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RESEARCH PAPER

Cenozoic uplift of the Tibetan Plateau: Evidence from the tectonic–sedimentary evolution of the western Qaidam Basin

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Abstract Geologists agree that the collision of the Indian and Asian plates caused uplift of the Tibet Plateau. However, controversy still exists regarding the modes and mechanisms of the Tibetan Plateau uplift. Geology has recorded this uplift well in the Qaidam Basin. This paper analyzes the tectonic and sedimentary evolution of the western Qaidam Basin using sub-surface seismic and drill data. The Cenozoic intensity and history of deformation in the Qaidam Basin have been reconstructed based on the tectonic developments, faults growth index, sedimentary facies variations, and the migration of the depositional depressions. The changes in the sedimentary facies show that lakes in the western Qaidam Basin had gone from inflow to still water deposition to withdrawal. Tectonic movements controlled

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deposition in various depressions, and the depressions gradually shifted southeastward. In addition, the morphology of the surface structures in the western Qaidam Basin shows that the Cenozoic tectonic movements controlled the evolution of the Basin and divided it into (a) the southern fault terrace zone, (b) a central Yingxiongling orogenic belt, and (c) the northern fold-thrust belt; divided by the XI fault (Youshi fault) and Youbei fault, respectively. The field data indicate that the western Qaidam Basin formed in a Cenozoic compressive tectonic environment caused by the India–Asia plate collision. Further, the Basin experienced two phases of intensive tectonic deformation. The first phase occurred during the Middle Eocene–Early Miocene (Xia Ganchaigou Fm. and Shang Ganchaigou Fm., 43.8–22 Ma), and peaked in the Early Oligocene (Upper Xia Ganchaigou Fm., 31.5 Ma). The second phase occurred between the Middle Miocene and the Present (Shang Youshashan Fm. and Qigequan Fm., 14.9–0 Ma), and was stronger than the first phase. The tectonic–sedimentary evolution and the orientation of surface structures in the western Qaidam Basin resulted from the Tibetan Plateau uplift, and recorded the periodic northward growth of the Plateau. Recognizing this early tectonic–sedimentary evolution supports the previous conclusion that northern Tibet responded to the collision between India and Asia shortly after its initiation. However, the current results reveal that northern Tibet also experienced another phase of uplift during the late Neogene. The effects of these two stages of tectonic activity combined to produce the current Tibetan Plateau.

1. Introduction

Large-scale crustal shortening and uplift resulted from the India–Asia collision beginning between 50 Ma and 60 Ma and formed Tibet Plateau, one of the most controversial orogens resulting from a continental collision. Researchers have studied the Tibetan Plateau uplift for a hundred years and have made considerable progress. However, no consensus yet exists on the timing, rates, modes, and mechanisms of the uplift (Harrison et al., 1992; Rea, 1992; Rea et al., 1998; Molnar et al., 1993; Turner et al., 1993; Coleman and Hodges, 1995; Garzione et al., 2000; Rowley et al., 2001; Rowley and Currie, 2006; Yin et al., 2002; Spicer et al., 2003; Beaumont et al., 2004; Currie et al., 2005; Ali and Aitchison, 2006, 2008; Aitchison et al., 2007, 2011; Chung et al., 2009; Kent-Corson et al., 2009; Wang et al., 2010a,b; Xia et al., 2011; Seno and Rehman, 2011). Generally, uplift models for the Tibetan Plateau can be classified into three categories: (1) wholesale uplift models (e.g., Harrison et al., 1992; Molnar et al., 1993; Yin and Harrison, 2000), (2) progressive growth models (e.g., Tapponnier et al., 2001), and (3) inherited plateau models (e.g., Wu et al., 1996). Northern Tibet plays a critical part in the wholesale uplift model. Different uplift models predict different timing of the uplift of northern Tibet. Therefore, understanding the uplift history and its modes in northern Tibet plays an essential role in evaluating previous uplift models for the Tibetan Plateau.

The Qaidam Basin, a Cenozoic petroliferous basin with syndepositional tectonic activity (Song and Wang, 1993), lies on the northeastern Qinghai-Tibet Plateau. The basin formation and evolution must have been controlled by the Plateau uplift and resulted directly from the distant effects of the plates' convergence and collision. Thus, the processes involved in the Tibetan Plateau uplift provide important tectonic constraints for understanding the tectonic and sedimentary evolution of the western Qaidam Basin. Conversely, the thick Cenozoic sediments in the Qaidam Basin have recorded the modes of uplift and the deformation history of northern Tibet since the India–Asia collision. At the same time, syntectonic strata recorded the region's Cenozoic deformation history and therefore can reveal much from sequential cross-section restorations and examination of growth faults. Considerable geophysical and geological data from field investigations (including drilling, 2D and 3D seismic surveys, and magnetotelluric soundings) resulted from extensive hydrocarbon exploration, providing this basin with some of the most abundant geological data in the northeastern margin of the Qinghai-Tibet Plateau. These data provide a good foundation for qualitative and quantitative analyses of tectonic deformation of the basin.

In recent years, numerous geologists have published detailed results of their research on the Qaidam Basin, including from fields such as geochronology (e.g., Liu et al., 1990, 1996, 1998; Shen et al., 1992; Yang et al., 1992; Sun et al., 2004, 2005; Zhang, 2006; Fang et al., 2007; Lu and Xiong, 2009) and structure and sedimentation (e.g., Xia et al., 2001; Zhu et al., 2003; Fang et al., 2006; Wang et al., 2006; Zhou et al., 2006; Zhu et al., 2006; Meng and Fang, 2008; Yin et al., 2008; Liu et al., 2009; Shi et al., 2009; Wang et al., 2010a,b; Zhuang et al., 2011), and these studies have achieved fruitful results. However, the tectonic and sedimentary history of this basin has yet to be fully understood. This study examines the tectonic and sedimentary evolution, using one seismic section CDM-024, basement lithology, and interpretations of district and regional tectonic movements. Our interpretation of the deformation history and sedimentary facies evolution characteristics has allowed us to partition the western Qaidam Basin according to the surface structural morphology. Our results provide a basis for interpreting Cenozoic crustal deformation processes in the Qaidam Basin and deciphering a record of uplift for the northern Tibetan Plateau.

2. Geological setting

The Altyn Tagh Mountains bound the Qaidam Basin (longitude 90°00′–99°20′ E, latitude 35°00′–39°20′ N) to the northwest; the Kunlun Mountains bound the Basin to the south, the Elashan Mountains to the east, and the Qilian Mountains to the northeast. The Basin has an average elevation of 3–3.5 km above sea level, in contrast to the surrounding mountains rising to elevations of 4–5 km (Fig. 1). The Qaidam Basin developed on the Proterozoic–Paleozoic basement, which consists mainly of metamorphic rocks, flysch, and carbonates, and can be divided into the western, central, and eastern

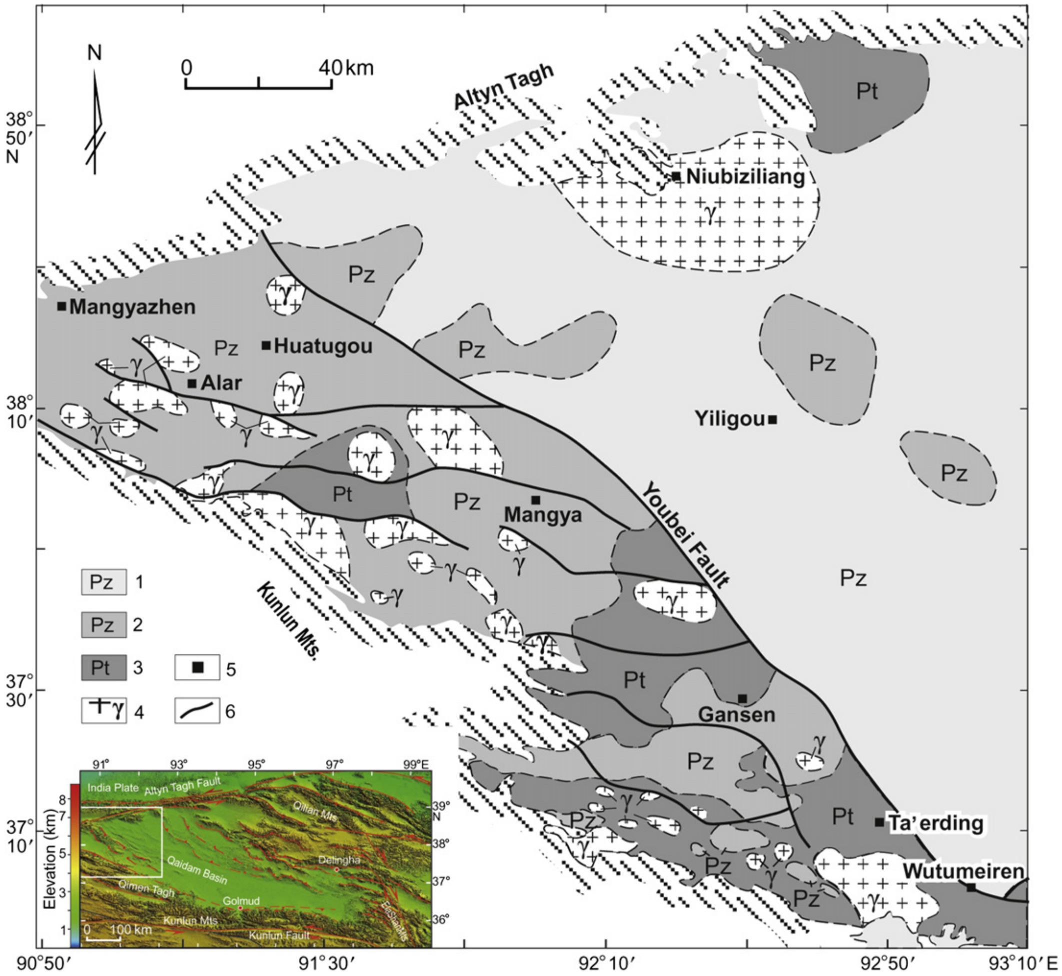

Figure 1 Distribution map of basement lithologies and faults in the western Qaidam Basin (1: Pz Un-metamorphosed or low grade metamorphic rock series; 2: Pz Metamorphic rock series; 3: Pt Metamorphic rock series; 4: Intrusive rocks; 5: Town; 6: Fault).

parts. The western Qaidam Basin includes areas west of Xitaijnar Lake, and the topographic high between Dongtaijnar Lake and Xidabuxun Lake forms the boundary between the central basin and the eastern basin (Wang and Coward, 1990). To the north, a number of north-dipping reverse faults now bound the basin, as do south-dipping reverse faults on the south. These reverse faults have placed Proterozoic and Mesozoic rocks over top of Cenozoic rocks as young as the Pleistocene, implying that the faults remain active.

The Qaidam Basin contains thick Mesozoic and Cenozoic fluvial-lacustrine sediments, which derived from surrounding mountains. North–south compressive stresses associated with the India–Eurasia plate collision caused uplift of the surrounding mountains (Royden et al., 1997; Wan and Zhu, 2002). The Cenozoic strata include a thickness of more than 12 km. Over the last 50 years, petroleum geologists have divided these into seven formations. The formation boundaries of these units have been labeled T_6, T_R, T_5, T_4, T_3, T_2', T_2, T_1, and T_0 from bottom to top, respectively. Paleomagnetic dating provides ages for these seven formations (Liu et al., 1990, 1996, 1998; Yang et al., 1992; Sun et al., 2004, 2005; Zhang, 2006; Fang et al., 2007) (Table 1).

The nature of the basement under a sedimentary basin provides a key to interpreting the origin of the basin (Allen and Allen, 1990). Magnetotelluric sounding and deep seismic refraction data show that a continental crust (consisting of Precambrian metamorphics and granites) underlies the Qaidam Basin (Xia et al., 2001). The western Qaidam Basin is clamped between the Altyn Tagh and Qimen Tahg-East Kunlun Mountains. The Youbei fault divides the Basin's basement into southern and northern parts (Fig. 1). The rigid southern basement consists of Paleozoic and Proterozoic metamorphic and intrusive rocks. The intrusive rocks outcrop along E–W faults. The more flexible northern basement consists of Paleozoic low grade metamorphic and non-metamorphosed rocks. The intrusive rocks here are less well developed. The basement lithology and surrounding orogenic belts controlled the development of faults and regional structures in the western Qaidam Basin. The Basin contains a series of NW–SE trending thrust-fold belts, which generally show signs of syndepositional tectonic activity (Fig. 2).

3. Methods and select profiles

Since Dahlstorm (1969) demonstrated the method of cross-section restoration, it has been widely used in geology to help analyze compression and thrusting (Dubey et al., 2001; Godin, 2003), extension (Erickson et al., 2000), inverted structures (McClay

Table 1 Cenozoic integrated magnetostratigraphy of Qaidam Basin.

Age of international standards (Ma) (Walker and Geissman, 2009)		Stratigraphy				Earthquake standard layer
		Epoch		Formation	Magneto-stratigraphy (Ma)	
0.01		Holocene		Qigequan	2.65–0	T_0
2.6		Pleistocene				
5.3		Pliocene		Shizigou	8.2–2.65	T_1
23.0	11.6	Miocene	Late	Shang Youshashan	14.9–8.2	T_2’
	16.0		Middle	Xia Youshashan	22–14.9	T_2
	23.0		Early			
33.9	28.4	Oligocene	Late	Shang Ganchaigou	31.5–22	T_3
	33.9		Early			
55.8	37.2	Eocene	Late	Xia Ganchaigou	Upper: 37.5–31.5	T_4
					Lower: 43.8–37.5	T_5
	48.6		Middle	Lulehe	53.5–43.8	T_R
	55.8		Early			
65.5		Paleocene		Mz	65–53.5	T_6

et al., 2000), and salt diaper structures (Kossow and Krawczyk, 2002). By reconstructing the deformed cross-sections to their initial states, structural geologists can interpret sub-surface structures; determine the original positions and attitudes of the structures, and determine the detailed deformation history of the structures. With the rapid development of computer techniques, calculating software (such as, 2DMove, GeoSec, LOCACE, and Restore) has greatly aided cross-section restorations. With different restoration methods (such as flexural slip and vertical/oblique slip algorithms), balanced cross-sections can take account of different tectonic regimes.

This study constructs one major geological section in the western Qaidam Basin based on interpretations from regional 2D seismic profiles in combination with geophysical, geologic, and drill hole data. Geologic sections obtained from balanced cross-section restoration provide the support for interpreting tectonic movements and sedimentary evolution during each stage of the Cenozoic. On the basis of these detailed data, this study analyzes the Cenozoic deformation history of the Qaidam Basin. The following presents our issues and conclusions on some key issues regarding the tectonic evolution of the Qinghai-Tibet Plateau.

The surface and near surface structures in the Qaidam Basin demonstrate an overall NE–SW direction of converge (Royden et al., 1997; Wan and Zhu, 2002). The Qinghai Oilfield Company conducted seismic geophysical exploration in the Qaidam Basin over the past decades, and prepared dozens of large seismic profiles through the basin along a SW–NE profile. This study examined one representative profile, CDM-024, in detail. This seismic profile starts from the piedmont of the East Kunlun Mountains, passing through the Kunbei step-fault zone, Youshashan, Youquanzi, Nanyishan, and Xiaoliangshan to Yueyashan (Fig. 3). The 2DMove software helped to establish paleo-structure models and the tectonic evolution history. Drilling data provided by the Qinghai Petroleum Sub-corporation of PetroChina Company Limited, Dunhuang, helped determine the sedimentary facies. By reconstructing the tectonic history, we calculated the growth indices for the Kunbei fault, Alar fault, XI (Youshi) fault, Youbei fault, and Yuenan fault, and analyzed the evolution of various sedimentary facies.

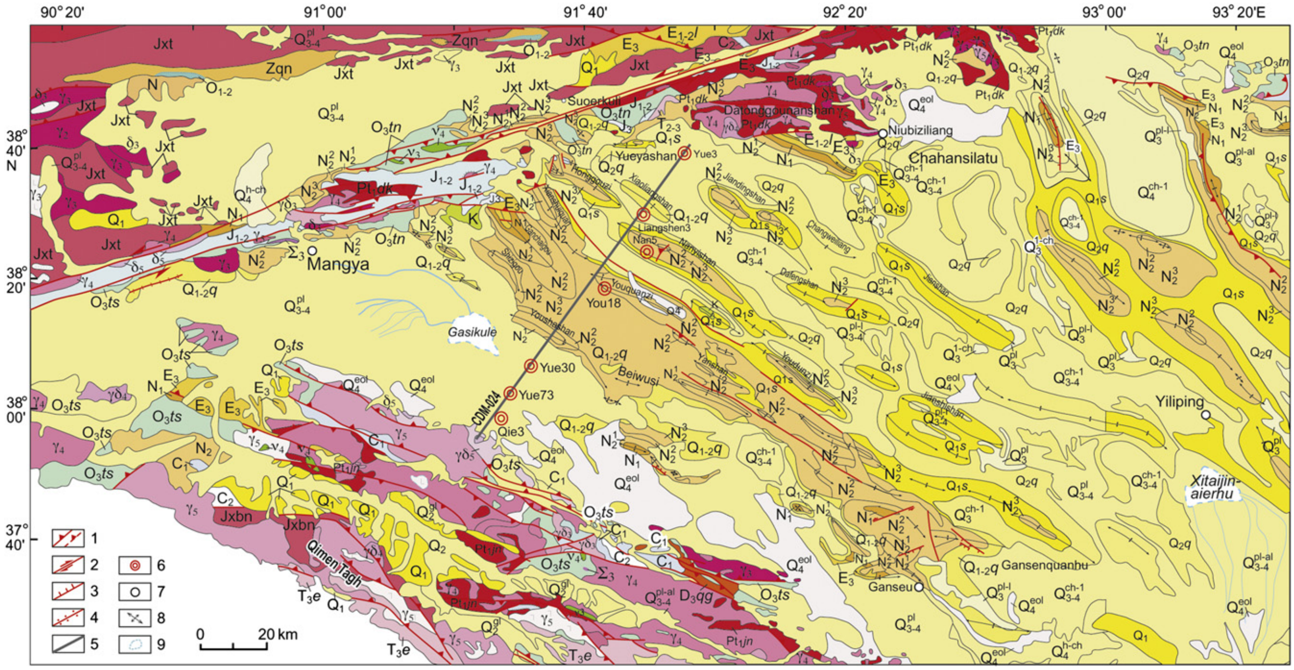

Figure 2 Structure of the western Qaidam Basin (1: Thrust fault; 2: Strike-slip fault; 3: Normal fault; 4: Unknown nature of fault; 5: Seismic profile; 6: Drill site; 7: Town; 8: Anticline; 9: Lake. $Q_{1\text{-}2}$: Early and Middle Pleistocene; $Q_{3\text{-}4}$: Late Pleistocene and Holocene; N_2: Pliocene; N_1: Miocene; E_3: Oligocene; $E_{1\text{-}2}$: Eocene; K: Cretaceous; J_3: Upper Jurassic; $J_{1\text{-}2}$: Middle–Lower Jurassic; T_3: Upper Triassic; C_2: Upper Carboniferous; C_1: Lower Carboniferous; D_3: Upper Devonian; O_3: Upper Ordovician; $O_{1\text{-}2}$: Lower Ordovician; Jxt: Taxi Daban Group; Jxbn: Binggou Group; Pt_1dk: Darken Daban Rock Group; Pt_1jn: Jinshuikou Rock Group; γ_5: Mesozoic granite; γ_4: Late Paleozoic granite; γ_3: Early Paleozoic granite; $\gamma\delta_5$: Mesozoic granodiorite; $\gamma\delta_4$: Late Paleozoic granodiorite; $\gamma\delta_3$: Early Paleozoic granodiorite; δ_5: Mesozoic diorite; δ_4: Late Paleozoic diorite; δ_3: Early Paleozoic diorite; δ_2: Proterozoic diorite; ν_4: Mesozoic mafic rocks; Σ_3: Early Paleozoic ultramafic rocks).

4. Tectonic–sedimentary evolution of the western Qaidam Basin

4.1. Cenozoic tectonic evolution revealed in the seismic section

Between the top of the Lulehe Fm. and top of the Xia Ganchaigou Fm. (53.5–31.5 Ma), active thrust faults between the southern and northern parts of the western Qaidam Basin included the Kunbei, Alar, XI, Youbei, Yuenan, and Yuebei faults. They were reactive pre-Cenozoic ones. The activity of these faults in the Lulehe Fm. was relatively less dynamic, indicated by small fault displacements. After that period, fault displacements increased and reached the maximum by about 31.5 Ma (the bottom of Shang Ganchaigou Fm.).

From the Shang Ganchagou Fm. to the Xia Youshashan Fm. (31.5–14.9 Ma), the distribution of the faults remained the state of the top of the Xia Ganchaigou Fm., but the XI and Youbei faults ceased their activity, and other faults decreased in their activity, based on decreased fault displacements. However, the Kunbei and Alar faults (in the southern part of the western Qaidam Basin) and the Yuebei and Yuenan faults (in the northern part) continued to thrust slowly into the basin. Especially in the southern part of basin, some small recoil faults developed in order to adjust for the extrusion generated by the thrust faults.

The Shang Youshashan Fm. (14.9–8.2 Ma) contains the Kunbei and Alar faults as the main active faults in the southern part of the western Qaidam Basin. In the central part of the Basin, the faults show no movement. In the northern part, the Yuenan fault ceased temporarily; whereas the Kunbei and Alar faults continued to thrust northward, and their activity increased. Because of these thrust faults, more adjustment faults and recoil faults developed in the southern part of the western Qaidam Basin. Tectonic movements in the southern part appear greater than in the northern part.

Tectonic activity increased during deposition of the Shizigou Fm. (8.2–2.65 Ma), compared to the previous period. The Kunlun fault system continued to thrust into the Basin and the thrusting spread northwestward. In the central part of the Basin, the Youbei fault reactivated and developed recoil faults. In the northern part of the western Qaidam Basin, the Nanyishan fault system began to develop.

The tectonic intensity further increased in the western Qaidam Basin, as indicated in the Qigequan Fm. (2.65–0 Ma). In the southern part of the Basin, the Kunlun fault system achieved peak activity in the Cenozoic and formed various fault patterns. The Youshi fault formed as a recoil fault of the XI fault and appeared to be related to increased extrusion of thrust. In the northern part of the Basin, the Xiaoliangshan fault system developed as a recoil fault, resulting from the movement along the Altyn Tagh fault.

Different periods of the Cenozoic tectonics created the section's current form, under the control of the master faults. The depth to basement and the thickness of the layers of the section vary greatly in the hanging and footwalls of the Kunbei fault. The Shang Youshashan Fm. and Shizigou Fm. no longer appear in the hanging wall, and the Cenozoic strata outcrop only in the footwall. To the

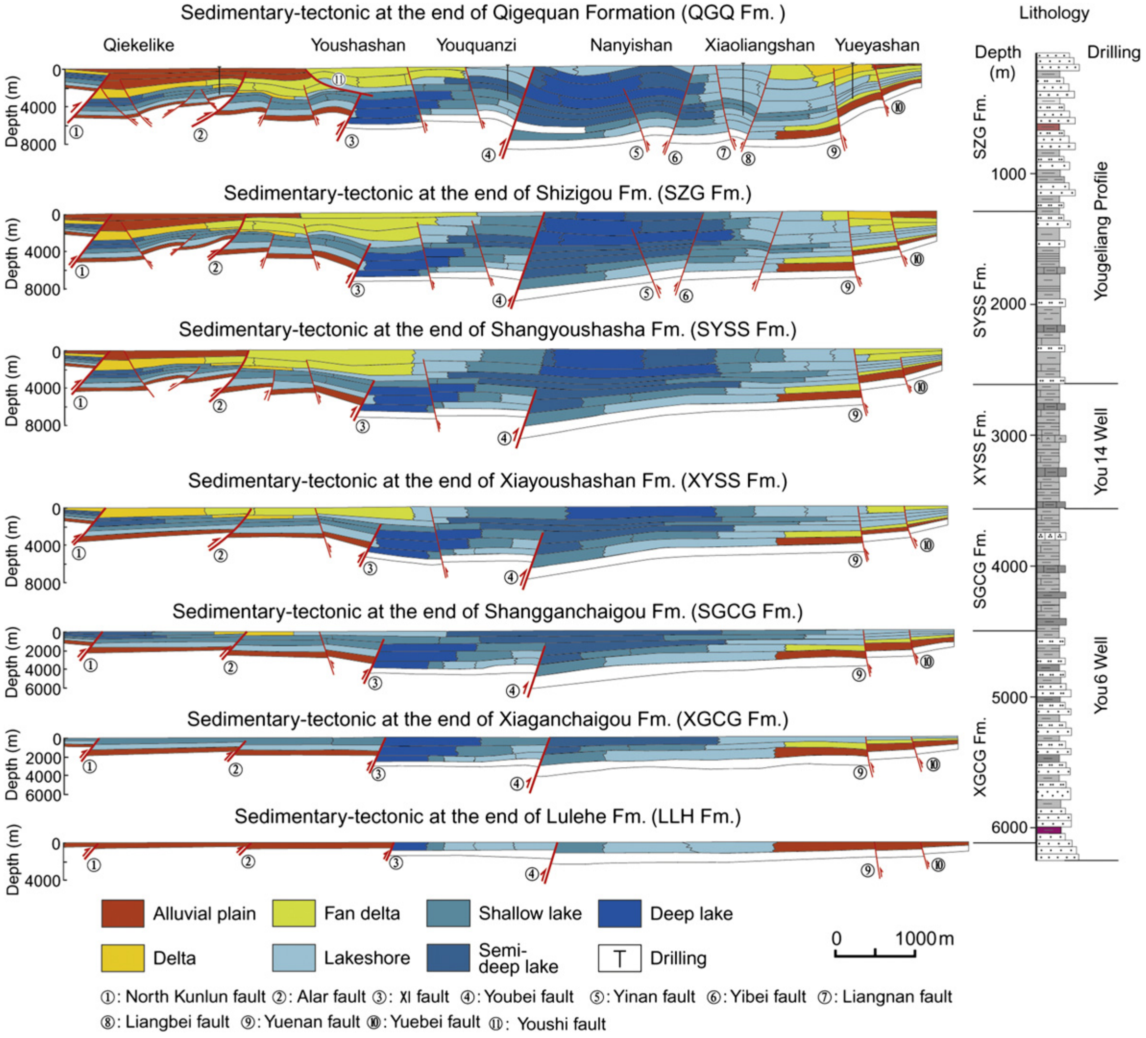

Figure 3 Sedimentary–tectonic evolution history of CDM-024 seismic geology profile in western Qaidam Basin.

south of the Alar fault, the Qiekelike depression appears to be a piedmont recoil fault-fold. Thin sedimentary strata show up on the hanging wall of this fault and appear to thicken toward the Kunbei fault. In the northern portion of the Alar fault, Alar and Hongliuquan structures emerge as fault-propagation folds, which have moved during the Cenozoic. The tectonic evolution history shows that the Kunbei and Alar faults thrust into the Basin during the Cenozoic. The XI fault does not pass through the Shang Ganchaigou Fm. The Youshi fault formed as a recoil fault of the XI fault and thrusted southward. The Youshashan structure is a double-layer fault-anticline controlled by the XI and Youshi faults. The Youbei fault dips to the south and thrusts northward, controlling the formation of the Youquanzi structure. The Nanyishan and Xiaoliangshan structures are fault-propagation folds controlled by the Yinan, Yibei, Liangnan, and Liangbei faults, respectively. The Yuenan and Yuebei faults controlled the Yueyashan structure, which was tilted into the basin because of the influence of the Altyn Tagh strike-slip fault (Fig. 3).

As faults grow, the stratigraphic thickness of the fault walls that are controlled by growth faults must change synchronously. The concept of growth index is used to measure their activity intensity. Growth index is defined as the difference of the strata thickness of the footwall and hanging wall of the growth faults, divided by the footwall thickness (Wang et al., 1990). When a growth fault starts to be active, the growth index would be more than 1; when its activity is strongest, the growth index would reach its highest value; then when the fault stops being active, the growth index would be 1.

Table 2 presents the growth indices of the Kunbei, Alar, XI (Youshi), Youbei, and Yuenan faults along the CDM-024 profile. Several faults initiated activity at around 53.5 Ma (Early Eocene), and their growth indices increased gradually, reaching a maximum at about 31.5 Ma (Early Oligocene, Upper Xia Ganchaigou Fm.). After that, the indices decreased, with the indices of the XI (Youshi) and Youbei faults returning to 1 by ∼15 Ma (Middle Miocene) (Fig. 4). Our observations found that activity of the faults began to increase again around 14.9 Ma (Middle Miocene), and continued to intensify until 2.65 Ma (Late Pliocene, Shizigou Fm.) (Fig. 4).

Based on the above analysis of the tectonic evolution history and growth faults in the western Qaidam Basin, strong tectonic periods occurred during the Early Oligocene and the Middle Miocene to Late Pliocene, whereas two inactive periods occurred during the Late Eocene and Early Miocene.

Table 2 Growth index of several faults in CDM-024 seismic profile.

Age of strata (Ma)	Fault growth index				
	Kunbei fault	Alar fault	XI (Youshi) fault	Youbei fault	Yuebei fault
8.2–2.65	2.81	1.95	1.45	1.32	1.65
14.9–8.2	2.30	2.07	1.32	1.21	1.44
22–14.9	2.09	1.51	1.00	1.00	1.14
31.5–22	1.94	1.38	1.00	1.00	1.16
37.5–31.5	2.15	1.76	1.57	1.35	1.23
43.8–37.5	1.38	1.22	1.20	1.08	1.13
53.5–43.8	1.50	1.51	1.25	1.04	1.21

4.2. The facies evolution of Cenozoic sediments represented in the seismic section

Cenozoic sedimentation in the Qaidam Basin began in the Eocene, synchronous with the India–Eurasia collision (Molnar and Tapponnier, 1975). The Lulehe Formation, from the Early–Middle Eocene (Lulehe Fm., 53.5–43.8 Ma), represents the earliest Cenozoic deposits in the Qaidam Basin. Deep lake facies, shallow-lake facies, and lakeshore facies occupy the footwall of the XI fault and hanging wall of the Youbei fault. From the footwall of the Youbei fault to the Yueyashan structure, shallow-lake–lakeshore facies shift into alluvial plain facies. The footwall of Youbei fault occupied a weak depression which accumulated the thickest strata. The layer gradually thins toward both sides of the piedmont (Fig. 3). On the piedmont of Qimen Tagh Mountain, a NW–SE cross-section shows the tectono-stratigraphic framework of the southwestern Qaidam Basin. Drill hole logs and cores help determine the depositional system of the section. The facies correspond to a lake-flooding and basin-filling stage (Xia et al., 2001).

Between the Middle Eocene and Early Oligocene (43.8–31.5 Ma), the Xia Ganchaigou Fm. can be divided into lower and upper parts. Strata are thin from the hanging wall of the XI fault to the Kunlun piedmont, and the sedimentary facies change from lakeshore facies in the lower Xia Ganchaigou Fm. to the shallow-lake facies in the upper Xia Ganchaigou Fm. On the footwall of the XI fault, deep lake facies and shallow-lake facies gradually extended from the lower to upper Xia Ganchaigou Fm. On the footwall of the Youbei fault, shallow-lake facies in Lulehe Fm. evolved into semi-deep lake facies in the Xia Ganchaigou Fm., in conjunction with increased tectonic movement activity. The extent of lacustrine sediments then further advanced to the piedmont. In the Yueyashan structure of the Altyn Tagh region, the strata remain very thin, but the sedimentary facies change from alluvial plain facies in the Lulehe Fm. to fan delta-lakeshore facies in the Xia Ganchaigou Fm. This section shows that waters deepened and lake areas increased in the western Qaidam Basin at the end of the upper Xia Ganchaigou Fm. deposition. The dark-colored mudstone, lime mudstone, and limestone in the Xia Ganchaigou Formation in the western Qaidam Basin can be up to 2000 m thick in the Mangnai depression (Huo, 1990). In addition, the boreholes reveal that the accumulated thickness of limestones and lime mudstones exceeds 300 m. Gu and Di (1989) show that lime mudstones generally form in a lacustrine setting.

The tectonic evolutionary history and the thickening of strata during the Early Oligocene–Early Miocene (Shang Ganchaigou Fm., 31.5–22 Ma) show the occurrence of interval of tectonic movements during the deposition of the Shang Ganchaigou Fm. Deep lake facies did not develop at this site; and semi-deep lake facies migrated to the Youquanzi and Nanyishan region. From Nayishan to Yueyashan, the sedimentary facies changed from shallow-lake facies into lakeshore facies. The central and southern parts of the western Qaidam Basin contain irregular sedimentary facies. From Youquanzi to Youshashan, semi-deep lake facies suddenly change to lakeshore facies. The lakeshore facies then shift into delta facies toward the Alar region. Semi-deep lake and shallow-lake facies developed on the Kunlun piedmont. From this section, we discern that the Kunlun and Altyn Tagh Mts. did not extend to any great height, and water spread throughout the entire basin. Inter-layered fine-grained sandstones, siltstones, and mudstones grade upward into gravelly sandstones and pebbly conglomerates, demonstrating a marked upward-coarsening trend at the basin margins. The sediments also change in color upward from dark brown and gray to red (Meng and Fang, 2008).

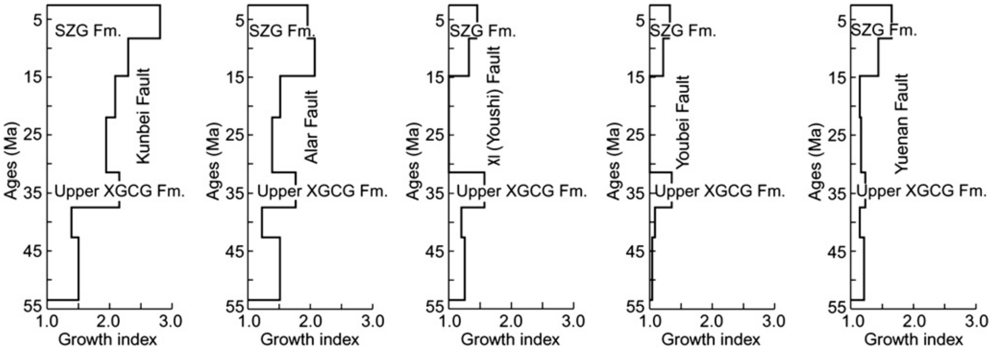

Figure 4 Growth index of several faults in CDM-024 seismic profile.

Deep lake facies developed in the Nanyishan region during the Early–Middle Miocene (Xia Youshashan Fm., 22–14.9 Ma). From Nanyishan to Xiaoliangshan and Yueyashan, the sedimentary facies gradually transformed from shallow-lake and lakeshore facies to fan delta facies. Lacustrine sediments only developed in the Youquanzi region of the southern part of the western Qaidam Basin. Fan deltas developed in both the Youshashan and Alar regions. Sedimentary facies changed into delta facies between Qiekelike and the Kunlun piedmont. The evolution of sedimentary facies and changes in stratigraphic thicknesses indicate that tectonic activity in the Kunlun Mts was stronger than in the Altyn Tagh regions. The depression of the western Qaidam Basin continued to migrate northward and the depth of the Youbei depression increased in conjunction with the uplift and extrusion of the Kunlun Mts. Compared with the previous period, the water covered area shrank significantly. Throughout the Qaidam Basin, coarse-grained facies are more common than in the Shang Ganchaigou Formation. Conglomeratic layers become more pronounced along the margins of the present-day Qaidam Basin, with the gravels most likely to have come from adjacent mountain belts. Fine-grained facies still dominate the middle part of the Basin and consist of thin-bedded siltstones, mudstones, and limestones, as revealed in both borehole cores and outcrops (Meng and Fang, 2008).

The area of deep lakes began to shrink as they changed into semi-deep lakes in the Middle–Late Miocene (Shang Youshashan Fm., 14.9–8.2 Ma). Lacustrine deposits developed mainly between the Youquanzi and Xiaoliangshan regions. The area of shallow-lake facies decreased within the Youquanzi structure and the area of shrinkage extended northward to the vicinity of Xiaoliangshan. Fan delta facies expanded into the basin on the Altyn Tagh piedmont. The sedimentary facies changed into alluvial plain facies between the Kunlun Mountains piedmont and the hanging wall of the Alar fault. The Youbei depression deepened due to compression from the mountains on both sides. The changes of the sedimentary facies in the Kunlun and Altyn Tagh piedmont show that the mountains uplifted significantly on both sides of the Basin; but the height of the Kunlun Mts. far exceeded that of the Altyn Tagh. The extent of the lake further narrowed and the depression of the western Qaidam Basin continued to migrate northward. The occurrence of coarser facies along the basin margins and finer facies in the middle of the basin indicate that the Shang Youshashan Fm. shares the same spatial facies zonation as the Xia Youshashan Fm. However, coarse-grained facies became increasingly more pronounced and they propagated well into the basin interior (Xia et al., 2001; Meng and Fang, 2008).

The sedimentary record shows that the area of deep lake facies became even smaller between the Late Miocene to the Middle Pliocene (Shizigou Fm., 8.2–2.65 Ma), and that lacustrine facies developed mainly in the Nanyishan and Xiaoliangshan regions. Fluvial facies moved further into the Basin. The depth of the Youbei depression continued to increase and it became the dominant depression of the western Qaidam Basin. The tectonic evolution suggests that the tectonic movements were relatively strong. The Kunlun and Altyn Tagh Mountains uplifted rapidly, generating considerable compression. The western Qaidam Basin ceased to be occupied by lakes. Alluvial conglomeratic deposits that clearly originated from the adjacent highlands dominate the Shizigou Formation along the basin margins (Meng and Fang, 2008).

Between the Middle Pliocene and Holocene (Qigequan Fm., 2.65–0 Ma), the Qigequan Fm. strata did not develop on the hanging wall of the Youbei fault. Other formations suffered varying degrees of erosion towards the Kunlun Mountains. Strata of the Qigequan Fm. developed on the footwall of the Youbei fault, between the Nanyishan to the Xiaoliangshan regions and were subsequently exposed, resulting in varying thicknesses of strata. As the basin dried up, the lake evolution ended. The Kunlun and Altyn Tagh Mountains uplifted rapidly in the southern and northern portions of the western Qaidam Basin, respectively. The Kunlun Mountains uplifted and with great power, generating compressional forces that migrated to the north of the central part of the western Qaidam Basin. This caused uplift and erosion in the southern part of the western Qaidam Basin. In the northern part of the western Qaidam Basin, the Altyn Tagh Mountains were faulted by the forces that led to strong regional compression along with basin depression. Conglomerates and sandstones dominate the lithologies of the Qigequan Fm. in the western and marginal parts of the Basin, which we interpret as having resulted from alluvial–fluvial deposition at the basin margins (Meng and Fang, 2008). The Shizigou and Qigequan Fms., dominated by fluvial, deltaic, and shallow lacustrine systems, were the last sequences in the Cenozoic. This sequence exhibits tight folds and thrust faults and has been strongly eroded. It may therefore represent an intense compressive tectonic environment (Xia et al., 2001).

The Cenozoic sedimentary evolution of the western Qaidam Basin can be divided into three stages: (1) Early stage (the Lulehe Fm. and lower Xia Ganchaigou Fm.): A depression formed in the footwall of the XI fault and developed deep/semi-deep lake facies sediments. The lake area was small, and the alluvial plain facies were distributed on the piedmonts; (2) Interim stage (upper Xia Ganchaigou Fm. and Shang Ganchaigou Fm.): The lake area reached its maximum (Fig. 3), and the thicknesses of lacustrine sedimentary strata increased; (3) Late stage (Xia Youshashan Fm. – Qigequan Fm.): Waters gradually withdrew from the basin with the rapid uplift of the Kunlun and Altyn Tagh Mountains, and the lake evolution ended. The depression of the western Qaidam Basin migrated to the Youbei depression.

5. Surface structure characteristics in the western Qaidam Basin

The present-day configuration and topographic features of the Qaidam Basin and adjacent areas result primarily from the late Cenozoic deformation. Cenozoic strata of the western Qaidam Basin have been folded, as displayed by surface traces of the fold layers and on seismic profiles (Fig. 3). Royden et al. (1997) concluded that the crust of the Tibetan Plateau underwent E–W extension and the N–S convergence during the Indian–Eurasia collision. The stress field from the plate–plate collision and the convergence of the Qaidam Basin orients to the NNE (Wan and Zhu, 2002). Based on the DEM (Digital Elevation Model) across the western Qaidam Basin (Fig. 5), the Basin can be divided into three parts by the XI (Youshi) and the Youbei faults. In the Basin's southern part (between the Kunbei and XI faults), faults have become well developed because of stresses from the Kunlun fault system. From south to north, the Kunbei, Alar, XI, and Youbei faults, along with their recoils, developed and controlled the formation of a series of fault-related folds (Figs. 3 and 5). The Yingxiongling orogeny then became active in the central part of the Basin (between the XI and Youbei faults). Thereafter, many growth and non-growth faults developed in this area (Wang et al., 2010a,b). The relative elevation difference between the southern and northern

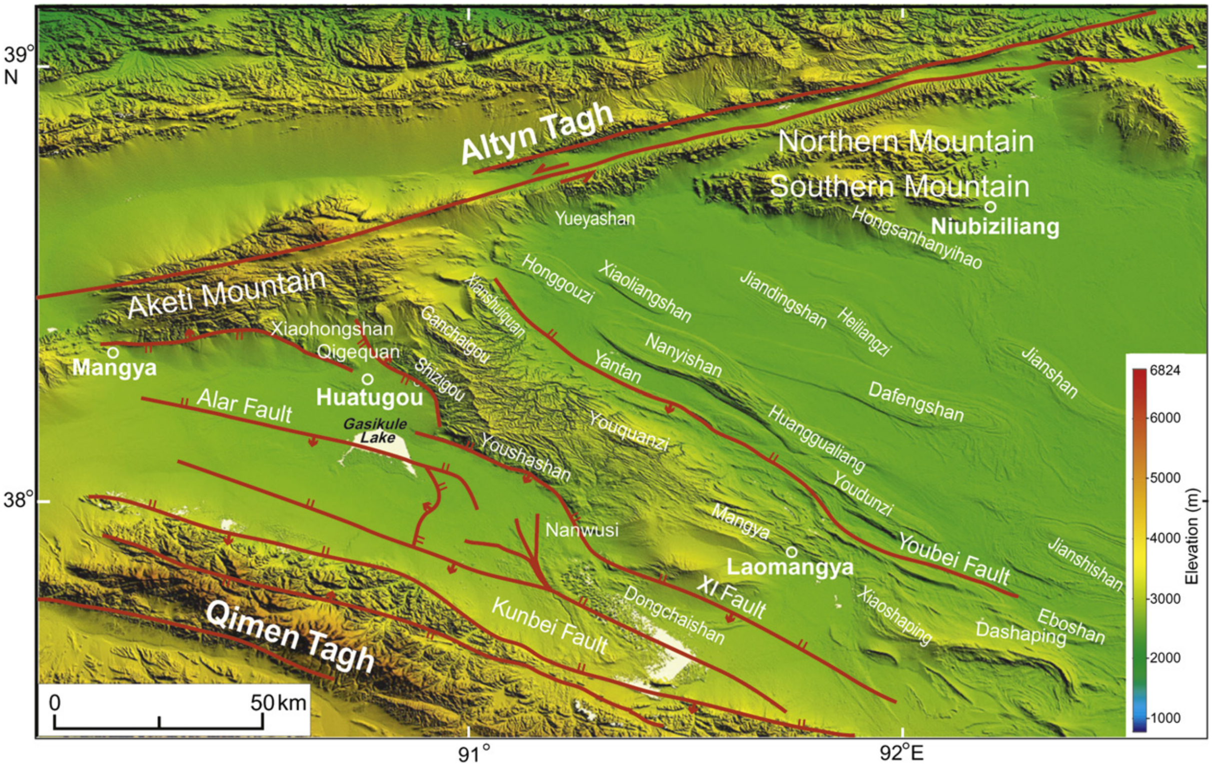

Figure 5 The morphology of surface structure and tectonic division of the western Qaidam Basin.

parts of the Basin reaches 800 m. Numerous thrust folds developed in the northern part (north of the Youbei fault), and the anticlines there were tighter and the synclines broader. The fold axes align with the Kunlun Mts. The terrain of this region alternated between depressions and rebounds (Fig. 5).

6. Discussion

The Cenozoic tectonic and sedimentary evolution history indicates that the western Qaidam Basin has been in a state of continuous extrusion and has experienced two periods of intensive tectonic deformation along with two relatively stable periods (Figs. 3 and 4). The surface and near surface structures in the western Qaidam Basin orient NE to SW and indicate that this was the direction of greatest convergence (Fig. 5). The Qaidam Basin formed as an intermountain basin at the northern margin of the Tibetan Plateau; hence, it developed thick Mesozoic and Cenozoic strata, which recorded the processes of the uplift and deformation of the Tibetan Plateau.

Geologic records show that the Cenozoic deformation of the western Qaidam Basin began between 53.5 and 43.8 Ma (Lulehe Fm., Early–Middle Eocene). The main pre-existing faults from the Mesozoic reactivated during this period, but with less intensity. The Basin deformed somewhat and filled with deposits of the Lulehe Fm. The initiation of deformation and deposition in the western Qaidam Basin during this period not only indicates the initial activity and Cenozoic uplift of the Kunlun and Altyn Tagh Mts., but more importantly, could have been a direct response to the initial collision between the Indian and Eurasian plates during this time (Zeitler, 1991; Zeitler et al., 1993; Klootwijk et al., 1992, 1994; Lee and Lawver, 1995; Searle, 1996; Patzelt et al., 1996; Mattauer et al., 1999; Yin and Harrison, 2000; Ali and Aitchison, 2006, 2008; Aitchison et al., 2007; Wu et al., 2008; Yin et al., 2008; Wang et al., 2010a,b; Xia et al., 2011). This timing coincides with many other geological events: (1) the initiation of crustal shortening and increase in sedimentary deposition in the western Qaidam Basin (Zhang, 2006; Zhou et al., 2006; Wang et al., 2010a,b); (2) initiation of thrusting in the northern and southern margins of the Qaidam Basin (Yin et al., 2002); (3) increased volcanic activity on the Tibetan Plateau after 51 Ma (Chung et al., 1998, 2005, 2009; Lai, 2000; Deng et al., 2000; Wang et al., 2001, 2010a,b; Mo et al., 2003; Liu et al., 2004; Li et al., 2005; Qu et al., 2009; Xia et al., 2010), and (4) formation of a series of Cenozoic basins within and near the edge of the Tibet Plateau (Liu et al., 2000; Liu and Wang, 2001; Zhao et al., 2000; Yue et al., 2000). This timing clearly suggests that the northern edge of the Tibetan Plateau sensed the Indian–Eurasian plate collision during the Early Eocene. But the initial collision of the two plates was probably relatively weak, as the margins of the plates deformed with first contact (Yin and Harrison, 2000; Cui et al., 2006; Xia et al., 2010). This first deformation occurred primarily within the collision zones, thus somewhat less stress was transferred northwards. Consequently, the mountains around the Qaidam Basin did not rise particularly high, resulting in relatively shallow lakes.

The first strong phase of deformation occurred between 43.8 Ma and 37.5 Ma (Xia Ganchaigou Fm., Middle Eocene), and reached its maximum at 31.5 Ma (Shang Ganchaigou Fm., Early Oligocene). The faults then extended much further into the Basin, indicating stronger uplift of the Kunlun and Altyn Tagh Mts. Increased tectonic activity between 37.5 Ma and 31.5 Ma corresponds with many other independent activities from within and outside Tibet. For example rapid crustal shortening occurred within the same area and time period (Zhou et al., 2006; Wang et al., 2010a,b). The sedimentary deposition rate significantly increased between 35.3 Ma and 31.5 Ma in the same basin (Zhang, 2006). The deposition rate of the Fenghuoshan Group in the Hoh Xil region (in the hinterland of the Plateau) increased dramatically at ∼34.5 Ma, and the early strata were strongly folded (Liu et al., 2000; Li, 2002). On the northern Tibet Plateau, the Subei and Jiuxi Basins do not record strata from the time interval between 38 Ma and 33 Ma, and the average magnetic declination in these two basins reveals a clockwise rotation of 18.7° (Gao, 2003; Dai et al., 2005). Furthermore, many studies have determined that rapid uplift of the southern Tibetan Plateau occurred during the Eocene–Oligocene, based on rock thermochronology (Zhong and Ding, 1996; Zhang et al., 2003; Chung et al., 2009; Qu et al., 2009; Xia et al., 2011). From the Eocene to the Oligocene, the Indian–Eurasian plates began their full collision (Patzelt et al., 1996; Wu et al., 2008; Xia et al., 2010). The collision zone itself could not accommodate all of the deformation, thus, forces no doubt propagated to the northern Tibet Plateau, which fits with evidence of deformation and uplift in northern Tibet (Horton et al., 2004; Dupont-Nivet et al., 2004).

After the Early Oligocene (Shang Ganchaigou Fm.), the intensity of deformation in the western Qaidam Basin gradually decreased (Figs. 3 and 4). At this time, the water in western Qaidam deepened and the area of deep lake facies expanded. The thicknesses of the resulting strata increased. This observation coincides with (1) the growth faults and growth strata of the western Qaidam Basin being reduced or ceasing by 15 Ma (Zhou et al., 2006; Yin et al., 2008; Wang et al., 2010a,b), (2) slowing of the crustal shortening in the same basin (Zhou et al., 2006; Liu et al., 2009; Wang et al., 2010a,b), and (3) the non-folded lacustrine strata widely preserved on the inner Tibetan Plateau (Wu et al., 2007).

The second and most intensive tectonic deformation occurred after 15 Ma (Shang Youshashan Fm., Middle–Late Miocene). From 8.2 Ma (Shizigou Fm., Late Miocene–Late Pleistocene), and especially at 2.65 Ma (Qigequan Fm.), many fault developed rapidly in the inner basin, water rapidly withdrew from the basin, and the sedimentary facies sharply changed from lacustrine into alluvial facies. Much of the piedmont strata in the western Qaidam basin were subsequently eroded. These observations indicate that the mountains around the Qaidam Basin uplifted strongly at that time, and the Basin transformed into an intermountain basin. The fault activity intensity increased significantly and the crustal shortening rate of the western Qaidam Basin increased dramatically, with the shortening rate exceeding that of previous periods by 2–3 times. Additional second growth strata and significant unconformities formed, which clearly separate the upper and lower tectonic layers. Furthermore, a large number of non-growth faults and growth faults developed in the upper tectonic layer (Yin et al., 2008; Wang et al., 2010a,b). The average deposition rate in the western Qaidam Basin increased sharply, from 109.1 m/Ma to 151.3 m/Ma (Zhang, 2006). Strong deformation and crustal shortening occurred in many places in northern Tibet, starting in the Late Miocene (Coleman and Hodges, 1995; Turner et al., 1993; Zhong and Ding, 1996; Blisniuk et al., 2001; Zhang et al., 2003; Fang et al., 2004, 2005, 2007). On the southern Tibet Plateau, the average elevation reached 5 km at 9 Ma. And during that period, the southern parts began an E–W extensional collapse under the N–S compression, forming a series of the N–S grabens (Harrison et al., 1992; Garzione et al., 2003; Gao, 2004). At ∼2.6 Ma, an unconformity and/or absence of strata occurred widely in many basins of northern Tibet, such as at the Kunlun Pass, Hexi Corridor, Linxia Basin, and Guide Basin (Cui et al., 1996; Li et al., 1996; Fang et al., 2004, 2005).

In summary, the western Qaidam Basin experienced two periods of intensive tectonic deformation. The first phase occurred between 43.8 Ma and 22 Ma (Middle Eocene–Early Miocene), and reached its peak at about 31.5 Ma (Early Oligocene). The second phase occurred between 14.9 Ma and 0 Ma (Middle Miocene–Present). The recognition of early deformation has confirmed previous suggestions that northern Tibet responded to the collision between the India and the Asia shortly after the collision. However, our results now emphasize that northern Tibet also experienced another phase of deformation and uplift during the late Neogene. This consisted of two stages of tectonic activity that worked together to produce the current Tibetan Plateau.

7. Conclusions

Examination of the pre-Mesozoic basement shows that the Cenozoic evolution of the western Qaidam Basin was controlled by Tibetan Plateau deformation and uplift, which was caused by the ongoing Indian–Eurasia plate collision. The western Qaidam Basin can be divided into southern, central, and northern parts by the XI (Youshi) and Youbei faults. The Cenozoic tectonic evolution consisted of four stages, and the areas covered by water and the resulting sedimentary facies changed regularly with the tectonic activity. The tectonic evolutionary history indicated in the seismic profile suggests that the western Qaidam Basin experienced two phases of relatively strong tectonic deformation during the Cenozoic. The first phase began during the Paleogene and reached its peak at about 31.5 Ma (Early Oligocene). The second phase occurred during the late Neogene (14.9–0 Ma), and this phase was even stronger than the first.

Recognition of this early deformation provides strong evidence that northern Tibet responded directly to the collision of the India–Asia plates shortly after the collision began. However, our results also demonstrate that northern Tibet experienced another phase of shortening and uplift during the late Neogene. The tectonic–sedimentary evolution history of the western Qaidam Basin provides a good record showing that the Tibetan Plateau and its surrounding mountains underwent repeated periods of uplift (Molnar and Chen, 1983). The sub-surface geology from drill hole records and seismic soundings thereby confirm that tectonic stresses from the plate–plate collision affected the tectonic stress field as far away as the western Qaidam Basin.

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