the Triassic.

Mountains area, a detachment fault develops in the Fengcheng Formation and is broken upward to create the upper Carboniferous–lower Permian basement fold before forming the Wuxia anticline (Fig. 6). The core and flanks of the anticline were denuded to create an erosional angular unconformity in two directions (Fig. 10). Subsequently, the basement fault became active again, and the unconformity deformed intensely. In seismic profile B–B′ (Fig. 6) and in the plane of the distribution of the unconformities (Fig. 7c), the Carboniferous rocks were covered by Triassic rocks, reflecting that the Hala'alat Mountain thrust was active in the Triassic and that a significant event subsequently occurred to push the Carboniferous upward. The western part of the Hala'alat Mountains likely formed during this period.

5.4. Unconformity between Jurassic and pre-Jurassic

The distribution range of this unconformity is significantly larger than that at the base of the Triassic strata (Fig. 7d), reflecting retrogradation features. In the western part of the Hala'alat Mountains area, reflectors at the base of the Jurassic cover the chaotic Carboniferous reflectors, suggesting a calm period after the intense uplift of Triassic (Fig. 6). Moreover, syn-tectonic sediment was discovered in the Jurassic reflectors, which suggests that the fault in the basement was once again active when the Jurassic rocks were depositing. In the eastern part of the Hala'alat Mountains area, similar characteristics of the unconformity developed as in the unconformity at the base of the Triassic. The thrust caused the footwall to rotate prior to denudation to form the angular unconformity (Fig. 5). The Permian reflectors are truncated by the Jurassic reflectors at a high angle near the mountain. Toward the interior of the basin, Triassic reflectors are truncated by the Jurassic at a low angle, and then develop into the disconformity in the interior part of the basin (Fig. 11). This result suggests the differences in tectonic features in the eastern and western parts occurred after the Triassic. The western part of the Hala'alat Mountains area features the core and flanks of the fold with erosion in two directions, however, the eastern part features the footwall rotation and a single-direction angular unconformity progressively developing into the disconformity in the interior of the basin.

5.5. Unconformity at the base of the Jurassic Xishanyao Formation

In the eastern part of the Hala'alat Mountains area, the features of this unconformity are similar to those of the unconformities at the bases of the Jurassic and Triassic strata (Fig. 7e). The footwall of the thrust rotated and eroded to form the angular erosional unconformity, then progressively developed into the disconformity in the interior of the basin. On the hanging wall, the Permian Xiazijie Formation was uplifted and denuded by the Jurassic Xishanyao Formation at a high angle in the opposite denudation direction to the footwall (Fig. 12). Moreover, in the eastern part of the Hala'alat Mountains area, the distribution range of the unconformity is significantly larger than that of the unconformity at the base of the Jurassic for the transgression in the middle Jurassic Xishanyao Formation. The unconformity at the base of the Xishanyao Formation was cut by the thrust, indicating significant tectonic movement after the Xishanyao Formation developed. In the western part of the Hala'alat Mountains area, the disconformity at the base of the Xishanyao Formation is significantly smaller, suggesting that the tectonic movement was weak and the topography was elevated at that time.

5.6. Unconformity between the Cretaceous and pre-Cretaceous

In this feature, the Cretaceous reflectors truncate the Jurassic reflectors below and onlap the unconformity surface (Fig. 13), suggesting that possible tectonic movement in the late Jurassic caused the Jurassic strata to rotate before denudation. The angle between the Cretaceous strata and the unconformity surface is approximately 5°, and that between the unconformity and the Jurassic strata below is approximately 20°. In the eastern part of the Hala'alat Mountains, the Cretaceous strata onlap the unconformity, however, the denudated strata below the unconformity are complex. The Cretaceous strata reflectors first onlap the chaotic

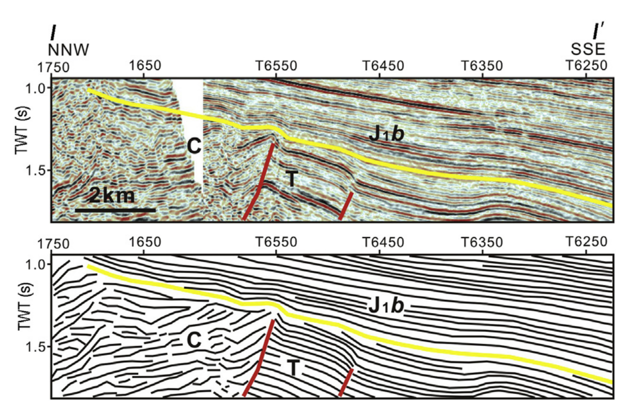

Figure 11. Seismic profile of the unconformity at the base of the Jurassic.

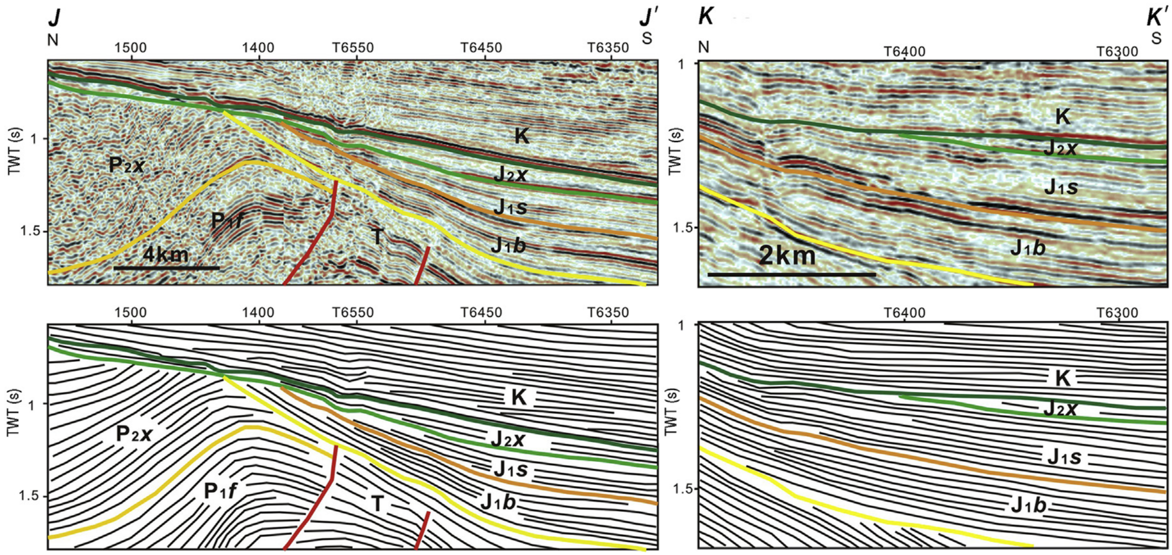

Figure 12. Seismic profiles of the unconformity at the base of the upper Jurassi Xishanyao Formation.

Carboniferous volcanic reflectors, and southward, the Permian strata reflectors are then truncated by Cretaceous strata reflectors at a high angle of 70°. Finally, the unconformity progressively develops into the disconformity in the interior of the basin (Fig. 7f), which agrees with the similar development in the western part of Hala'alat Mountains, implying multistage tectonic uplifts occurred in the eastern part of the Hala'alat Mountains.

5.7. Unconformity at the base of the Cenozoic

Well correlations reveal that the entire upper Cretaceous is absent, forming a ca. 75 Ma sedimentary hiatus (Fig. 4). In fact, the upper Cretaceous rocks are absent in the entire northern margin of the Junggar Basin, implying a regional uplift in the late Cretaceous. This unconformity cannot be identified in seismic profiles because the energy in the shallow rock is too weak to image.

6. Formation processes of syn-tectonic unconformities: restrictions from balanced sections

The present-day structural styles of the study area are displayed in detail in Figs. 5 and 6. In the eastern region of the Hala'alat Mountains (Fig. 5), two low-angle basement thrusts that develop in the Carboniferous disappear in the lower Permian with N–S inclination, and a fault-bend fold forms in the Carboniferous and lower Permian. Deep in the Hala'alat Mountains, two thrust nappes exist, including a Permian nappe composed of the Permian Jiamuhe, Fengcheng, Xiazijie and Wuerhe formations superimposing on the basement fault-bend fold, and a Carboniferous nappe superimposing on the Permian nappe. The structural features in the western region of the Hala'alat Mountains are similar to those in the east. In the western region of Hala'alat Mountains, two low-angle basement faults with N–S inclination also develop in the Carboniferous and lower Permian to form fault-bend folds. In the depths of Wuxia fault zone, a fault-propagation fold in the upper Permian is superimposed on the underlying basement fault-bend fold. In the depths of Hala'alat Mountains, two thrust nappes exist including a upper Carboniferous–lower Permian nappe superimposing on the basement fault-bend fold, and a Carboniferous nappe superimposing on the upper Carboniferous–lower Permian nappe. Wells Hashan-1 and Haqian-6 have penetrated these two nappes.

We have restored these two seismic profiles (Figs. 5 and 6) of the Hala'alat Mountains in Figs. 14 and 15. In the eastern region of

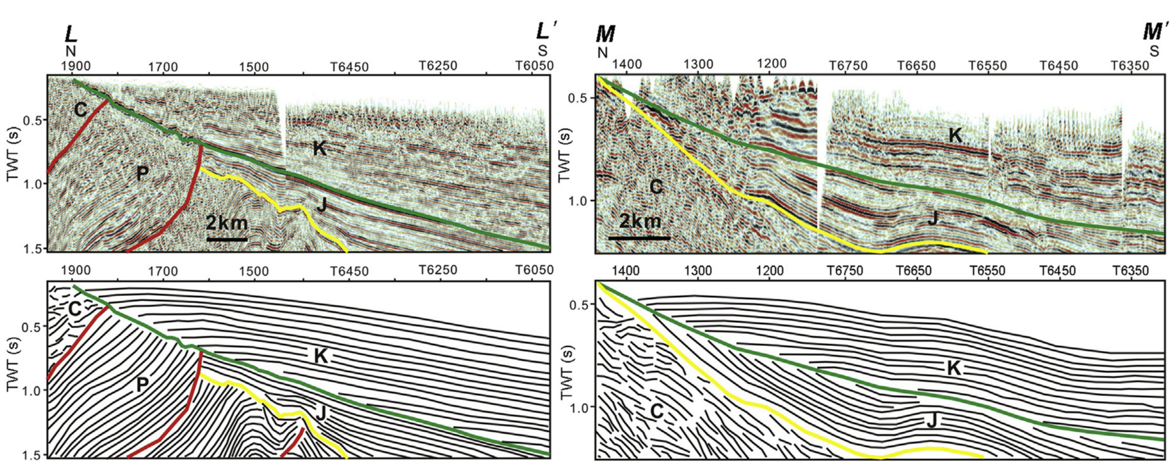

Figure 13. Seismic profiles of the unconformity between the Jurassic and Cretaceous.

the Hala'alat Mountains (Fig. 14), the basement faults in the Carboniferous were active in the early Permian, and the Carboniferous and lower Permian fault-bend fold formed. In the late Permian–early Triassic, the detachment fault in the Permian Fengcheng Formation was active with a small slip and weak deformation. In the Jurassic, the Permian nappe formed, and some secondary faults developed in the nappe's interior. In the Cretaceous, the Carboniferous nappe formed upon which the upper Cretaceous strata onlapped. In the western part of the Hala'alat Mountains (Fig. 15), the basement faults were active in the early Permian to form a fault-bend fold in the Carboniferous and lower Permian formations. In the late Permian the detachment fault in the Permian Fengcheng Formation was active, and the slip disappeared gradually in the Permian Wuerhe Formation to form the fault-propagation fold superimposing on the underlying basement fault-bend fold. In the late Permian–Triassic the basement faults were active again, and formed the Carboniferous–Permian large scale fault-bend fold in the depths of the Hala'alat Mountains. In the late Triassic–Jurassic the Carboniferous–lower Permian nappe formed. In the Cretaceous, the Carboniferous nappe was thrust to the surface and was onlapped by the upper Cretaceous formations.

7. Discussion: the kinematic evolution of syn-tectonic unconformities and their tectonic significance

On the basis of the described regional seismic profiles and balanced sections, these unconformities can be classified into four sequences (Figs. 14 and 15). These include the Carboniferous–early Permian, the late Permian–Triassic, the late Jurassic–early Cretaceous and the late Cretaceous syn-tectonic unconformity sequences, which indicate that the Hala'alat Mountains area experienced at least four tectonic events since the Carboniferous (Fig. 16).

7.1. The Carboniferous–early Permian syn-tectonic unconformity sequence

This sequence includes the nonconformity between the Carboniferous and Permian Jiamuhe Formation and the angular unconformity between the Permian Jiamuhe and Fengcheng formations. Balanced seismic sections of the Hala'alat Mountains show back-thrusting in the basement in the Carboniferous–early Permian that is closely related to this unconformity sequence. Consistency of these two unconformities in occurrence and the results of the balanced sections indicate that the Hala'alat Mountains area was in a compressional environment in the Carboniferous–early Permian and that the Junggar Basin was larger at that time.

Choulet et al. (2012b) have suggested that the Permian Durbut sinistral fault overprinted the ductile shearing and split the Karamay Unit ca. 100 km apart. According to this model, the western Karamay accretionary complex to the north of the Durbut was located at the northern Hala'alat Mountains. Calk–alkaline rocks with adakitic affinities aged at 320–300 Ma (Zhang et al., 2006; Geng et al., 2009; Tang et al., 2010) and high-Mg diorite dykes (Yin et al., 2010) were recently described; slab melting related to the ridge subduction was proposed to account for their genesis. Moreover, several authors reported that the subduction ended before the early Permian (Choulet et al., 2012b). However, the transition from the Carboniferous calk–alkaline magmatic to Permian alkaline volcanic rocks proves that the subduction ended in the Carboniferous–Permian and marked the final stage of continental crust assembly. Therefore, this unconformity sequence is related to subduction and collision.

7.2. The late Permian–Triassic syn-tectonic unconformity sequence

This unconformity sequence includes the unconformities at the base and top of the Triassic. In localized areas near the Hala'alat Mountains, the Triassic or Jurassic strata cover the Carboniferous volcanic rocks directly by a nonconformity. An angular unconformity developed at the fault zones and progressively developed into the disconformity in the interior of the basin. The balanced sections indicate that this unconformity is related to the thrust or nappe in this area, which caused the blocks to uplift and rotate.

In this period, differences in structural features also existed in the eastern and western parts of the Hala'alat Mountains. In the western part, the region experienced intense uplift to form the Hala'alat Mountains, and no significant tectonic movement existed in subsequent geological history. The eastern part also experienced multistage uplifts in this period; however, they did not contribute significantly to the formation of the eastern part of the Hala'alat Mountains. The eastern part in this period experienced two stages of thrust activity. The strata on the hanging wall were denuded and absent; however, the layers on the footwall underwent rotation and denudation to form the unconformities. The western part underwent at least one stage of thrust activity, and the unconformity at the base of the Triassic deformed, rotated and was denuded by the Jurassic. The Hala'alat Mountains area in this period was still in a compressional stress field, and the back-thrusts were intense. This activity also marked a key moment for the formation of the western part of the Hala'alat Mountains.

The CAOB formed via the assembly of various tectonic units, and the lithosphere remained unstable in the Paleozoic (Buslov et al., 2004; Buslov, 2011). Reconstruction in the Mesozoic and Cenozoic formed the present structural styles (Dumitru et al., 2001; De Grave et al., 2007; Chen et al., 2011). Choulet et al. (2012b) noted that the Permian Durbut sinistral fault split the west Karamay complex ca. 100 km and that this fault formed mainly through the interaction between the Kunlun block and the Tarim craton in the late Permian and the collision between the Qiangtang block and the Eurasian plate the in late Triassic. The unconformities of this period and the sinistral Durbut slip fault are consistent in time and space. The red molasse units in the Permian Xiazijie Formation were the produced by this tectonic event. In this period, the tectonic activity began to show differentiation between the western and eastern parts. In addition to the collision between the Kazakhstan plate and the Junggar block, this event is likely related to the Altai and Tian Shan Orogenic Belts.

7.3. The late Jurassic–early Cretaceous syn-tectonic unconformity sequence

This unconformity sequence includes the unconformities at the base of the Jurassic Xishanyao Formation and the Cretaceous strata. The eastern part of the Hala'alat Mountains area underwent at least two stages of uplifting or thrust activity which included the hanging wall denudation at a large inclination, and the footwall rotation followed by the thrust that uplifted the Carboniferous rocks. In the western part of the Jurassic Xishanyao Formation, reflectors were parallel to the unconformably underlying reflectors. These findings suggest that the area was calm in the late Jurassic but resumed activity in the western part in the Cretaceous, which uplifted the Carboniferous rocks and rotated the Jurassic layers.

The formation of the large-scale thrusting and nappe may be closely related to the Durbut dextral slip in the late Mesozoic. In this period the Altai Orogenic Belt to the north and the Tian Shan Orogenic Belt to the south were active again, and the West Junggar located between these two belts was forced into a reconstruction phase. Alternatively, they may be distal effects of the late Jurassic

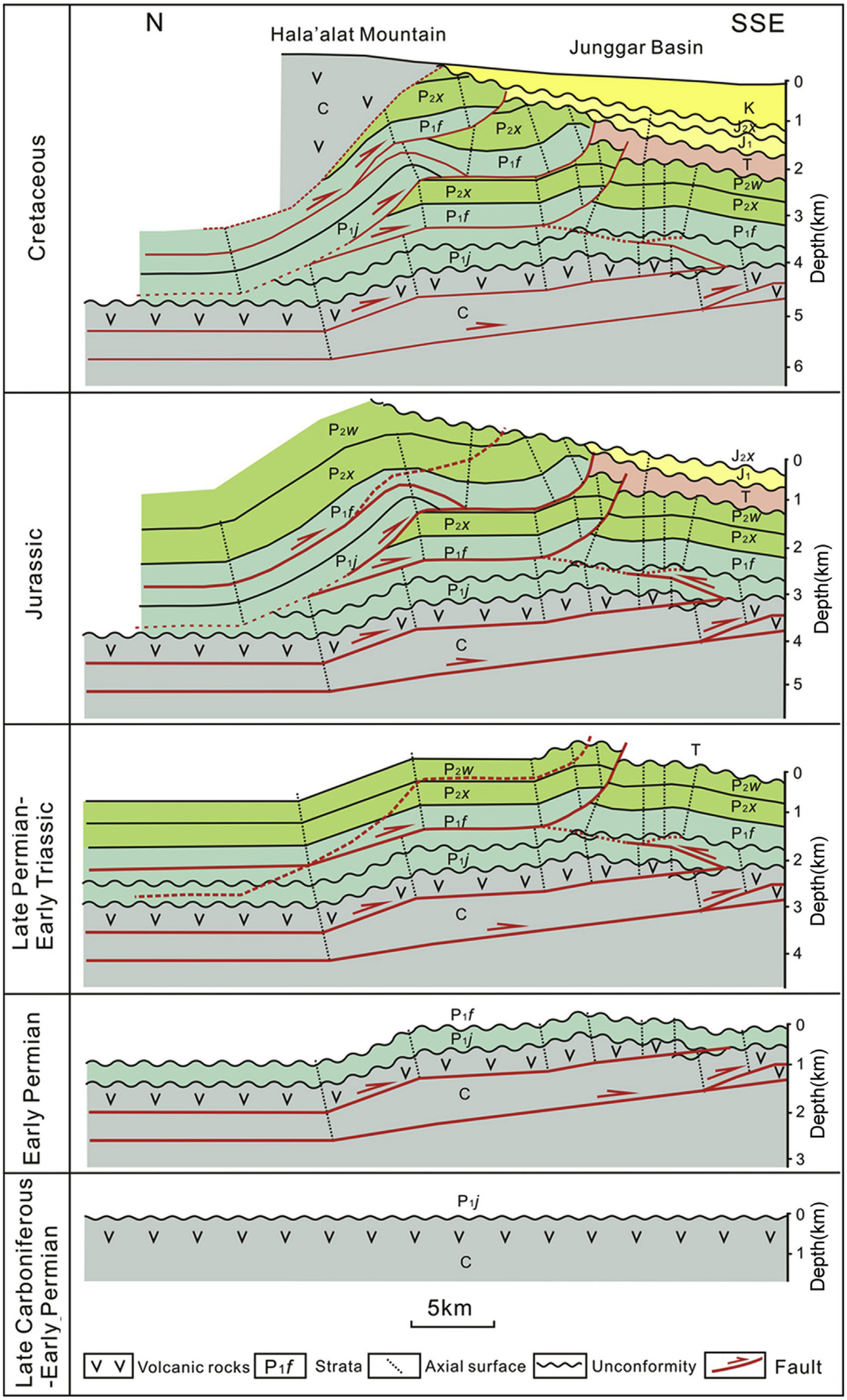

Figure 14. Evolution of the A–A′ seismic profile.

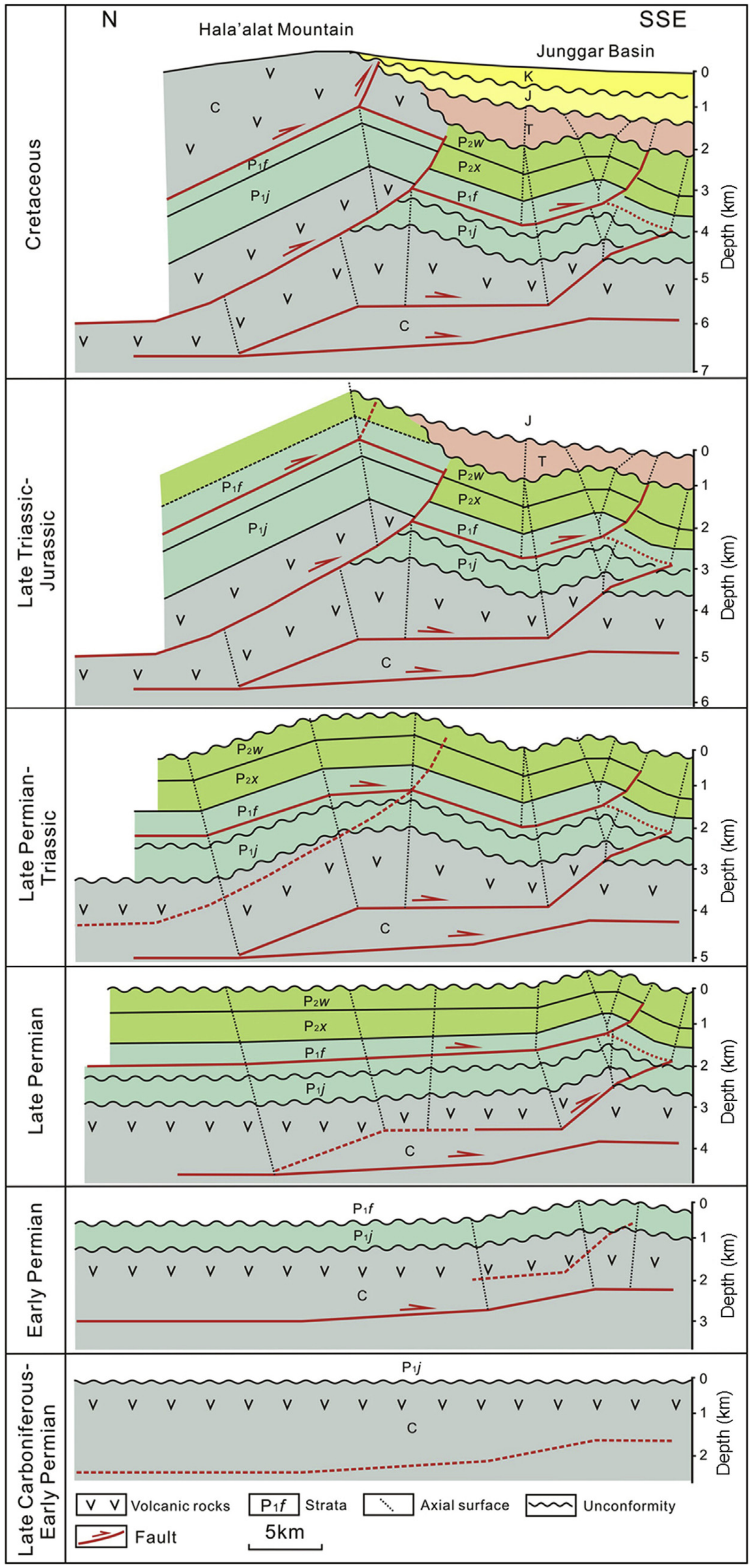

Figure 15. Evolution of the B–B′ seismic profile.

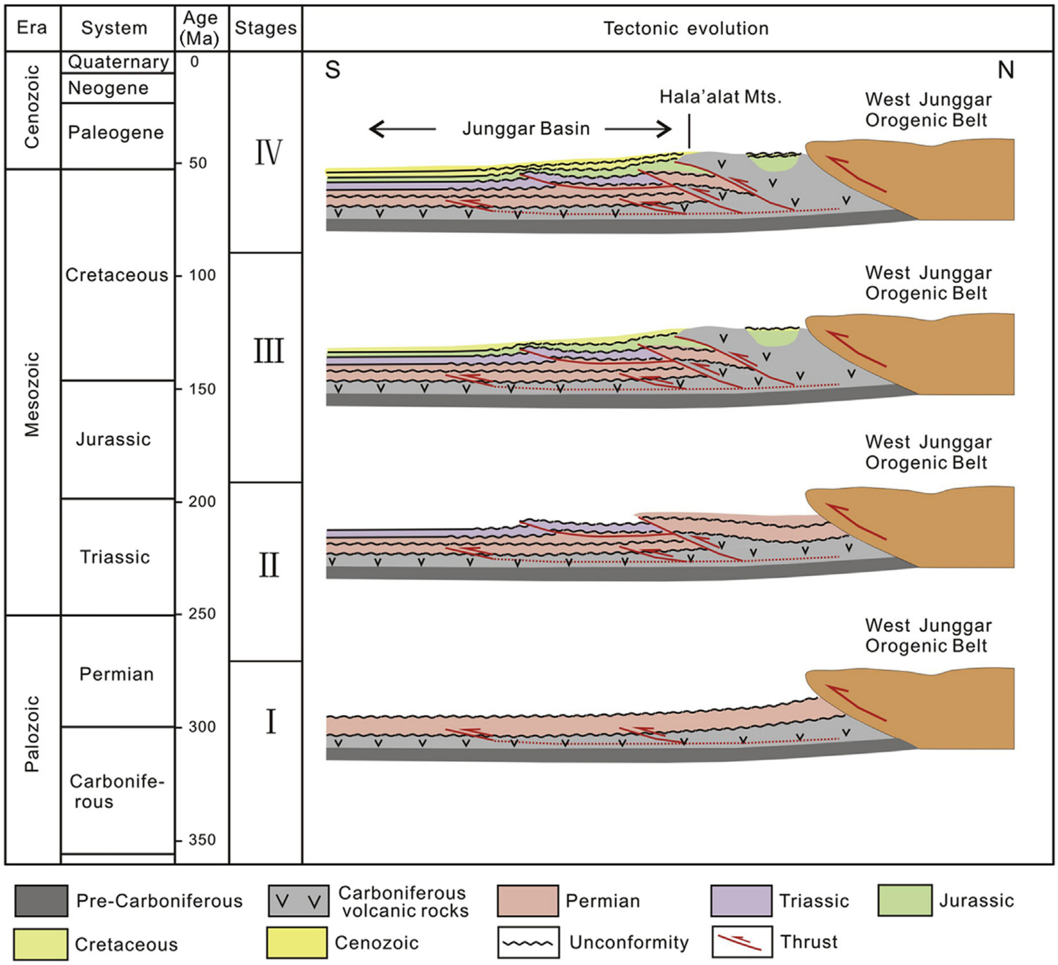

Figure 16. Syn-tectonic unconformities in the Hala'alat Mountains and the response to the West Junggar.

and early Cretaceous collision between the Lhasa block and the Eurasia plate, and the closure of the Mongolia–Okhotsk Ocean in the Jurassic and early Cretaceous (De Grave et al., 2007).

7.4. The late Cretaceous syn-tectonic unconformity sequence

This sequence of syn-tectonic unconformity is represented by the absence of the upper Cretaceous both in the Hala'alat Mountains area and in other areas at the northern margin of the Junggar Basin, suggesting regional uplift. This unconformity sequence may be related to reactivation of the Altai Orogenic Belt.

8. Conclusions

The Hala'alat Mountains area is located in the transition between the Junggar Basin and the West Junggar in the CAOB. Complete syn-tectonic unconformities from the base upward were observed in the wells and seismic profiles. On the basis of the features of syn-tectonic unconformities and balanced sections, these unconformities were classified into four sequences that represent the products of multistage tectonic events via of erosion of uplifts or rotated fault blocks. In addition, these unconformities also underwent reconstruction.

Combined with the geological background of the surrounding areas, we conclude that the unconformities at the bases of the Permian Jiamuhe Formation and Fengcheng Formation are likely related to the subduction and closure of the Junggar Ocean during the late Carboniferous–early Permian. The unconformities at the bases of the Triassic and Jurassic may be related to the Permian sinistral Durbut slip fault and may serve as a distal response of the interaction between the Kunlun block and the Tarim craton, and the collision between the Qiangtang block and the Eurasia plate. The unconformities at the bases of the Jurassic Xishanyao Formation and the Cretaceous strata may be related to the dextral Durbut slip fault in the late Jurassic–early Cretaceous as response to the collision between the Lhasa block and the Eurasia plate, and the closure of the Mongolia–Okhotsk Ocean. The entire upper Cretaceous strata are absent at the northern margin of the Junggar Basin, which is likely related to the intense uplift of this area. All these findings indicate that the West Junggar was not calm after the late Paleozoic and experienced at least four stages of tectonic movement in the Mesozoic and Cenozoic.

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