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Tectonic and sedimentary evolution of basins in the northeast of Qinghai-Tibet Plateau and their implication for the northward growth of the Plateau

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Abstract

The northeast of the Qinghai-Tibet Plateau, from the Hoh Xil Basin to the Hexi Corridor Basin, demonstrates a basin-ridge geomorphy that is the result of the long-term uplift of the Qinghai-Tibet Plateau. The geological evolution of the Qinghai-Tibet Plateau is recorded in its associated basins. From the Cenozoic sedimentary filling pattern in the Hoh Xil, Qaidam and Jiuquan Basins, we find that the evolution of these basins is similar: they began as strike-slip basins, evolved into foreland basins, and then to intermontane basins. Foreland basins are the direct result of orogenic activity in the northeast of Qinghai-Tibet Plateau, and can be documented to have formed over the following time periods: 49–23 Ma for the Hoh Xil foreland basin, 46–2.45 Ma for the Qaidam foreland basin, and 29.5–0 Ma for the Jiuquan foreland basin. This northward migration in the timing of foreland basin development suggests that the northeastern part of Tibet grew at least in part by accretion of Cenozoic sedimentary basins to its northern margin.

Keywords: Qinghai-Tibet Plateau; Strike-slip basin; Foreland basin; Hoh Xil Basin; Qaidam Basin; Jiuquan Basin

1. Introduction

The Qinghai-Tibet Plateau has an average altitude of about 5000 m and has a distinct southern boundary at the Himalaya. There are a series of tectonic and geographic features from east to west in the north of the Qinghai-Tibet Plateau. Divided by the Altyn Tagh Fault, the West Kunlun Shan (Shan = mountains in Chinese) and the Tarim Basin are located in the west, while a series of basin-ridge geomorphological systems are located in the eastern part of the Qinghai-Tibet Plateau. These span six latitude zones and are respectively from south to north the Hoh Xil Basin, East Kunlun Shan, Qaidam Basin, Qilian Shan and Jiuquan Basin (Hexi Corridor Basin) (Fig. 1). The average elevation of these basins decreases from south

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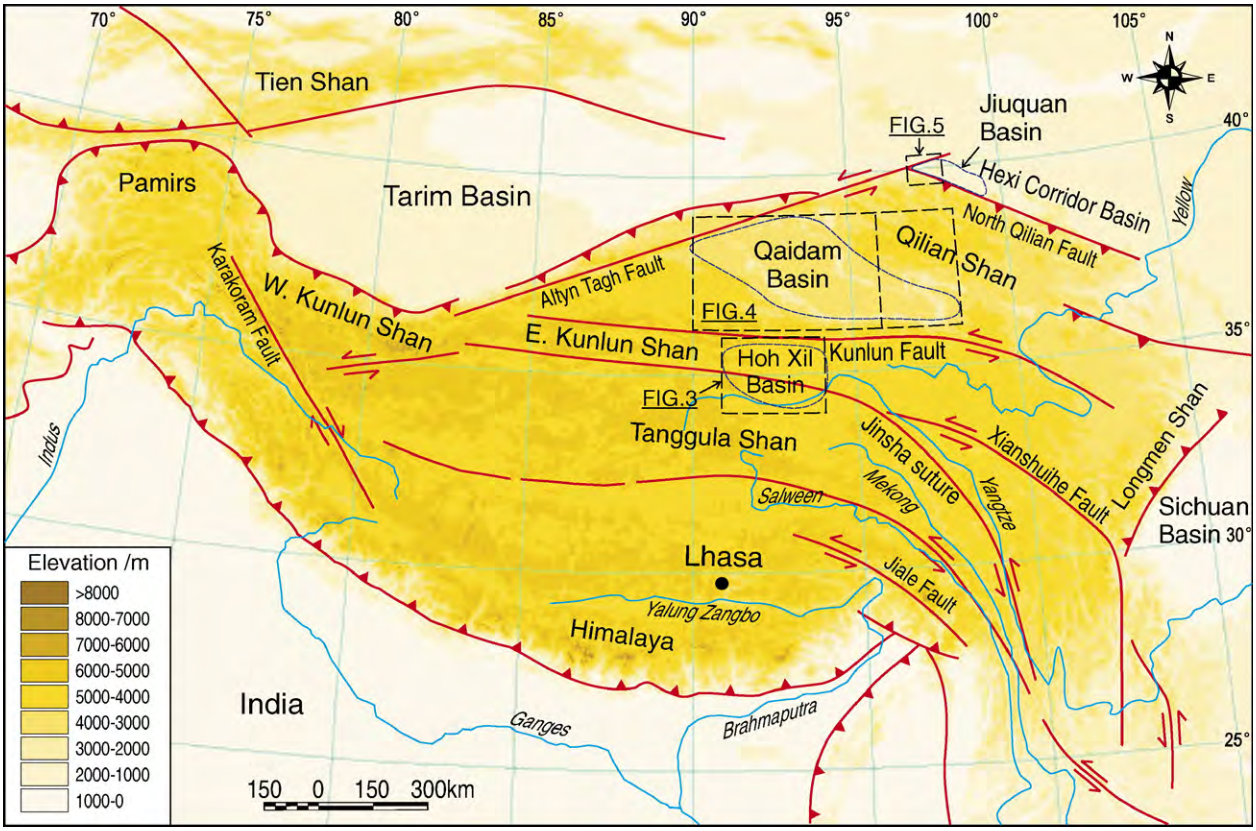

Fig. 1. Sketch of structure in the Qinghai-Tibet Plateau and Cenozoic sedimentary basins in the north of the Plateau.

to north: the height of Hoh Xil Basin is 4600–4800 m, the Qaidam Basin is 2600–2800 m and the Jiuquan Basin is 1000–1400 m.

Sedimentary basin fills record not only the formation history and evolution of a basin, but also the process of tectonic evolution of the adjacent orogens. The unique basin-ridge geomorphology in the northeast of the Qinghai-Tibet Plateau is the result of the tectonic processes that have operated during the building of the Qinghai-Tibet Plateau, and which are also recorded in the sediment filling the basins. However, most previous research has been focused on the tectonic evolution of the region (Tapponnier and Molnar, 1976, 1977; Molnar et al., 1987; Burchfiel and Royden, 1991; Avouac and Tapponnier, 1993; Yin and Nie, 1996; Cui et al., 1999; Zhu et al., 2004) or on paleomagnetic studies (Li et al., 2001; Wu et al., 2002; Dupont-Nivet et al., 2002). Basin analysis is limited to single basins (Chen et al., 1999; Song et al., 2001; Zhao et al., 2001; Yue et al., 2001; Wang et al., 2002; Yue et al., 2003) or even to the stratigraphic correlation between basins (Meyer et al., 1998; Yin et al., 2002). The purpose of this paper is to present a correlation of the tectonic processes that have affected the northeast Qinghai-Tibet Plateau, focusing on the sedimentology of the associated basins.

2. Hoh Xil Basin tectonic and sedimentary evolution

The Hoh Xil Basin formed in the Tertiary and is located in the hinterland of the Qinghai-Tibet Plateau. It has a surface area of 55,000 km^2 and an average elevation of 4800–5000 m. The Kunlun Fault and the Tanggula Shan form its north and south boundary, and the Jinsha suture penetrates the basin's mid-south part in a west–east direction (Fig. 1).

The Hoh Xil Basin is filled mainly by Cenozoic terrigenous clastic sediments. The Tertiary sediments are about 5800 m thick, and comprise terrigenous red sandstones and conglomerates (Fenghuoshan Group and Yaxicuo Group), as well as lacustrine limestones (Wudaoliang Group). On the basis of paleomagnetic dating results (Zhao et al., 2000; Liu et al., 2003), the age of the sequences are determined to be Fenghuoshan Group

(51–31 Ma), Yaxicuo Group (31–30 Ma) and Wudaoliang Group (23–20 Ma) (Fig. 2a). The morphology of Hoh Xil Basin allows each formation to be described (Fig. 3) on the basis of measured lithostratigraphic sections (Liu et al., 2001). The character of the Cenozoic sedimentary fill shows that the depocenter migrated

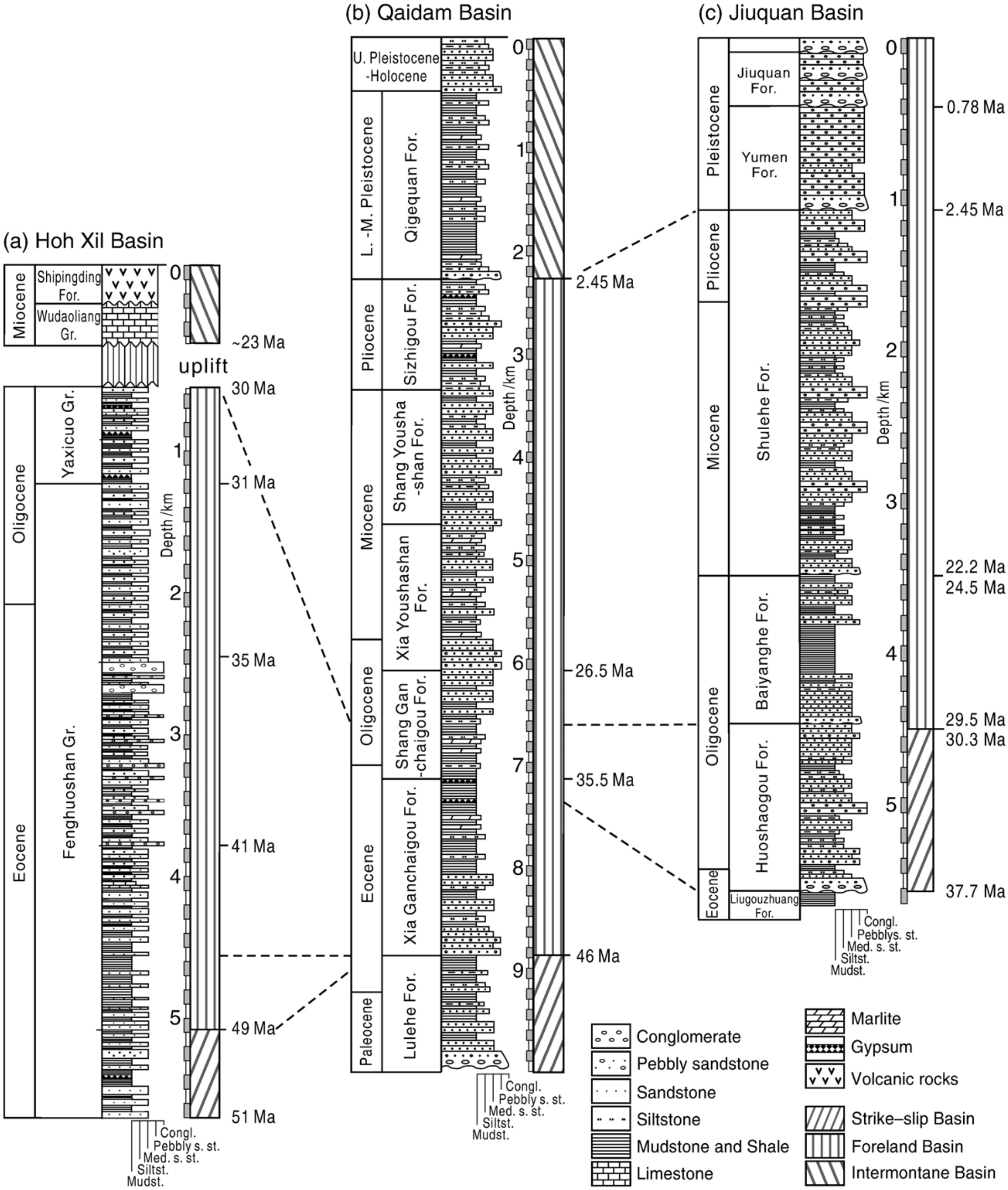

Fig. 2. Correlation of tectonic and sedimentary evolution of the basins in the north of Qinghai-Tibet Plateau.

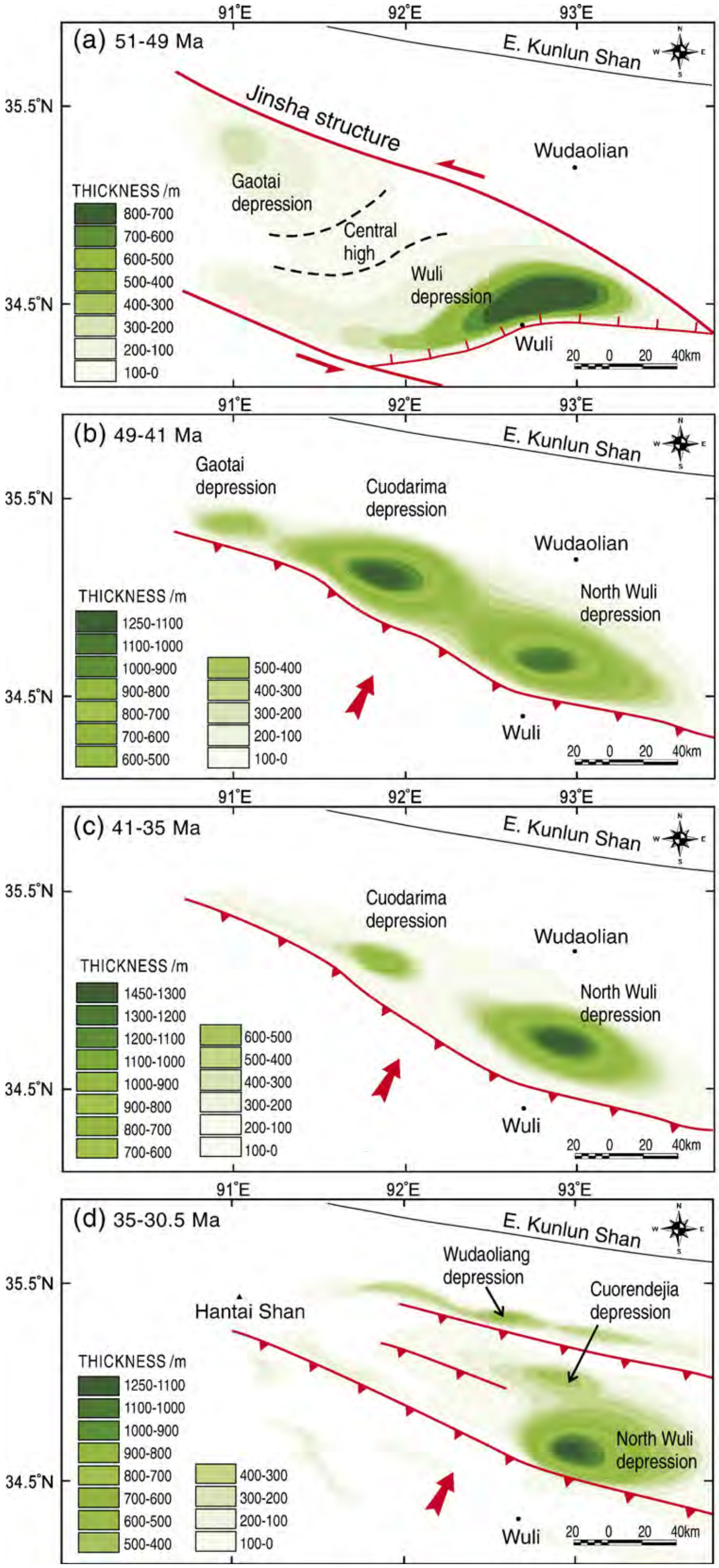

Fig. 3. Controlling-basin structures and stratigraphic isopach line in Hoh Xil Basin (adapted from Liu et al., 2001).

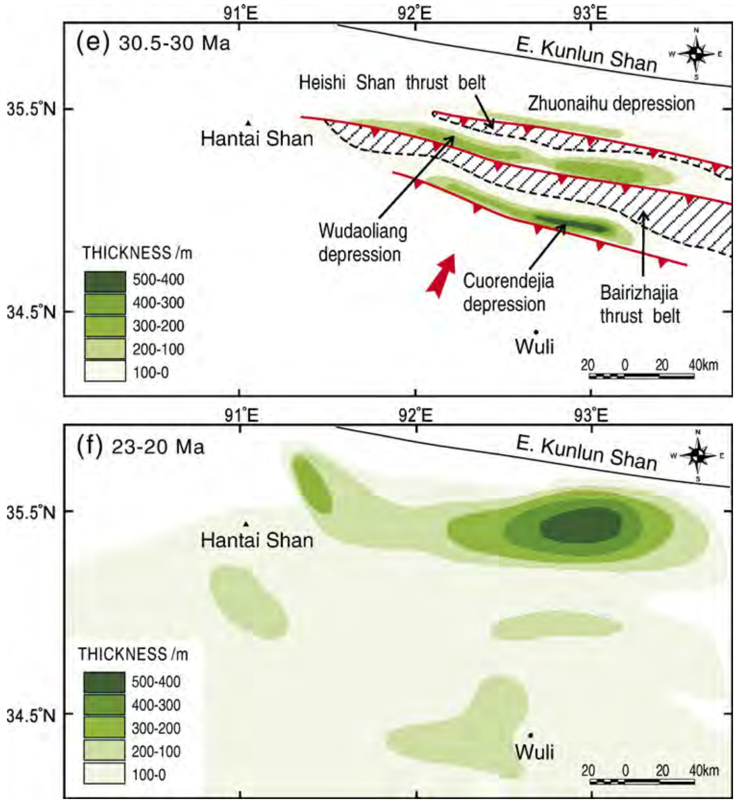

Fig. 3 (*continued*).

northward and three stages of tectonic evolution can be identified.

2.1. Strike-slip and pull-apart basin stage in the Paleocene (51–49 Ma)

During this interval time, the depositional area was localized by the Jinsha Suture, and sedimentary rocks of this age form the lower part of the Fenghuoshan Group, which is mainly made up of sandstone, mudstone, and intercalated gypsum. The basin extended in a west–east direction. A NE-trending submarine high divided the basin into two depositional depressions: the Gaotai Depression in the west and the Wuli Depression in the east. Extension of the depocenter of the Wuli Depression was parallel with the strike of the central high and took on a S-shape, which was tangential to the boundary faults in the north and south. The orientation of the high and depocenter indicates that the basin was controlled by left-lateral faults located to the north and south boundary. Tectonic activity and contemporary subsidence and deposition were controlled by the left-lateral strike-slip movement on the Jinsha Suture. The basin formed in a strike-slip tectonic setting as a pull-apart basin (Fig. 3a).

2.2. Foreland basin stage from the Eocene to Oligocene (49–30 Ma)

During this period, the northern part of the Hoh Xil Basin gradually extended to the north while the southern basin shrank and was uplifted. The depression spread linearly in an east–southeast direction, and the depocenter was located in the southern part of the basin, which took on an asymmetric shape, i.e. deep in the south, and shallow in the north. This character of the basin is consistent with northward thrusting. Three sub-stages are identified within the context of the northward growth.

During the first sub-stage (49–35 Ma) (Fig. 3b,c), the middle part of the Fenghuoshan Group was deposited, with sediments coarsening-upwards from alternating mudstones and sandstones with intercalated limestones in the lower part, and sandstones and conglomerates in the upper part. The depositional area was located between the Gaotai Depression, Cuodarima Depression and the eastern part of the Wuli Depression (Fig. 3b). These three depressions were divided by submarine highs, and the southwestern part of Wuli Depression was uplifted. All of these basins showed that the southern part of the Hoh Xil Basin was uplifted during the Oligocene.

During the second sub-stage (35–30.5 Ma) (Fig. 3d), sandstone and mudstone of the upper part of Fenghuoshan Group and the lower part of the Yaxicuo Group were deposited. In this sub-stage, the Gaotai Depression and Cuodarima Depression were uplifted entirely, but the eastern part of the Wuli Depression was still a depositional area. At the same time, the Cuorendejia Depression and Wudaoliang Depression started to develop and the depositional area of the Hoh Xil Basin spread northward. Depressions on the south of the basin shrank towards the east during the earlier period and two sub-depressions paralleling the strike of the thrust faults formed in the east of the basin. In the later part of the period, a series of small scale depressions appeared, which were orientated in an east–west direction and separated by faults.

The third sub-stage (30.5–30 Ma) (Fig. 3e) saw the upper part of Yaxicuo Group deposited. This is mainly made up of alternating mudstones and sandstones with intercalated gypsolith. In this sub-stage, the eastern Wuli Depression was gradually uplifted, although the Cuorendejia and Wudaoliang Depressions still existed. At the same time, the Zhuonaihu Depression in the north formed, as a result of the formation and northward thrusting of the Heishi Shan thrust belt. The Wudaoliang Depression still existed in the middle part of the basin, and was separated from the Zhuonaihu Depression by the Heishi Shan thrust belt. In the southern part of the basin, the depositional range of the Wuli Depression was localized to the north part of the depression, near the Bairizhajia thrust belt. In this sub-stage, the southern part of the Hoh Xil Basin continually shrank and the northern part extended northward.

2.3. Intermontane lake basin stage in the Early Miocene (23–20 Ma)

As a result of tectonic uplift and denudation, the Hoh Xil Basin experienced hiatus at 30–23 Ma. Subsequently the Wudaoliang Group was deposited widely across the whole of the Hoh Xil Basin, even over the previously uplifted areas. Regionally, the Wudaoliang Group forms an angular unconformity with the underlying Fenghuoshan Group (Eocene–earlier Oligocene) and Yaxicuo Group (earlier Oligocene). An exposure surface, red paleosol, and a basal conglomerate about 20 cm thick can be found at the bottom of the Wudaoliang Group. Above them, there is a package of lacustrine carbonates. Although the Wudaoliang Group is distributed almost across the whole of the Hoh Xil Basin, the thickest sediments (600 m) are at the Kunlun Shan front. In other regions, the depositional thickness was no more than 50 m (Fig. 3f). This variation in depositional thickness shows that there were lower relief areas and only weak tectonic activity in the mountains surrounding the basin, allowing lacustrine sediments to form. From about 20 Ma onwards volcanic rocks were erupted and were distributed widely in the west part of the Hoh Xil Basin and the East Kunlun Shan. Basin evolution ended with northwards thrusting.

3. Tectonic and sedimentary evolution of the Qaidam Basin

The Qaidam Basin is located to the south of the Kunlun Shan, and is separated from the Jiuquan Basin by the Qilian Shan. The Altyn Tagh Fault forms the northwest boundary of the Qaidam Basin. The Cenozoic strata in the basin exceed 15,000 m in thickness (Huang et al., 1996). On the basis of biostratigraphic (CPCTS, 1991) and magnetostratigraphic (Sun et al., 2004) research, strata in the basin can be divided into the following seven formations: Lulehe Formation (60–46 Ma), Xia Ganchaigou Formation (46–35.5 Ma), Shang Ganchaigou Formation (35.5–26.5 Ma), Xia Youshashan Formation(26.5–9 Ma), Shang Youshashan Formation (9–5.3 Ma), Shizhigou Formation (5.3–2.4 Ma) and Qigequan Formation (2.4–0.13 Ma) (Fig. 2b). The morphology of each formation is described (Fig. 4) on the basis of seismic and drill data (QTOFEG, 1990; Shen et al., 1992; Huang et al., 1996). Because the shape of a basin and its sedimentary history can reflect the nature and activity of a basin's boundary structures, we divide the Cenozoic tectonic evolution history of the Qaidam Basin into three stages on the basis of changing characters of the sedimentary fill of the basin.

3.1. Strike-slip basin stage in the earlier period (60–46 Ma)

The sedimentary rocks deposited during this stage are named the Lulehe Formation. The lower part of the Lulehe Formation is made up of brown and fuchsia colored boulder conglomerate and pebbly sandstone. Alternating mudstone and sandstone appear in the middle part of the section and mudstone and calcareous mudstone increase gradually in the upper part. This kind of lithological variation forms an upward-fining sequence. The basin was controlled by two sets of faults, one in the north with a WNW-trend and another in the south with a NNW-trend. The basin was divided by the Z-shaped Niubiziliang Rise into two parts: the Mangya Depression in the west and the Center Depression in the east. The thickest depocenter was located to the east of the rise and it also forms a series of Z-shaped structures. The spreading direction of the depressions and the basin

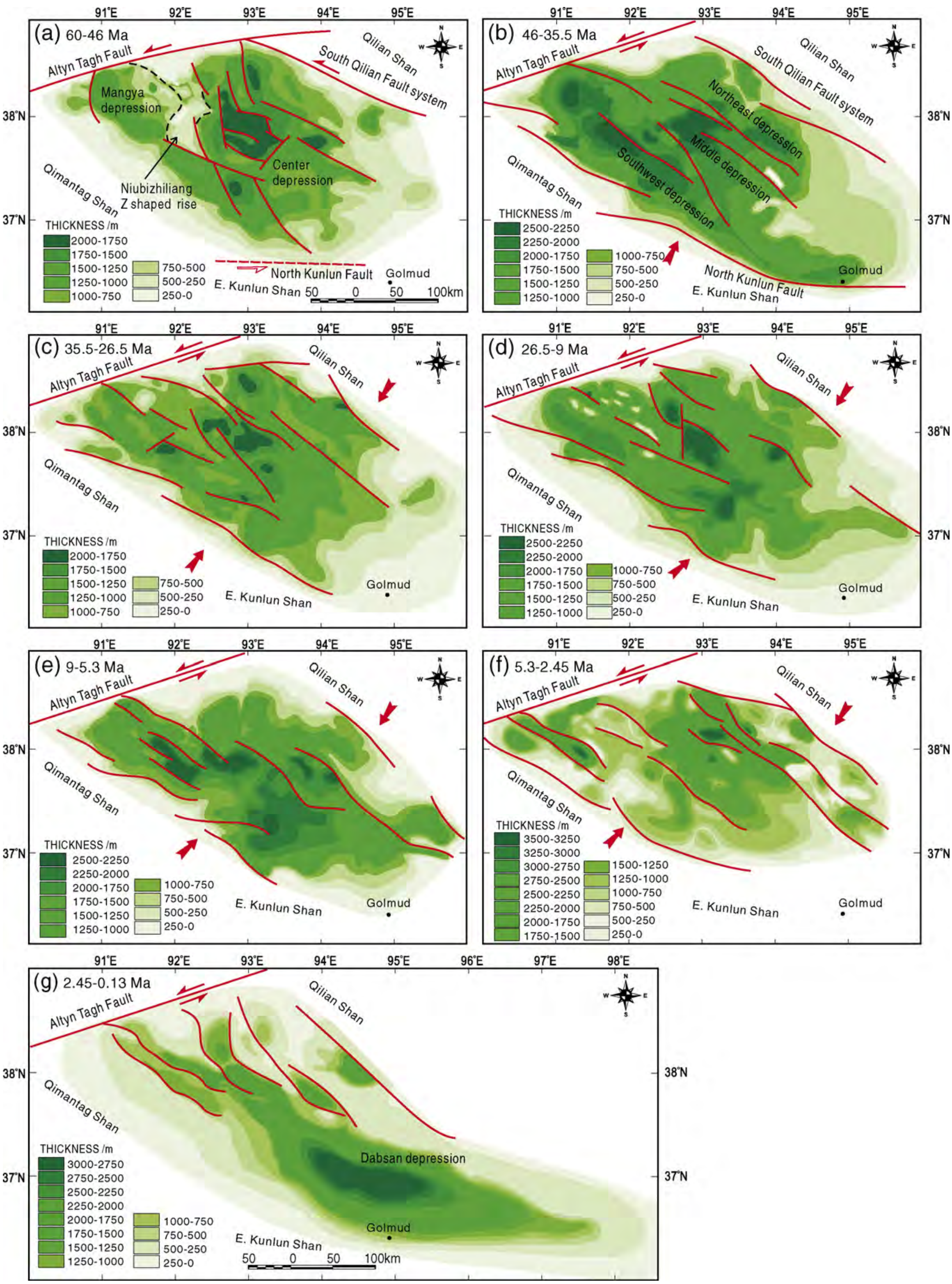

Fig. 4. Controlling-basin structures and stratigraphic isopach line in the Qaidam Basin (adapted from QTOFEG, 1990; Huang et al., 1996).

controlling faults are tangential to the South Qilian Fault system, the North Kunlun Fault, and the Altyn Tagh Fault (Fig. 4a). This shows that the sedimentary fill of the Qaidam Basin was controlled by the Altyn Tagh, South Qilian, and North Kunlun left-lateral strike-slip faults before 46 Ma.

3.2. Foreland basin development (46–2.4 Ma)

Five units of sedimentary rocks deposited during this stage: the Xia Ganchaigou, Shang Ganchaigou, Xia Youshashan, Shang Youshashan and Shizhigou Formations. The depressions of the basin are oriented in an ESE-trend, which was parallel to the strike direction of the northeastern and southwestern boundary faults of the basin. Additionally, the character of seismic reflections within the basin (QTOFEG, 1990) shows that the sedimentary filling of the basin was controlled by thrust faults at its northeastern and southwestern margins. Noticeable characters in the western part of the basin near the Altyn Tagh Fault are alternating low rises and shallow depressions. These characters indicate that the Altyn Tagh Fault began to control the fill morphology in the west of the Qaidam Basin at this stage (Huang et al., 1996). However, the range and intensity of the faulting cannot be compared with those produced by the thrust faults along the northeastern and southwestern boundaries. The basin was a compound foreland basin, composed of two foreland basins in the northeastern and southwestern areas, and was produced by opposite thrusting along the northeastern and southwestern boundary faults. Along the northwest edge of the basin, left-lateral strike-slip activity took place at the same time. Four sub-stages can be identified on the basis of the range and deformation character of the Qaidam Basin depocenter location.

a. The first sub-stage (46–35.5 Ma) (Fig. 4b). During this interval the Xia Ganchaigou Formation was deposited, being comprised of conglomerate and sandstone in the lower part, and mudstone intercalated with siltstone in the middle and upper parts. Three depressions appeared in the southwest, middle and northeast of the basin. However, the southwest depression in front of the Qimantag Shan was the largest, which reflected the initiation of the Kunlun-Qimantag Thrust northward that subsequently became the basin-controlling fault.
b. The second sub-stage (35.5–26.5 Ma) (Fig. 4c). During this interval the Shang Ganchaigou Formation was deposited, and formed an upward-coarsening sequence of mudstone in the lower part, changing to sandstone in the upper part. The area of the middle depression was largest during this sub-stage. The activity weakened in the southern depression, but strengthened in the northern depression, which shows that active thrust faulting took place at the southern front of the Qilian Shan at the northeastern edge of the basin.
c. The third sub-stage (26.5–5.3 Ma) (Fig. 4d–e). The Xia Youshashan and Shang Youshashan Formations were deposited during this sub-stage, and are made up of sandstone, mudstone and minor conglomerate and marl. Deposition extended eastward, and depressions in the west of the basin began to reduce, suggesting that influence from the Altyn Tagh Fault increased.
d. The final sub-stage (5.3–2.4 Ma) (Fig. 4f). Sediments deposited during this sub-stage are named the Shizhigou Formation, and are coarser in the west of the basin and finer in the middle and east. In the west of the basin, near the Altyn Tagh Fault, sedimentary rocks comprise conglomerate with sandstone interlayers. However, in the middle and east, the main rock types were sandstone and mudstone. This kind of lithologic distribution reflected the fact that the basin was affected intensively by the Altyn Tagh Fault.

3.3. Intermontane basin stage in the later period (2.45–0 Ma)

The sediments of this stage are named the Qigequan Formation. They are clastic sedimentary rocks that unconformably overlie Tertiary strata. The Qigequan Formation is distributed widely and almost covered the whole basin. The grain size of the sedimentary rocks changed from finest in the depocenter to coarser in front of the surrounding mountainous areas. During this sub-stage, the depocenter migrated southeastwards to the Dabsan Depression, which is oriented in a WNW direction. The subsidence range of the depression was about 2500–3200 m (Fig. 4g), being deepest in the lower and middle Pleistocene. Seismic reflection data show that the boundary faults had no control on basin character. Sedimentary rocks were thicker in the center of the basin, but thinner in other areas and overlapped earlier sedimentary rocks. The northeastern and southwestern boundaries were topographical boundaries due to earlier tectonic activity, but were not active faults at this time. However, uplift took place at the west edge of the basin due to activity the Altyn Tagh Fault.

4. Tectonic and sedimentary evolution of the Jiuquan Basin

The Jiuquan Basin is located at the western end of the Hexi Corridor, north of the Qinghai-Tibet Plateau; it is a foreland basin to the modern plateau. The Altyn Tagh Fault forms the northwest boundary of the Jiuquan Basin, and the Qilian Shan fold and thrust belt forms the southern boundary and separates the basin from the Qaidam Basin. On the basis of paleomagnetic data (Huang et al., 1993; Cao, 1997) strata in the basin can be divided into the Huoshaogou (37.7–30.3 Ma), Baiyanghe (29.5–24.5 Ma), Shulehe (22.2–2.45 Ma), Yumen (2.45–0.78 Ma) and Jiuquan Formations (0.78–0.13 Ma) (Fig. 2c). The morphology of the Jiuquan Basin can be described on the basis of seismic reflection profiles and drill data from Yumen Oil Field Branch Company surveys (1973–2004) (Fig. 5). Two stages of basin development can be identified on the basis of the sedimentary character and fill of the Jiuquan Basin.

4.1. Strike-slip basin stage (37.7–30.3 Ma)

Sedimentary rocks of the Huoshaogou Formation form an upward-coarsening sequence: reddened conglomerate and sandy mudstone in the lower part; sandstone, sandy mudstone intercalated with fine conglomerate in the middle part; and sandstone and fine conglomerate in the upper part. There were two depressions, the Hongliuxia and Chijin Depressions, distributed along the southwestern edge of the Altyn Tagh Fault (Fig. 5a). The Huoshaogou Formation was not deposited north of the Altyn Tagh Fault.

The distribution of the depocenters of the Hongliuxia and Chijin Depressions, near the Altyn Tagh Fault, shows that differential shortening took place in the northwestern part of the basin, and a related reverse fault system was active along an ESE–WSW direction, operating against a background of eastward to east–northeastward left-lateral strike-slip motion on the Altyn Tagh Fault.

4.2. Thrust foreland basin stage (29.5–0 Ma)

During this stage, the strike of the basin was parallel with the strike of the North Qilian thrust fault, and the depocenter migrated gradually from the center of the basin to the front of the mountains to the south. The strata are composed of several coarsening-upward sequences, which reflect the fact that the basin was a foreland basin controlled by the faults along the thrust front of the North Qilian Shan. There are three unconformity interfaces in this stage: between the Baiyanghe and the Huoshaogou Formations (depositional break for 0.8 my), between the Shulehe and the Baiyanghe Formations (depositional break for 2.3 my), and between the Shulehe and the Yumen Formations (depositional break for 1.35 my). On the basis of the fill morphology, the sedimentary fill and tectonic character, this stage can be divided into three sub-stages:

a. The first sub-stage (29.5–24.5 Ma). The Baiyanghe Formation was deposited during this period, as a series of sandstones and mudstones, in upward-coarsening sequences. The depressions of the basin are orientated in a west–northwest direction, and were parallel to the spreading direction of the Qilian Shan thrust structures (Fig. 5b). The Baiyanghe Formation overlapped westward on the southern part of the Althyn Tagh Fault. This sedimentary character reflects the fact that the nappe structure zone existing in the earlier Oligocene had stopped motion and uplift as the southern area near the Qilian Shan began to subside. An approximately 100-m-thick set of conglomerates distributed at the front of the Qilian Shan indicates that the Qilian Shan were eroded and possibly uplifted quickly and became the control on basin structure of the West Jiuquan Depression. At the same time, the Altyn Tagh Fault, which had controlled the basin in the earlier Oligocene weakened or even stopped activity. From the stratigraphic isopach map of the formation on the basis of the section survey, drill and seismic data, we find that the extension direction of the isopach of the Baiyanghe Formation is in an east–southeast direction and is parallel with the strike direction of the Qilian Shan.
b. The second sub-stage (22.2–3.8 Ma). The strata deposited in this period, the Shulehe Formation, are very widely distributed, even in the northern area near the Althyn Tagh Fault. At the same time, the basin extended eastward, westward and northward. The orientation of the depocenter was parallel with the strike of the thrust faults in front of the North Qilian Shan, which reflects the fact that intense activity along the North Qilian thrust zone had became the main source of sediment.

   Limited by the poor results of shallow seismic reflection and the absence of the drill log data, we can only draw the sedimentary isopach map of the Shulehe Formation and Quaternary sediments in this basin (Fig. 5c). As the thickness of the Shulehe Formation was almost twice that of the Quaternary sediments, and lateral thickness variations of Quaternary sediment are smaller than those of the Shulehe Formation, the stratigraphic isopach character of the sediments from the Miocene to Quaternary mostly reflects the relative thickness variability of the Shulehe Formation.
c. The third sub-stage (2.45–0 Ma). The sedimentary rocks deposited during this sub-stage are the Yumen

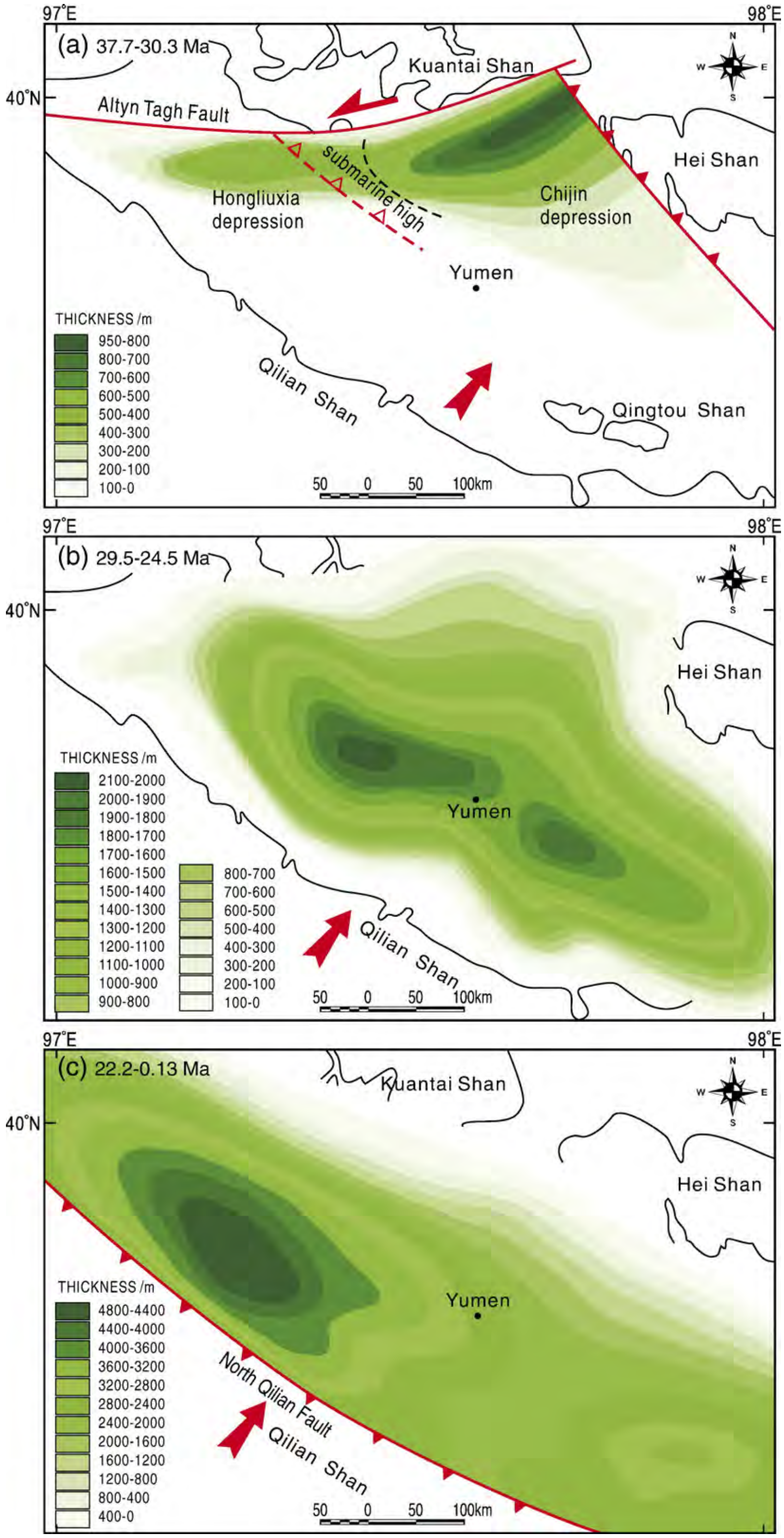

Fig. 5. Controlling-basin structure and stratigraphic isopach line of the Jiuquan Basin.

and Jiuquan Formations. The depositional area was mainly distributed to the east of the Altyn Tagh Fault and north of North Qilian Fault. The depocenter was located in front of the Qilian Shan, and the sediment deposited was mainly cobblestone. However, sandstone interlayers increased northward.

5. Basin-mountain evolution in northeast Qinghai-Tibet Plateau

From the above discussion of the sedimentary evolution of the Hoh Xil, Qaidam and Jiuquan Basins, we show that the evolution sequences of the three basins are similar, featuring an early strike-slip stage, a foreland basin stage and a terminal stage intermontane basin. However, formation of the three basins were progressively later from south to north (Fig. 2).

The time of change from the strike-slip to foreland basin in the Hoh Xil Basin was at 49 Ma, where the foreland basin was consistent with northward thrusting. Differential elevation and subsidence took place at 23 Ma. The Qaidam Basin ended its extending strike-slip stage at 46 Ma, after which the foreland basin formed and was controlled by the left-lateral strike-slip movement of the Altyn Tagh, South Qilian and North Kunlun Faults. The intermontane basin phase began at 2.45 Ma. The extruding strike-slip stage of the Jiuquan Basin started at 37.7 Ma, which was the result of left-lateral strike-slip movement of the Altyn Tagh Fault, so that the basin became a foreland basin from 29.5 Ma to present. The basin evolution of the northeast Qinghai-Tibet Plateau reflects the propagation of thrusting related to the plateau's northward growth.

6. Conclusions

GPS data (Chen et al., 1998, 2000; Bendick et al., 2000; Shen et al., 2000; Zhang et al., 2002) show that the area at the northeast of the Qinghai-Tibet Plateau is moving northward, with a progressively decreased rate. The dynamic force originates from the northward motion of the India plate and is reflected in the folding, uplift and thrusting of sedimentary basins around the edge of the Qinghai-Tibet Plateau. The evolution of the foreland basins to the north of the Qinghai-Tibet Plateau represents the uplift history of the northern Plateau.

The Cenozoic tectonic evolutions of the basins in the northern part of the Qinghai-Tibet Plateau show progressive northward migration. The foreland basins from south to north respectively were: the Hoh Xil foreland basin (49–23 Ma), the Qaidam foreland basin (46–2.45 Ma) and the Jiuquan foreland basin (29.5–0 Ma), reflecting the fact that the area east of the Altyn Tagh Fault and the north of the Qinghai-Tibet Plateau grew gradually during the Cenozoic. Although the influence of the Altyn Tagh Fault over the Qaidam and Jiuquan Basins started during the Oligocene, the intensity and the character of the sedimentary rocks are different. The influence of the Altyn Tagh left-lateral strike-slip fault on the Qaidam Basin increased continually, and the structural highs and depressions formed during an earlier stage, compared to the differential elevation and subsidence events in the Qaidam Basin. In the Jiuquan Basin, the Altyn Tagh Fault controlled basin faulting in the earlier Oligocene (37.7–30.3 Ma), and fault activity decreased and even stopped during the Late Oligocene to late Pliocene (29.5–2.45 Ma). The temporal and spatial variation of the influence of the Altyn Tagh Fault was related to the rate of motion of the fault, and also to the overthrust movement of the east wall of the Altyn Tagh Fault. The overthrusting resulted directly in the differential northward movement of the east wall of the Altyn Tagh Fault. The northward growth of the Qinghai-Tibet Plateau was the result of the successive northward thrusting. The left-lateral strike-slip movement of the Altyn Tagh Fault, lead to different morphostructure features forming in the eastern and western areas near the fault zone, and also provided dynamic force to the northwestward growth of the eastern end of the Altyn Tagh Fault.

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