Cenozoic tectonic development of the Qaidam basin in the northeastern Tibetan plateau

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ABSTRACT

The Qaidam basin constitutes a major portion of the northeastern Tibetan plateau, and the understanding of its tectonic development will help decipher how the Tibetan plateau grew. This study presents some key subsurface data, in conjunction with analysis of stratigraphic and sedimentary evolution, to reconstruct Cenozoic tectonic history of the Qaidam basin. It is shown that Late Cretaceous–Paleocene deposits of the southwestern Qaidam basin can be well correlated with their counterparts of the southwestern Tarim basin, indicating that they were in a single depositional basin during that period of time. The Qaidam basin commenced subsiding in compression in the Eocene, and subsequently evolved into an independent basin since the Miocene. The main depocenter was noticeably persistent in the middle of the basin in the Tertiary, although it shifted to the east during the Quaternary. Based upon spatial stratigraphic correlation and restoration of sedimentary processes, it is surmised that there existed a proto-Qaidam basin in the Eocene–Oligocene, with the Suhai and Kumukol basins being its original northern and southern margins, respectively. The Suhai and Kumukol basins were then isolated from the Qaidam basin as a result of basinward thrusting in marginal areas. It is argued that the Qaidam basin was generated as a result of crustal buckling or folding, and it in practice manifested itself as a synclinal depression. The crustal folding model can well account for a number of observations: localization of depocenter in the middle of the basin, nearly concomitant deformation on the south and north sides of the Qaidam basin, occurrence of major high-angle reverse faults at the basin margins, and tectonic development of adjacent intermontane Suhai and Kumukol basins. It is further shown that the western Qaidam basin experienced three distinct stages: the first-stage was characterized by a simple synclinal depression; the second-stage was marked by development of reverse fault at inflection points of the mega-fold and continued subsidence in middle of the basin; and third-stage was featured by intrabasinal deformation and uplift. The eastern Qaidam basin underwent diverse evolution owing to differential regional stress field. A tectonic model is advanced accordingly to illustrate the Cenozoic tectonic development of the Qaidam basin.

Key words: Qaidam basin, northeastern Tibetan plateau, crustal folding; tectonics, Cenozoic

INTRODUCTION

The Tibetan plateau was generally accepted to have formed as a result of collision of the Eurasian and Indian continents around 50 Ma (Patriat and Achache, 1984), but how it vertically grew and laterally expanded has been a matter of debate (Tapponnier et al., 1986; Houseman and England, 1993). Cenozoic tectonics of the northern margin of the Tibetan plateau is considered the consequences of far-field effect of continued Eurasia–India convergence (Tapponnier et al., 2001). Previous studies focused primarily on crustal and lithospheric deformations of structural belts, such as the Karakorum (Searle, 1996, Lacassin et al., 2004), the eastern Kunlun (Burchfiel et al., 1989b; Van der Woerd et al., 1998; Mock et al., 1999; Jolivet et al., 2003; Fu et al., 2006), the Altyn Tagh fault (Peltzer et al., 1989; CSBS, 1992; Meyer et al., 1998; Sobel et al., 2001; Yin et al., 2002; Cowgill et al., 2003; Liu et al., 2007), and the Qilian Shan (Tapponnier et al., 1990; Ding et al., 2004;).

The Qaidam basin constitutes a considerable portion of the northeastern Tibetan plateau, and is bounded on all sides by active faults and structural belts (Fig. 1). The Qaidam basin was regarded to have originated from flexural subsidence duo to basinward thrust displacements of the eastern Kunlun on the south and the southern Qilian on the north (Gu and Di, 1989; Wang and Coward, 1990; Tapponnier et al., 1990; Meyer et al., 1998), and thus expresses itself as a huge intermontane basin. Hsü et al. (1988) postulated that the Qaidam basin was formed in a back-arc setting, and floored with oceanic crust. A number of studies have been conducted in an attempt to unravel tectono-sedimentary development of the Qaidam basin (Hsü et al., 1988; Wang and Coward, 1990; Zhu et al., 1994; Huang et al., 1996; Mètivier et al., 1998; Xia et al., 2001), but arrived at different conclusions. Xia et al. (2001) thought that the Qaidam basin experienced two-stage evolution, with the first-stage developing in an extensional setting in the early Tertiary and the second-stage featured by strong basin inversion. In contrast, most other studies showed that the Qaidam basin developed in contractional settings throughout the Cenozoic, and was controlled predominantly by basinward displacement of bounding fold-and-thrust belts on both north and south sides (Gu and Di, 1989; Song and Wang, 1993; Chen et al., 1999; Yin et al., 2002). The Qaidam basin was filled with clastic successions with thickness varying from 3 km in margins up to 15 km in its middle (Gu and Di, 1989), but provenances and dispersal processes of the sediments are debated. Mètivier et al. (1998) thought that sediments were mainly sourced from adjacent rising structural belts, and the depositional processes of the Qaidam basin was described as a “bathtub infilling”. In contrast, Wang et al. (2006) conjectured that most of the sediments were transported into the basin far from the western Kunlun through a paleo-river, which was subsequently eliminated as a result of left-lateral faulting of the Altyn Tagh fault. $^{40}Ar/^{39}Ar$ dating of detrital muscovites is recently used to constrain the sources of basin infills, and the results show that potential provenances would be the Altyn Tagh, Qiman Tagh, Nan Shan, and presumably a far western source (Rieser et al., 2005, 2006).

Although Cenozoic Qaidam basin has been extensively studied, there still remain lots of questions unresolved. One of the prominent uncertainties is what caused the subsidence of the basin. This study presents some key subsurface data, including basin-scale geological profiles, isopach maps of main stratigraphic units, and local seismic sections, to deal with tectonic development of the Qaidam basin. Our study argues that the Qaidam basin was initiated as a consequence of lithospheric or crustal buckling in horizontal compression, and in particular, the western Qaidam basin underwent three-stage evolution. The buckling model can well account for Cenozoic tectonic subsidence and depositional processes of the Qaidam basin, as well as a number of geological observations, which are in conflict with previous models.

REGIONAL GEOLOGY

The Qaidam basin is one of major Cenozoic oil-bearing basins of China (Gu and Di, 1989; Huo, 1990; Wang and coward, 1990; Tang et al., 2000), and relevant explorations have yielded a wealth of information about its internal structures, stratigraphy, and depositional history. The present-day Qaidam basin covers a rhomb-shaped area of ~120,000 km^2, and have an elevation of

~3000 m (Fig. 2). However, original framework and position of the basin are not well understood due to late Cenozoic strong crustal shortening (Burchfiel et al., 1989a; Tapponnier et al., 1990) and large-magnitude NE-directed displacement (Wang et al., 2006; Liu et al., 2007). Few drilling holes arrived at basement rocks in the middle part of the Qaidam basin, and thus, it has been uncertain about the basement nature of the basin, especially in the western Qaidam basin. Proterozoic crystalline rocks crop out in adjoining mountains, such as the Dakendaban Group in the southern Qilian (or called as the Nan Shan), which might represent the metamorphic basement of the basin. Early Paleozoic Qaidam basin was either regarded as an accretionary complex (Hsü et al., 1995) or interpreted as a magmatic arc system (Gehrels et al., 2003). Early Paleozoic suture zones have been recognized in the northern Qilian Shan (Xu et al., 2000; Xia et al., 2003), the northern edge of the Qaidam basin (Yang et al., 2002), the Altyn Tagh (Sobel and Arnaud, 1999), and the eastern Kunlun (Yang et al., 1996; Bian et al., 2004), indicating that the northeastern Tibetan plateau was made up of mosaic terranes that was once amalgamated at the end of the early Paleozoic. Late Paleozoic saw a period of widespread marine deposition in the Qaidam basin, as particularly characterized by Carboniferous shallow-marine limestone that can be well correlated with its counterparts in the Tarim basin to the west (Meng et al., 2001). The Upper Permian, together with the whole Triassic, is missing in the Qaidam basin, and their absence is ascribed to the Indosinian shortening event, presumably related from closure of Paleo-Tethys (Tang et al., 2000; Roger et al., 2003).

Mesozoic strata are mostly composed of Jurassic and Cretaceous continental strata in the Qaidam basin. It is controversial about tectonic settings for Mesozoic basin evolution. The Qaidam basin was considered to have formed in response to Mesozoic contractional deformation of the Qilian Shan (Ritts and Biffi, 2001), and subsided as a moderately flexural basin (Zhou et al., 2003). Other studies, however, argued that both the Qaidam basin and adjoining regions evolved in an extensional setting (Tang et al., 2000; Chen et al., 2003). Some seismic sections in the northern Qaidam basin display that the Lower–Middle Jurassic deposition was clearly controlled by normal listric faults (Liu et al., 2004). The Upper Jurassic is mostly missing, whereas Cretaceous sedimentation occurred not only in the north but also in the southwest of the Qaidam basin. The widespread absence of Upper Jurassic strata might imply a crustal shortening event that led to the inversion of Early–Middle Jurassic extensional basins and the regional uplift of the

Qaidam basin. Crustal extension was possibly again established in Cretaceous time (Xia et al., 2001), and Late Cretaceous marine invasion occurred in the southwest of the Qaidam basin (Meng et al., 2001). Tectonic scenarios of the Qaidam basin are still poorly understood and need to be investigated.

Present-day structural framework and topographic expressions of the Qaidam basin and adjacent areas are primarily established in late Cenozoic (Fig. 2). The Qaidam basin is bounded on the north by a number of N-dipping reverse faults and on the south by S-dipping reverse faults (Fig. 3). These reverse faults have displaced Proterozoic–Mesozoic rocks over Cenozoic sequences as young as the Pleistocene, implying that they are still active in the Quaternary. The left-lateral Altyn Tagh fault and right-lateral Wenquan fault develop on the northwestern and eastern sides of the Qaidam basin, respectively, and they are thought to have accommodated the northward indentation of the Qaidam basin (Dupont-Nivet et al., 2004; E. Wang et al., 2004). Cenozoic successions of the western Qaidam basin has experienced folding and faulting, as clearly displayed by surface traces of fold layers (Fig. 2) and seismic profiles. In contrast, the eastern Qaidam basin underwent little internal deformations. It is worth noting that there exist two subordinate basins, the Suhai basin to the north and the Kumukol basin to the south of the Qaidam basin, respectively (Fig. 3). Evolution of the two basins appears to have been associated with the Qaidam basin, and is to be addressed in details.

STRATIGRAPHY

Cenozoic lithostratigraphy of the basin has long been established, but ages of individual formations are not well constrained, in particular, for lower Tertiary units (Xia et al., 2001; Qiu et al., 2003). Previous studies used to simply correlate lithostratigraphic units with chronostratigraphic epochs because of the lack of absolute age constraints. Two recent studies present two similar Cenozoic stratigraphic sequences for the Qaidam basin (Rieser et al., 2005; Zhou et al., 2006), which indicate the age intervals of individual lithostratigraphic units. The new Cenozoic stratigraphy is mainly based upon lithofacies sequences with abundant fossils of different types, such as ostracods, spores, and pollens, in the western Qaidam basin where Cenozoic secessions are dominated by finer-gained fluvial–lacustrine deposits (Huo, 1990). Typical fossil associations can put constraints upon the ages of lithostratigraphic units.

Magnetostratigraphic studies have been recently carried out to put tight constraints upon ages of lithostratigraphic units of the Qaidam basin (Sun et al., 2005). Basinwide correlations of Cenozoic strata are achieved by tracing reflection horizons of boundaries of stratigraphic units in conjunction with borehole data (Zhou et al., 2006)). Fig. 4 represents a generalized stratigraphic chart of the Qaidam basin and adjacent Suhai and Kumukol basins. We also make a comparison of stratigraphic sequences between the southwestern Qaidam and southwestern Tarim basins (Fig. 5), which shows that the two regions share identical stratigraphic evolution from late Proterozoic to Cenozoic times. Striking is that the two regions received marine deposits from Late Cretaceous to Paleocene times (Tang et al., 1989; Hao et al., 1998; Meng et al., 2001), thus indicating that they must be in the same depositional area during that time interval.

SEDIMENTOLOGY

Cenozoic sedimentary successions in the Qaidam basin are composed predominantly of alluvial, fluvial, and lacustrine deposits, and display marked facies variations in space and time (Wang and Coward, 1990). We are not going to investigate sedimentation in detail in this paper, but provide an overall description of sedimentary facies and their brief interpretations.

Lulehe Formation:

The Lulehe Formation represents the earliest deposits of Cenozoic successions that rest unconformably over the underlying units of differing ages. Conglomeratic lithofacies are mostly developed in the northern margin of the Qaidam basin, and present in basal portion of the formation. Conglomerate is thick-bedded matrix- and clast-supported, and consists primarily of metamorphic gravels (Fig. 6a). Paleo-currents are restored according to pebble imbrications, indicating that gravels must have been sourced from the Qilian Shan in the north. Conglomeratic lithofacies pass upwards into finer facies such as sandstone and siltstone. The Lulehe Formation in other parts of the Qaidam basin, however, is dominated by sandstone and siltstone, particularly in the west. The conglomeratic facies are interpreted as debris-flow deposits in alluvial environment on account of their massive structure, whereas the sandstone and siltstone facies resulted from fluvial deposition. The gray-colored fine-grained facies in the western Qaidam basin are considered as products of lacustrine sedimentation. The Lulehe Formation only occurs in the west of the basin, pinching out toward the east (Fig. 7a). Several depocenters can be discerned according to spatial variations of thickness, but the main depocenter, called the Yiliping depression, is located in the middle of depositional area (Fig. 7a). In practice, the Lulehe Formation also occurs in the Suhai basin to the north (Fig. 3), and is characterized by proximal lithofacies similar to those in the northern Qaidam basin (Fig. 4). The similarity in lithofacies implies that the Suhai basin was presumably an integrated part of the proto-Qaidam basin in the Eocene.

Xiaganchaigou Formation

The Xiaganchaigou Formation is usually divided into two Members, with the lower Member dominated by coarse-grained facies like conglomerate interlayered with sandstone and mudstone (Fig. 6b), and the upper Member characterized by fine-grained facies such as dark-colored mudstone and muddy limestone. Dark-colored fine-grained facies of the upper Member mainly occur in the western Qaidam basin. The coarse-grained facies of the lower Member are interpreted as fluvial deposits. Dark fine-grained facies of the upper Member in the western Qaidam basin are thought to form in lacustrine setting (Fig. 6c), and serve as source rocks for generation of oil and gas in the Qaidam basin (Huo, 1990). The lower Member displays similar spatial distribution and facies zonation to those of the underlying Lulehe Formation, and its main depocenter was basically coincident with previous one (Fig. 7b). The upper Member, however, expanded significantly in area, propagating to the east.

Shangganchaigou Formation

The Shangganchaigou Formation is characterized by red-colored coarse-grained facies like conglomerate and sandstone at basin margins (Fig. 6d), which are interpreted as alluvial-fluvial deposits. In contrast, fine-grained sandstone, siltstone/mudstone, and muddy limestone are dominant in the middle of the basin, representing lacustrine environment. The isopach map of the Shangganchaigou Formation indicates that the Yiliping depression was persistent in the middle part of the basin, with its thickness up to 2000 m (Fig. 7c).

Xiayoushashan Formation

The Xiayoushashan Formation is similar to the underlying Shangganchaigou Formation in both spatial facies variations and localization of main depocenter (Fig. 7d). Coarse-grained facies occurs mainly along the present-day basin margin, such as massive conglomerate and thick-bedded coarse- and medium-grained sandstones. It is worth noting that conglomeratic layers become more pronounced along the northwest boundary or in front of the Altyn Tagh.

Fine-grained facies are dominant in the middle part of the basin, such as thin-bedded siltstone, mudstone, and limestone, as revealed by borehole cores. The coarse-grained facies associations are interpreted as fluvial deposits, representing proximal sedimentation of the basin, whereas the fine-grained facies associations are indicative of distal lacustrine deposition in the basin center. The proximal coarse-grained facies fairly defined the basin boundary, and suggested that the Qaidam basin began shrinking. The main depocenter kept developing in the middle of basin, with thickness up to 2500 m (Fig. 7d).

Shangyoushashan Formation

The Shangyoushashan Formation shares the same spatial facies zonation as the Xiayoushashan Formation, as characterized by coarser facies occurring along the present-day basin edge and the finer facies dominating the middle of the basin. However, differences do exist. Coarse-grained facies got more and more pronounced at basin boundaries, and propagated into basin interior considerably. Lacustrine dark mudstone became less developed in the Shangyoushashan Formation compared with the Xiayoushashan Formation in the middle of the basin, and instead, purple-colored fine-grained sandstone and siltstone got predominated, indicating that river floodplain sedimentation was prevailing. As indicated by isopach map (Fig. 7e), the Yiliping depression continued developing in the middle of the basin, with thickness up to 2500 m, whereas some subordinate depocenters came into being along the northern and southern margins of the basin.

Shizigou Formation

Although dominated by conglomeratic deposits along basin margins, the Shizigou Formation is primarily composed of gypsum, carbonaceous mudstone, and yellowish siltstone/mudstone. The main depocenter became less distinguished and began developing several depocenters (Fig. 7f). In the western Qaidam basin, sedimentation of the Shizigou Formation was obviously coeval with contractional deformation, and its cross-sectional geometry expresses itself as typical growth strata, as evidenced by seismic profiles (Zhou et al., 2006). Eastern portion of the Qaidam baisn continued subsiding, and was mainly filled with fluvial and lacustrine deposits.

Quaternary

Quaternary strata are dominated by conglomeratic facies in the western and marginal parts of the basin, with widespread occurrence of salt layers. In contrast, fine-grained facies, such as interbedded siltstone and mudstone as well as gypsums, constitute the eastern part of the basin. Quaternary depocenter have migrated to the eastern Qaidam basin, with thickness up to 3000 m (Fig. 7g). Synchronously, folding and faulting became more active in the western Qaidam basin, and Quaternary units manifest themselves as growth strata.

BASIN ANALYSIS

Provenance

Provenances for sediments of the Qaidam basin have been a matter of debate. Métivier et al. (1998) suggested that the Qaidam basin was an internally drained basin, and filled mainly with sediments from the Eastern Kunlun on the south. Wang et al. (2006) advanced a model, postulating that the Qaidam basin was a displaced basin that received sediments mostly from western Kunlun, rather than from adjacent mountain ranges, in particular, during the Paleogene. Rieser et al. (2005) carried out a study of sandstone provenance of the Qaidam basin, and concluded that no dramatic changes took place in compositions of Tertiary sequences. $^{40}Ar/^{39}Ar$ dating of detrital white mica puts further constraint on Tertiary provenance, suggesting that they were mostly derived from bordering mountains (Rieser et al., 2006) Although uncertainties exist about source regions for Paleogene sequences, sediments of the Qaidam basin were likely sourced from adjacent mountain belts in the Neogene. The eastern Kunlun had been exhumed by ~30 Ma (Mock et al., 1999), and the southern Qilian is also demonstrated to have undergone rapid denudation around the same period of time (F. Wang et al., 2004). In addition, the Altyn Tagh has been substantially uplifted since the Early–Middle Oligocene (Jolivet et al., 2001; Chen et al., 2001; Yin et al., 2002; Cowgill et al., 2003), thereby providing sediments to the Qaidam basin from the northwest.

It is interesting to note that the contour lines are obviously truncated by the Altyn Tagh fault in isopach maps of the Lulehe and Xiaganchaigou Formations (Fig. 7a–b), whereas the contour lines go around the edges of topographic highs in front of the Altyn Tagh fault in isopach maps of the Shangganchaigou, Xiayoushashan, and Shangyoushashan Formations (Fig. 7c–e). These phenomena suggest that the Altyn Tagh fault and adjacent topographic highs should not have served as the northwestern border of the Qaidam basin during deposition of the Lulehe and

Xiaganchaigou Formations, but began exerting obvious control on sedimentation of the Shangganchaigou Formations. Therefore, the Altyn Tagh should have commenced rising since the Oligocene and acted as a provenance shedding sediments to the western Qaidam basin. This inference is consistent with other studies about denudation history of the Altyn Tagh (Jolivet et al., 2001; Chen et al., 2001; Yin et al., 2002; Cowgill et al., 2003).

Seismic section clearly shows that the Lulehe and Xiaganchaigou Formations are in fault contact with basement rocks of the Altyn Tagh to the northwest, whereas the overlying units overlap the Altyn Tagh to the northwest (Fig. 8). The continuous, parallel and high-spacing pattern of seismic reflections of the Lulehe and Xiaganchaigou Formations suggest that they are composed of fine-grained facies like thin-bedded siltstone and mudstone, and thus do not represent proximal deposits. In contrast, the overlying units unconformably rest the Altyn Tagh and get thinning to the northwest, thus indicating that they were deposited at basin edge.

Syn-deformational Sedimentation

Tertiary sedimentary sequences have been folded in the western Qaidam basin. As clearly shown on seismic profiles, some stratigraphic units were deposited either synchronously with active folding in the basin interior or simultaneously with basement uplifting at basin edges. These syn-deformational sedimentary successions are referred to as growth strata (Suppe et al., 1992), and can be used to interpret the timing, geometry, kinematics of fold-and-thrust systems (Burbank and Vergés, 1994), as well as interaction of sedimentation with active deformation (Burbank et al., 1996). Individual stratigraphic units of the Qaidam basin might be deposited as pre-growth strata in one region, but as growth strata in other areas. On the northern fringe of the Qaidam basin, the Lulehe and Xiaganchaigou Formations display constant thickness, around 1600 m, toward the Serteng (Fig. 9a), and the thickness is also compatible with that of their counterparts in the Suhai basin north of the Serteng. It is therefore considered that the Lulehe and Xiaganchaigou Formations had formed prior to the uplift of the Serteng, or were pre-growth strata. In contrast, the stratigraphic units become tapering toward the edge of the Serteng on the north since deposition of the Shangganchaigou Formation (Fig. 9a), manifesting themselves as growth strata. This observation indicates that the Serteng came into being since the Oligocene when the Shangganchaigou Formation developed. In contrast, the successions from the Lulehe up to

Xiayoushashan Formations in basin interior show no striking thickness variation, indicating that they were still pre-growth strata (Fig. 9b). The thinning from limbs to crests of folds can be perceived of the Shangyoushashan Formation, and becomes more pronounced in the Shizigou Formation and the Quaternary (Fig. 9b). These observations demonstrate that deformations did not take place in the basin interior until the Middle Miocene. It is accordingly implied that Cenozoic deformations occurred earlier at basin margins than in the interiors of the western Qaidam basin.

Depocenter

It has been realized that depocenter was located in the western Qaidam basin in the Tertiary, and then shifted to the eastern Qaidam basin during the Quaternary (Gu and Di, 1989; Wang and Coward, 1990). The eastward migration of depocenter was considered as the consequence of strong deformation and uplift of the western Qaidam basin toward the end of the Tertiary (Wang and Coward, 1990). It is important, however, to notice that main depocenter had been persistent in the middle of the Qaidam basin (Fig. 7), although some subordinate depocenters did develop at basin margins, particularly since the Middle Miocene. The accumulated thickness of Tertiary sediments is up to 17 km in the Yiliping depression in striking contrast with Tertiary thickness in the basin margins in the western Qaidam basin (Fig. 10).

The Mangnai depression represents a prominent subordinate depocenter that lies on the southwestern portion of the Qaidam basin, striking in NW–SE (Fig. 7). It is worthwhile to note that this depression was filled dominantly with Paleogene lacustrine fine-grained facies, which might be deposited continuously from underlying Late Cretaceous marine facies associations (Meng et al., 2001). Contour lines of the Mangnai depression in the Paleogene isopach maps are apparently truncated by the Altyn Tagh fault in the northwest (Fig. 7a-d), suggesting that the persevered depression is only part of original depocenter.

Fault Systems

The present-day Qaidam basin is bounded on both the north and south by basin-directed reverse fault systems, in particular in the western Qaidam basin (Fig. 3). The major border faults on the south are termed as the northern Kunlun fault system (NKF) that manifests itself as high-angle south-dipping reverse faults (Fig. 3). Interestingly, the Lulehe, Xiaganchaigou, and Shangganchaigou Formations shows little change in thickness when reaching the NKF from basin interior in the western Qaidam basin, whereas the overlying strata get thinning toward the NKF (Fig. 10 b–b`). This observation suggests that the NKF was not initiated until deposition of the Xiayoushashan Formation, and then exerted a control over sedimentation of subsequent stratigraphic units. The northern border fault system can be divided into several segments, with the northwestern segment called the southern Serteng fault (SSF) (Fig. 3). Similar to the NKF, the SSF did not control deposition of the Lulehe and Xiaganchaigou Formations, in that the two Formations show constant thickness across the SSF and the Serteng.

Another prominent feature is the occurrence of reverse faults in the middle of the Qaidam basin, which are mostly basement-rooted and penetrate into covers at different levels (Fig. 10). These reverse faults are usually high angle, and dips ether to the north or to the south. Except for a few faults that extend upward to the Upper Miocene–Pliocene or even reach the surface, most of the reverse faults die out upwards, with their displacement decreasing to zero upward as well (Fig. 10). The intra-basinal reverse faults mostly occur in the westernmost portion of the Qaidam basin, and become fewer in the middle and absent in the east. There also develop a number of reverse faults within Tertiary sedimentary successions (Fig. 10). This sort of faults is closely associated with folds, or occurs as conjugate faults at inflection points of fold limbs (Fig. 10).

Subordinate Basins

The present-day Qaidam basin is bounded on all sides by mountain ranges (Fig. 2, 3). It is worthwhile to notice that there exist some subordinate basins within the surrounding mountains, such as the Suhai basin in the southern Qilian, Kumukol basin in the eastern Kunlun, and the Tula and Xorkoli basins within the Altyn Tagh. The understanding of Cenozoic stratigraphy and sedimentation of these basins will provide insight into tectonic development of the Qaidam basin. We choose to analyze the Suhai and Kumukol basins to reveal possible early-stage linkage of the subordinate basins with the Qaidam basin.

The Suhai basin occurs to the north of the Qaidam basin, separated by the Serteng. Based upon available seismic profiles and borehole data, it is shown that there only develop the Lulehe, Xiaganchaigou, and Shangganchaigou Formations in the Suhai basin, with most of the overlying Neogene stratigraphic units missing (Fig. 4). The Lulehe Formation is composed of conglomerate and coarse-grained sandstone in the lower part, and then passes upward into siltstone and mudstone with interlayered sandstone (Fig. 4). It is ~550 m thick in the middle of the basin, and shows no striking variations to its southern edge, as revealed by seismic profiles. The Xiaganchaigou Formation is dominated by sandstone and sandy siltstone, with minor portion of conglomerate. It rests conformably over the Lulehe Formation, and ranges from 400–600 m in thickness. The lower portion of the Shangganchaigou Formation consists of facies associations similar to those of the Xiaganchaigou Formation, but gets finer upwards (Fig. 4). The Xiayoushashan Formation is only locally distributed, and overlain by Quaternary sediments.

It is noticeable that the Lulehe and Xiaganchaigou Formations in the Suhai basin consist of sedimentary facies similar to those of their counterparts on the northwestern fringe of the Qaidam basin, and their thickness is also compatible in general. These facts suggest that the Suhai basin should have been the northern portion of the Qaidam basin, and there is no topographic barriers separating the two basins from each other at least before deposition of the Shangganchaigou Formation. Thinning of the Shangganchaigou Formation in both the Suhai and northwestern Qaidam basins toward the Serteng indicates that the Serteng began undergoing uplift since the Oligocene. In consideration of the absence of most of the Neogene strata, the Suhai basin is considered to have been experiencing uplift since the Late Oligocene. The Suhai basin manifests itself as a typical intermontane basin during the Quaternary, and presumably acts as a piggyback basin over a south-directed thrust sheet.

The Kumukol basin is located south of the Qiman Tagh, and has been uplifted to an elevation of ~4500 m (Fig. 2). The basin is filled with Oligocene to Pliocene sequences, and moderately deformed into a syncline (Fig. 11a). Tertiary sequences can be divided into four stratigraphic units in an upward trend, the Huatiaoshan, Hongshiliang, Fengchenkou, and Jiantuliang Formations (Fig. 4). The Huatiaoshan Formation, up to 3000 m thick, is dominated by coarse-grained facies associations in the lower portion, like conglomerate and coarse-grained sandstone, which then passes upward into fine-grained facies, such as interlayered fine-grained sandstone and siltstone/mudstone (Fig. 4). The Huatiaoshan Formation is assigned to be Oligocene on the basis of the fossils in the fine-grained layers (Zhang et al., 1996;). Given that the fossils occur in the upper portion of the Huatiaoshan Formation and some fossils can also appear in Eocene strata, we thus considered that the Huatiaoshan Formation might span from Eocene to Oligocene, and cab be correlated with the Xiaganchaigou and Shangganchaigou Formations of the southwestern Qaidam basin. The Hongshiliang Formation is composed of thin-bedded sandstone and siltstone in its lower portion and passes upward into thick-and medium-bedded coarse-grained sandstone and some conglomerate (Fig. 4). It is distributed throughout the basin, up to 1800 m thick, and rests conformably over the Huatiaoshan Formation. The Hongshiliang Formation is thought to be Early Miocene in age (Zhang et al., 1996). Coarse-grained facies like sandstone and conglomerate make up the bulk of the Fengchenkou Formation (Fig. 4), which is observed to rest unconformably over the Hongshiliang Formation. The Fengchenkou Formation is assigned to be Middle Miocene in age according to estheria assemblages (Zhang et al., 1996). The Jiantuliang Formation is characterized by deposition of massive gypsum and associated calcareous mudstone in its lower portion, which then change upward into red-colored sandstone and thin-bedded siltstone and mudstone. Angular unconformities are observed in places between the Jiantuliang Formation and underlying units. There exist abundant fossils, such as bivalves and gastropods, which assign the Jiantuliang Formation to be of Pliocene–Pleistocene in age (Zhang et al., 1996).

It is interesting to note that alluvial conglomeratic facies of the Huatiaoshan Formation mainly develop in the south of the Kumukol basin, and change into dark-colored fine-grained facies toward the north (Fig. 11b). In addition, restored paleo-flows are uniformly toward the north according to cross-bedding and pebble imbrications in the Huatiaoshan Formation (Fig. 11b), indicating that the sediments of the Huatiaoshan Formation should have come from the south (Xiao et al., 2005). Noticeable is that paleo-flows became multiply directed during the period of the Hongshiliang Formation deposition (Fig. 11c). In particular, sediments began debouching to the basin from the north during the period of deposition of the Fengchenkou and Jiantuliang Formations, as evidenced by south-directed paleo-flows restored in the northern margin of the Kumukol basin (Fig. 11d).

It is inferred that the southern border of the Kumukol basin had already been established in the Eocene and Oligocene, and the Qiman Tagh Shan, as the northern border of the present-day basin, did not exist in this time interval. This inference is supported by the facts: (1) proximal facies only occur on the southern margin of the basin, which change laterally into finer facies associations toward the north to the Qiman Tagh (Fig. 11b); (2) paleo-flows are consistently to the north (Fig. 11b); (3) the finer facies associations of the northern Kumukol basin can be correlated with lacustrine fine-grained deposits of the Lulehe and Xiaganchaigou Formations in the southwest of the Qaidam basin. It is therefore plausible that the two basins were once connected during the Eocene and Oligocene, with the Kumukol basin as the southern margin of the proto-Qaidam basin. The Kumukol basin evolved into an isolated and internally drained intermontane basin since the Miocene in that it began to possess its own depocenter surrounded by proximal alluvial–fluvial coarse-grained facies, as evidenced by spatial distribution of facies zonation of the Hongshiliang Formation (Fig. 11c). The Kumukol basin continued developing throughout the Neogene, and was eventually uplifted to a higher elevation with the Eastern Kunlun.

IMPLICATIONS FOR BASIN TECTONICS

A number of models have been advanced to account for tectonic evolution of the Qaidam basin, and all of them share the idea that subsidence of the Qaidam basin resulted from basinward emplacement of thrust systems along the northern and southern edges of the basin (Wang and Coward, 1990; Mètivier et al., 1998; Meyer et al., 1998; Cowgill et al., 2003). It was postulated that the north-directed thrust system on the south of the basin was attributed to a hidden S-directed subduction of the mantle that was decupled from the upper plate (the Qaidam basin) through a weak zone in the lower crust (Tapponnier et al., 2001). It was further suggested that a middle-crustal detachment might exist beneath the Qaidam basin, which branches upwards to form the Qilian thrust system in the north (cf. Tapponnier et al., 1990). The N-dipping reverse faults at the northern edge of the Qaidam basin are considered as the consequence of the backthrusting of the Qilian thrust system (Meyer et al., 1998). Mètivier et al. (1998) also claimed that a series of thrust-related basins was generated duo to northward propagation of N-dipping thrusts/reverse faults that became successively younger to the north. The stepwise development of the basins was attributed to northward prorogation of left-lateral displacement of the Altyn Tagh fault in the Tertiary (Yin et al., 2002; Cowgill et al., 2003).

However, there are some flaws with the previous models because they are in conflict with some crucial observations and recent studies. First, Tertiary depocenters of the Qaidam basin were located in the middle of the basin, rather than lie close to basin edge. The cumulated Tertiary thickness in the Yiliping depression is up to 17 km, strikingly contrasting with that of the basin margin (Figs. 7 and 10). If the basin were generated by crustal flexure due to tectonic loads imposed by thrust sheets, depositional loci would have been near thrust front (Beaumont, 1981;

Flemings and Jordan, 1989). Second, the thrusting and uplifting is shown to have been roughly synchronous in the eastern Kunlun and the southern Qilian around ~30 Ma (Mock et al., 1999; F. Wang et al., 2004). The exhumation of the northern Qilian also turn out to be as early as the Early Miocene (George et al., 2001), much earlier that previous estimates of 6–2 Ma (e.g., Tapponnier et al., 1990; Meyer et al., 1998). The simultaneity of deformation in the northeastern Tibetan plateau thus throws doubt on the stepwise growth model. Third, generation of N-dipping thrust systems in the northeastern Tibetan plateau appeals to the presumption of southward subduction of the mantle beneath the eastern Kunlun (Tapponnier et al., 2001), but this sort of mantle-subduction process, unfortunately, has not been imaged yet.

It is proposed in this study that the Qaidam basin originated presumably from lithospheric or crustal buckling or folding, which can well account for some key observations and geologic evolution, such as localization of main depocenters, stratigraphic and sedimentary evolution, initiation and nature of fault systems, and interrelationship of both the Qaidam and adjacent intermontane basins (Fig. 12). Continental lithospheric-scale folding is considered to be one of primary responses to horizontal compression (Cloetingh et al., 1999), and has been applied to explain active intracontinental deformations in a number of regions, such as Tibetan plateau (Burg and Podladchiloe, 1999), Central Asia (Nikishin et al., 1993; Burov et al., 1993; Cobbold et al., 1993), European continents (Cloetingh et al., 2002), and central Australia (Stephenson and Lambeck, 1985). A variety of analogue and numerical modelling have been carried out to investigate periodic instability and folding of the lithosphere or crust during horizontal compression (Martinod and Davy, 1994; Burg et al., 1994; Cloetingh et al., 1999; Sokoutis et al., 2005). The results show that continental lithosphere and crust will experience folding at initial and intermediate stages during horizontal shortening, and then there occurs faulting at inflection points of folds. Further shortening will eventually lead to the closing of synclinal depressions (cf. Sokoutis et al., 2005). The modelling results also indicate that fold wavelengths are primarily controlled by lithospheric thickness and thermal structure, with long wavelength corresponding to thick and cold lithosphere (Cloetingh et al., 1999). Lithospheric-scale folding usually display long wavelengths of 250–360 km (Nikishin et al., 1993). In practice, periodicity of lithospheric- and crustal-scale folds can be quite irregular in wavelength and amplification in view of crust–mantle coupling/uncoupling, strain localization, and intensity of erosion (Cloetingh et al., 1999). Another interesting result of analogue and numerical experiments is that pre-fold tectonic fabrics, such as old sutures or faults, exert little influence on lithospheric folding (Martinod and Davy, 1993; Gerbault et al., 1999), and continuous folding behavior of faulted lithosphere is possibly due to fault locking as a result of gravity and friction (Cloetingh et al., 1999).

Modelling of continental lithospheric and crustal folding provides insight on the origin and tectonic evolution of the Qaidam basin. It is surmised in this study that the Qaidam basin underwent three-stage evolution in the Cenozoic (Fig. 12). The first stage was characterized by relative slow subsidence possibly due to crustal folding in the Paleocene–Early Oligocene interval when the Lulehe and Xiaganchaigou Formations were formed (Fig. 12b). A proto-Qaidam basin manifested itself as a synclinal depression that consists of both the Qaidam basin and the Kumukol basin on the south and the Suhai basin on the north. There also simultaneously developed two antformal uplifts, the eastern Kunlun on the south and the Qilian on the north, respectively. Depocenter was located in the middle of the basin, corresponding to the trough of the crust-scale mega-fold with its wavelength being ~300 km in the western Qaidam basin. The raised Qilian and eastern Kunlun provided sediments to the pro-Qaidam basin (Fig. 12b).

The second stage saw a period of further development of the mega-fold during the Late Oligocene to early Middle Miocene when the Shangganchaigou and Xiayoushashan Formations were deposited. Reverse faults commenced at basin margins, and depocenter kept developing in the middle of the basin (Fig. 12c). The S-dipping NKF on the south and N-dipping SSF on the north typically represent the basin-margin reverse faults. With development of the reverse faults, proximal regions of the proto-Qaidam basin was gradually isolated by fault-related uplifts, such as the Qiman Tagh and the Serteng, thereby producing the Suhai and Kumukol basins on the north and south, respectively. Oligocene uplifting of the Serteng is recorded by inception of growth strata (Shangganchaigou Formation) on the southern side of the Serteng, coeval with the exhumation of the Qaidam Shan to the east of the Serteng (F. Wang et al., 2005). Tertiary stratigraphic development further suggests that the Suhai basin had been gradually uplifted since the Late Oligocene (Fig. 4) because the Shangganchaigou and Xiayoushashan Formations are relatively thin and locally distributed. In addition, Neogene strata are almost missing in the Suhai basin. The Qiman Tagh was also gradually exhumed around 30 Ma, and had become a northern provenance for the Kumukol basin since the Early Miocene. Occurrence of the Fengchenkou and

Jiantuliang Formations indicates that the Kumukol basin continued subsiding in Middle Miocene–Pliocene times, contrasting with synchronous uplifting of the Suhai basin. Development of Middle Miocene and Pliocene strata in the Kumukol basin, up to 3500 m thick (Zhang et al., 1996; Xiao et al., 2005), seems to agree with the inferred extensional setting in the eastern Kunlun in that time interval, as suggested by recent studies (Mock et al., 1999; Jolivet et al., 2003; Fu and Awata, 2007). In the context of crustal-scale folding, we suggest that the reverse faults on the basin margins were generated at inflection points of the resulting megafold with continued horizontal shortening (Fig. 12c). Therefore, occurrence of reverse faults at the basin margins can be envisioned as a corollary of the ongoing folding. Accordingly, the north-dipping reverse faults on the northern border of the Qaidam basin were not necessarily the result of backthrusting related with northward prograding Qilian or Nanshan thrust system (Meyer et al., 1998).

The Qaidam basin entered the third stage when it underwent strong contractional deformations characterized by intrabasinal folding and faulting. Most of the intrabasinal reverse faults are basement-rooted, and some of them can penetrate upward to the surfaces (Fig. 10). Various-scale folds and faults are clearly related, and have very striking surface expressions in the western Qaidam basin (Fig. 2). Neogene successions, in particular, the Shangyoushashan and Shizigou Formations, formed as typical growth strata (Fig. 12d), and as a consequence, previous main depocenter in the middle of the western Qaidam basin was gradually disrupted, and evolved into several subordinate depocenters separated by growing anticlinal highs (Fig. 7f). With increased horizontal shortening, the Suhai basin was uplifted on account of absence of Neogene strata. The Kumukol basin might continue subsiding in an extensional setting. In practice, Neogene extension of the Kumukol basin was implied by coeval occurrence of volcanism and extensional basins in adjacent regions Jolivet et al., 2003; Q. Wang et al., 2005). It is also noticeable that the Eastern Kunlun fault was initiated in the Late Miocene (around 10 Ma), and manifests itself as one of major left-lateral strike-slip faults in the northern Tibet (Fu and Awata, 2007). The left-lateral displacement or strain partitioning along the eastern Kunlun fault might contribute in part to Neogene extension of the eastern Kunlun (Jolivet et al., 2003).

It is assumed in this study that development of the Qaidam basin was probably attributed to crustal folding that was decoupled from the mantle along the lower-crustal weak zone. There is ample evidence that indicates the existence of a low-density or weak lower crust in northern Tibet

(Zhu and Helmberger, 1998), and it is as thick as 20–30 km beneath the eastern Kunlun south of the Qaidam basin (Zhu et al., 1995; Zhao et al., 2006). The weak lower crust might be able to flow, and thus could accommodate the upper-crustal folding processes in compression. The lithospheric mantle would be subducted, but subduction polarities are not necessarily to the south, as suggested by previous studies (Meyer et al., 1998; Tapponnier et al., 2001).

The three-stage model mainly accounts for the tectono-sedimentary evolution of the western Qaidam basin, whereas the eastern Qaidam basin displays different tectono-sedimentary history. Actually, the eastern Qaidam basin behaved as the eastern margin of the proto-Qaidam basin during the Paleogene, and then gradually evolved into a main part of the Qaidam basin, as shown by temporal and spatial evolution of Cenozoic sediments (Fig. 7). The eastern Qaidam basin has become main depositional loci during the Quaternary, simultaneous with active intrabasinal faulting and folding in the western Qaidam basin (Fig. 7g). The eastern Qaidam basin also localized its depocenter in the middle of the basin, with thickness up to 3 km (Fig. 7g), thereby implying that its subsidence could be also attributed to crustal buckling. It is worth noting that there exists another subordinate Cenozoic basin, i.e. the Delingha basin, which is separated from the eastern Qaidam basin by the NW-trending Emunik (Fig. 3). It is assumed that the Delingha basin was previously the northern margin of the eastern Qaidam basin in that they share similar stratigraphic successions. Separation of the Delingha basin from the eastern Qaidam basin is considered to have taken place at the end of the Tertiary. This inference is based upon the two observations: (1) thickness of Tertiary strata is compatible across the southern Emunik ranges, as indicated by seismic profiles, and (2) Tertiary successions are strongly folded harmonically, with little Quaternary deposition in the Delingha basin. Compared with the three-stage evolution of the western Qaidam basin, the eastern Qaidam basin appears to have only experienced the first two stages. There exist, however, no major reverse faults breaking the southern margin of the eastern Qaidam basin. It is suggested that absence of major reverse faults was presumably due to reduction of orthogonal compression due to strain partitioning by left-lateral displacement of the Kunlun fault since the Late Miocene (Fu and Awata, 2007).

Discrepancy of tectono-sedimentary histories between the western and eastern Qaidam basin is thought to originate from spatial variation of stress field in the Cenozoic. The western Qaidam is bounded on the northwest by the Altyn Tagh fault (ATF), and large-magnitude left-lateral displacement of the ATF must have exerted a strong influence on stress regime of the western Qaidam basin. Recent activity of the Altyn Tagh fault system has been well documented (Peltzer et al., 1989; Bendick et al., 2000), but its geological evolution is debatable. It is generally thought that the ATF did not commenced until the Oligocene (Ritts and Biffi, 2000; Meng et al., 2001; Yue et al., 2001; Chen et al., 2004), although some studies argued that inception of the ATF could be as early as late Mesozoic (Y. Wang et al., 2005; Liu et al., 2007). Seismic tomographic imaging reveals present-day deep structure of the ATF, showing that it cuts through the crust and penetrates downward as deep as ~140 km (Wittlinger et al., 1998). Accordingly, the ATF would have been acting as an accommodation zone to adjust different strain regimes between the Tarim and Qaidam basins. It is suggested that progressive left-lateral slip of the ATF must have promoted the crustal folding of the Qaidam basin during the Cenozoic. We, however, are not able to reconstruct detailed mechanical processes of the crustal buckling in this study because of meager information on deep thermo-mechanical structure of the northeastern Tibetan plateau, in particular, beneath the Qaidam basin.

Fig. 13 presents cartoons to illustrate sequential tectonic evolution of the Qaidam basin during the Cenozoic. It is assumed that the Qaidam basin was connected with the southwestern Tarim basin in Late Cretaceous–Paleocene times, and marine invasion reached the southwestern portion of the Qaidam basin (Fig. 13a). Rest parts of the Qaidam basin was expressed as highland with scattered late Mesozoic relict extensional basins. The crust began to fold in the northeastern Tibetan plateau since the Oligocene, and the Qaidam basin was initiated as a synclinal depression (Fig. 13b). Crustal folding in the western Qaidam was accommodated by left-lateral slip of the Altyn Tagh fault, and the sediments were shed from both the northern and southern anticlinal highs. Another possible provenance was the western Kunlun at this stage. With continued horizontal compression, reverse faulting became active at the basin margin or at inflection points of the crustal mega-fold (Fig. 13c). The resulting fault-related highs gradually divided the basin margin areas, leading to the formation of some isolated intermontane basins, such as the Suhai basin. The Qaidam basin had completely separated from the Tarim basin, with the uplift of the Altyn Tagh, which then provided sediments to the basin. Depocenter had been kept in the middle of the basin with the continuation of the crustal folding. The western Qaidam basin was folded and uplifted in the Quaternary as a consequence of continued shortening in the western Qaidam basin, and depositional area was forced to migrate eastwards. Depocenter was located in the middle of the eastern Qaidam basin (Fig. 13d). Active left-lateral slip of the Kunlun fault occurred since ~10 Ma, and resulted in partitioning of orthogonal or S–N stress on the southern margin of the eastern Qaidam basin.

There exists another Cenozoic basin to the south of the Qaidam basin, the Hohxil basin, which is bounded on the north by the eastern Kunlun and on the south by the Tanggula Shan (Fig. 1). The basin was initiated in the Early Eocene, and filled with fluvial–lacustrine sediments, as represented by Eocene Fenghuoshan Group and Lower Oligocene Yaxicuo Group (Liu et al., 1998; Wang et al., 2002). The basin then experienced contractional inversion at the end of the Oligocene, leading to strong deformation of Paleogene succession. The Lower Miocene Wudaoliang Group then unconformably overlies the folded Paleogene succession, which is mostly composed of lacustrine limestone up to 800 km thick (Liu and Wang, 2001). Of great interest is that the depocenters were persistently located in the middle of the basin, with Paleogene cumulative thickness up to 5 km (Liu et al., 2001). It is suggested that the Hohxil basin might have also arisen from the crustal folding, with its original wavelength to be ~300 km, similar to that of Qaidam basin.

CONCLUSION

The Qaidam basin experienced a three-stage evolution during the Cenozoic, and its tectonic subsidence is considered to have resulted from crustal folding in response to horizontal compression. The basin was initiated as a synclinal depression ~300 km wide in the first stage from Eocene to Oligocene, and flanked by anticlinal highs that were southern Qilian on the north and the eastern Kunlun on the south, respectively. Sediments were shed from both the southern Qilian and the eastern Kunlun, whereas the Altyn Tagh appeared not to be a topographic highland in this stage. The second stage was featured by occurrence of reverse faults at inflection points of the basin margin in the Miocene, which then evolved into the northern and southern border faults of the Qaidam basin. Original basin-margin areas were isolated by border faults and related uplifts, and manifested themselves as intermontane basins, such as the Suhai basin on the north and Kumukol basin on the south. The Pliocene and Quaternary saw the third stage when the western Qaidam basin was deformed and uplifted, with the depocenter shifting to the east. The crustal folding model can well account for a number of phenomena, such as persistent localization of depocenter in the middle of the basin, synchronous deformation on both sides of the basin, and occurrence and basinward displacements of reverse faults at basin margins. The Qaidam basin was presumably attached to the southwestern Tarim basin in the Late Cretaceous and Paleocene, and then displaced to the northeast. The Altyn Tagh fault has been acting to accommodate the crustal folding of the Qaidam basin since the Oligocene.

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FIGURE CAPTIONS

Fig. 1, Simplified tectonic map of the Tibetan plateau and its adjacent regions, showing the position of the Qaidam basin and its present tectonic setting.

Fig. 2, Topography of the Qaidam basin and surrounding mountains. Note that the western Qaidam basin has been folded, as evidenced by marked surface expressions. In contrast, the eastern Qaidam basin shows little deformation. The Altyn Tagh and the Kunlun faults are featured by their strikingly linear traces.

Fig. 3, Tectonic sketch showing the Qaidam basin and its relationship with adjacent intermontane basins. Refer to Fig. 2 for topographic expressions of different tectonic elements.

Fig. 4, Stratigraphy of the Qaidam basin and its correlation with those of the Suhai and Kumukol basins. In general, stratigraphic successions of the Qaidam basin start from the Early Eocene, but its southwestern portion might possesses continuous Cretaceous–Paleocene sequences. Refer to text for the reasoning.

Fig. 5, Composite stratigraphic columns and facies interpretation for southwestern margin of Tarim basin and southwestern portion of Qaidam basin. Note that the two regions display remarkably similar stratigraphic and depositional sequences (late Neoproterozoic to early Paleogene), and that both are bounded on the south by an early Paleozoic suture.

Fig. 6, Field photos of some Tertiary sedimentary facies: (a) Conglomerate in the basal portion of the Lulehe Formation, with gravels being mostly metamorphic rocks, in the northern edge of the western Qaidam basin. Hammer (35 cm long) for scale. (b) Thick conglomerate beds interlayered with finer facies in the lower part of the Xiaganchaigou Formation, in the northern edge of the western Qaidam basin. The frontal view is ~40 m wide. (c) Cores of dark-colored siltstone and silty mudstone of the Xiaganchaigou Formation in the southwest of the Qaidam basin. Coin (~1 cm in diameter) for scale. (d) Cretaceous rock (right) is displaced over the Shizigou Formation (left) in the northern edge of the Qaidam basin.

Fig. 7, Isopach maps of key stratigraphic units of the Qaidam basin. Note that main depocenter is located in the middle of the western Qaidam basin during the periods of deposition of the Lulehe (a), Xiaganchaigou (b), Shangganchaigou (c), and Xiayoushashan (d) Formations.

Depocenter of the Shangyoushashan Formation (e) is interrupted in the western Qaidam basin, which was then deformed, with the Shizigou Formation (f) and the Quaternary (g) deposited synchronously with the folding. Depocenter migrated to the eastern Qaidam basin (g).

Fig. 8, Seismic section showing that the Lulehe and Xiaganchaigou Formations are apparently truncated by high-angle transpressional reverse fault, whereas the overlying stratigraphic units become thinning and pinching-out northwestwards over the basement rocks. Refer to Fig. 3 for the section locality. Abbreviations: Mz—Mesozoic; E_{1-2}—Lulehe Formation; E_3^1—Lower Member of Xiaganchaigou Formation; E_3^2—upper Member of Xiaganchaigou Formation; N_1—Shangganchaigou Formation; N_2^1—Xiayoushashan Formation; N_2^2—Shangyoushashan Formation; N_2^3—Shizigou Formation; Q—Quaternary.

Fig. 9, Seismic sections showing different ages of growth-strata inception in the margin and interior of the Qaidam basin. (a) Seismic section in the northwestern edge of basin, with the Shangganchaigou Formation (N_1) manifested as growth strata tapering to the northeast; (2) Seismic section in basin interior, exhibiting that growth strata did not develop until deposition of the Shangyoushashan Formation (N_2^2), which become thickening from crest to limb of the fold. Refer to Fig. 3 for localities of the sections.

Fig. 10, Basin-scale geologic profiles across the Qaidam basin, showing that Cenozoic depocenters are located in the middle of the basin, and cumulative thickness of Cenozoic successions in the western Qaidam basin can be up to 17 km (a). Also noticeable is that the Lulehe (E_{1-2}), Xiaganchaigou (E_3^1 and E_3^2), and Shangganchaigou (N_1) Formations exhibit no obvious thickness variation toward the northern Kunlun fault (NKF), whereas the Xiayoushashan Formation (N_2^1) gets thinning to the NKF (b). Basement-rooted high-angle reverse faults occur in the middle of the basin, particularly in the western Qaidam basin, but relatively less develop toward the east (c). Refer to Fig. 2 for locations of the profiles, and see Fig. 8 for the meanings of abbreviations of other stratigraphic units. Paleo-environmental reconstruction and paleo-flow directions are mainly after Zhang et al. (1996) and Xiao et al. (2005).

Fig. 11, (a) Simplified geologic map; (b) Alluvial facies only occur in the south of the basin, which gradually change into fluvial, deltaic, and lacustrine facies toward the north during the Huatiaoshan Formation deposition; (c) The basin displays a concentric pattern of facies distribution during the period of the Hongshiliang Formation deposition, with sediments debouching into the basin from all sides; (d) The Fengchenkou and Jiantuliang Formations also exhibit a concentric distribution of sedimentary facies, receiving clastic sediments from surrounding mountains. Refer to text for detailed discussion.

Fig. 12, 2-D crustal-buckling model for 3-stage development of the western Qaidam basin in the Cenozoic: (a) Pre-bucking stage; (b) The northeastern Tibetan plateau commenced buckling from the Eocene, with its wavelength being ~300 km. Pro-Qaidam basin was initiated as synclinal depression, and anticlinal highs developed synchronously, building up the southern Qilian the north and the eastern Kunlun on the south. Depocenter was located in the middle of the basin, and filled with sediments sourced from adjacent anticlinal highs; (c) Major reverse faults became active at inflection points of the mega-fold, leading to formation of the Qiman Tagh and the Serteng, as well as isolation of Suhai and Kumukol basins at the basin margins; (d) The western Qaidam basin underwent intra-basinal folding and faulting due to continued horizontal shortening. The Suhai basin was raised, but the Kumukol basin continued subsiding presumably in an extension setting. Refer to text for a full discussion.

Fig. 13, Cartoons illustrating tectonic scenario of the Qaidam basin, and its possible linkage with other tectonic processes in adjoining regions: (a) The Qaidam basin was connected the Tarim basin, and together received Paleocene marine deposition; (b) The crust began folding in response to horizontal compression, and the Altyn Tagh fault was initiated to accommodate different stress fields between the Qaidam and Tarim basins. The Qaidam basin manifested itself as a synclinal depression with depocenter in the middle; (c) Continued compression resulted in formation of major reverse faults and related topographic highs at inflection points in basin-margin areas. Subordinate intermontane basins such as the Suhai basin came into being; (d) The western Qaidam basin experienced intra-basinal folding and inversion, and deposition area was forced to migrate to the east. Depocenter is still located in the middle in Quaternary time.

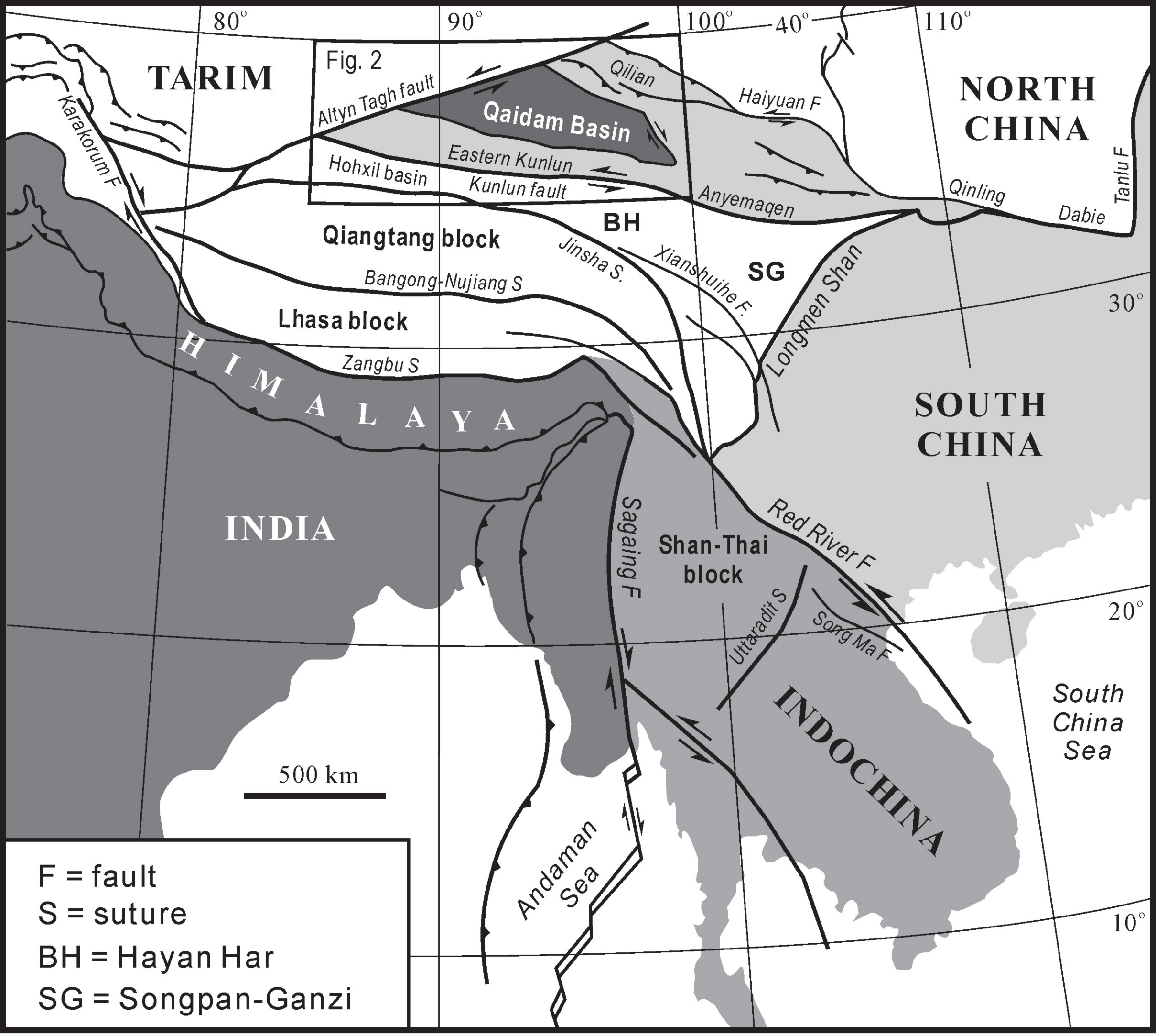
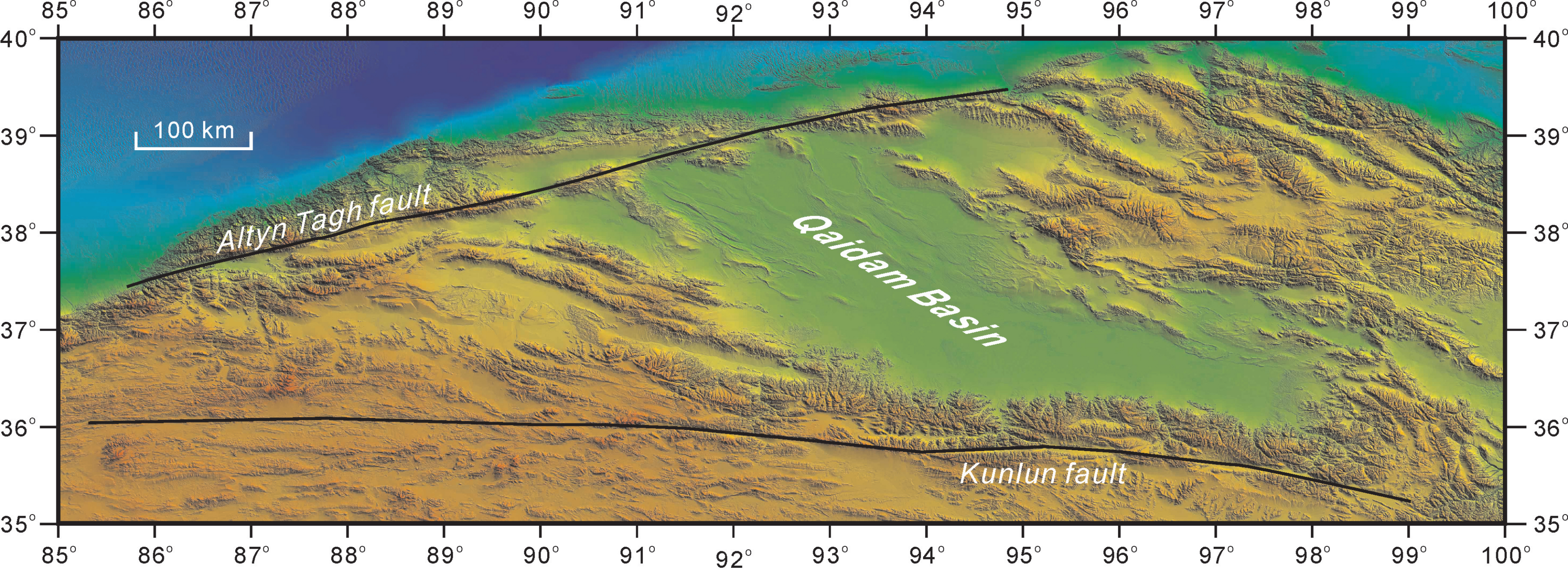


Figure 1 (Meng et al.)



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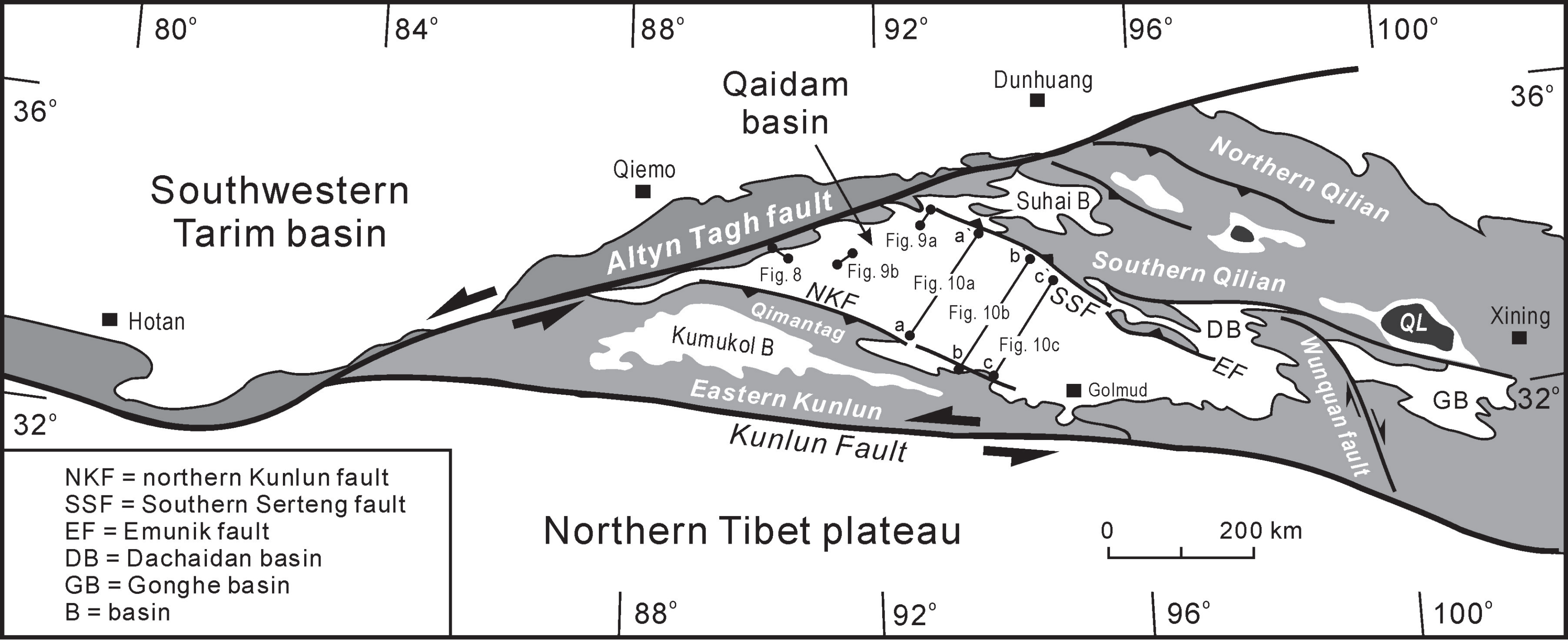

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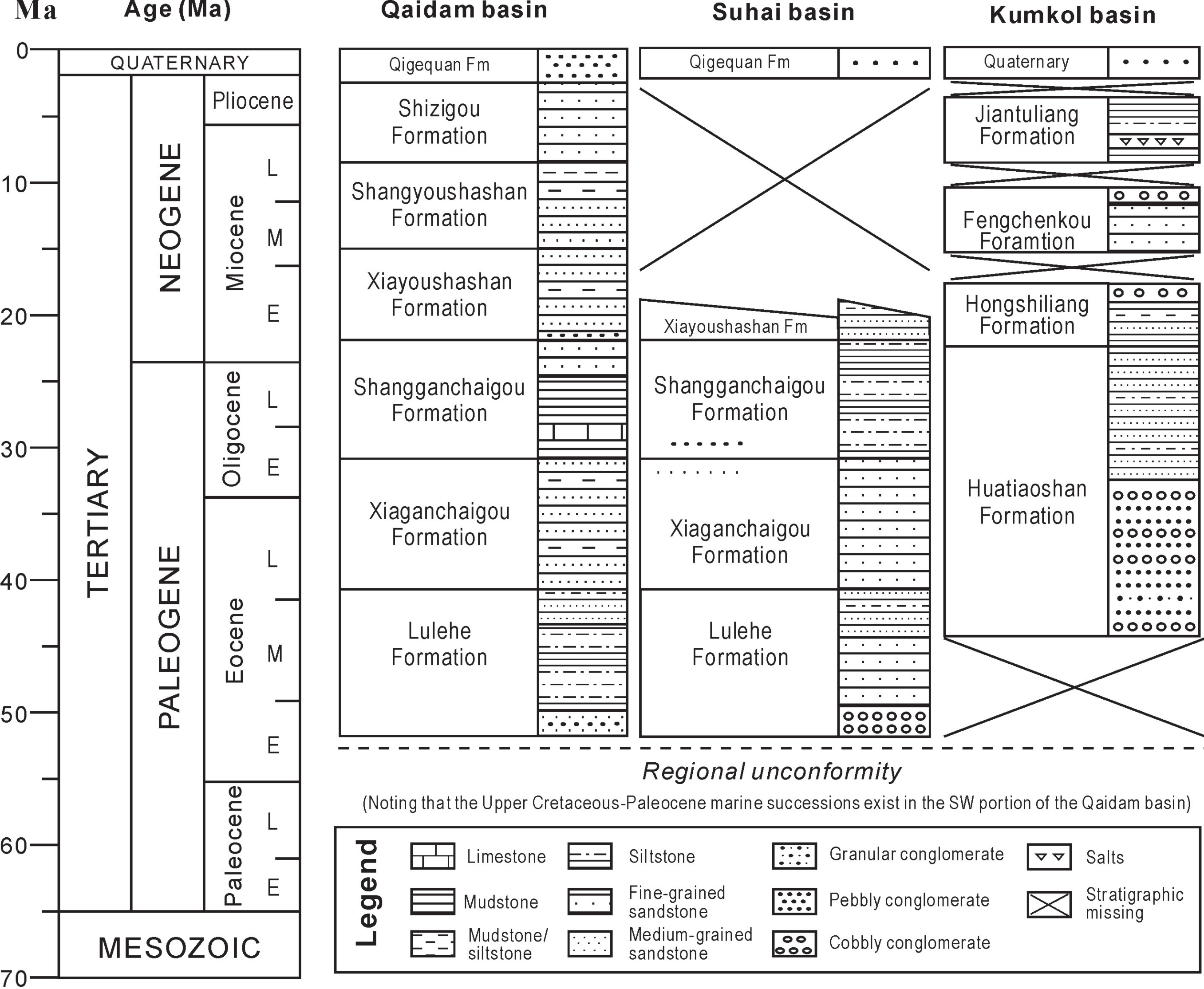

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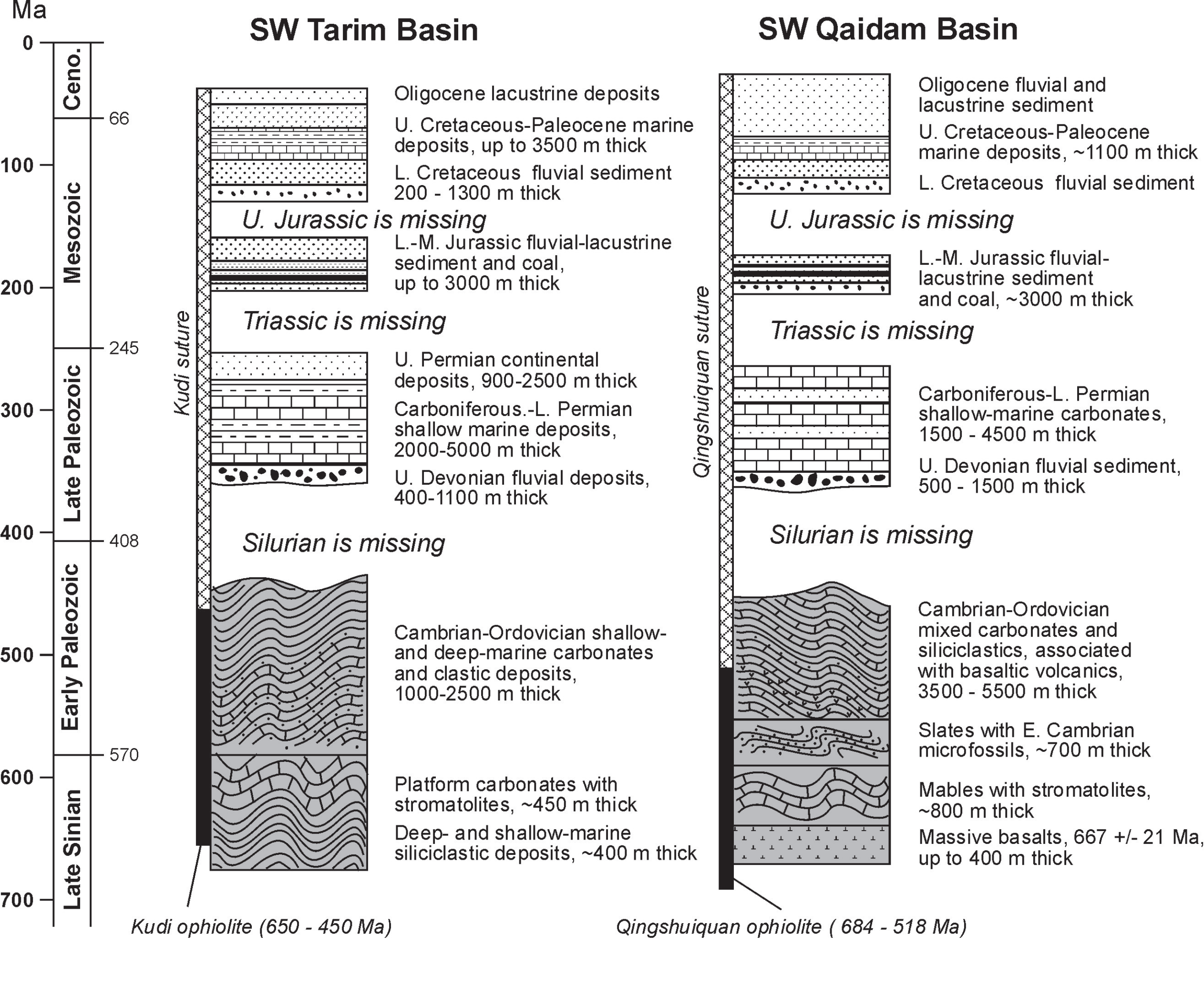

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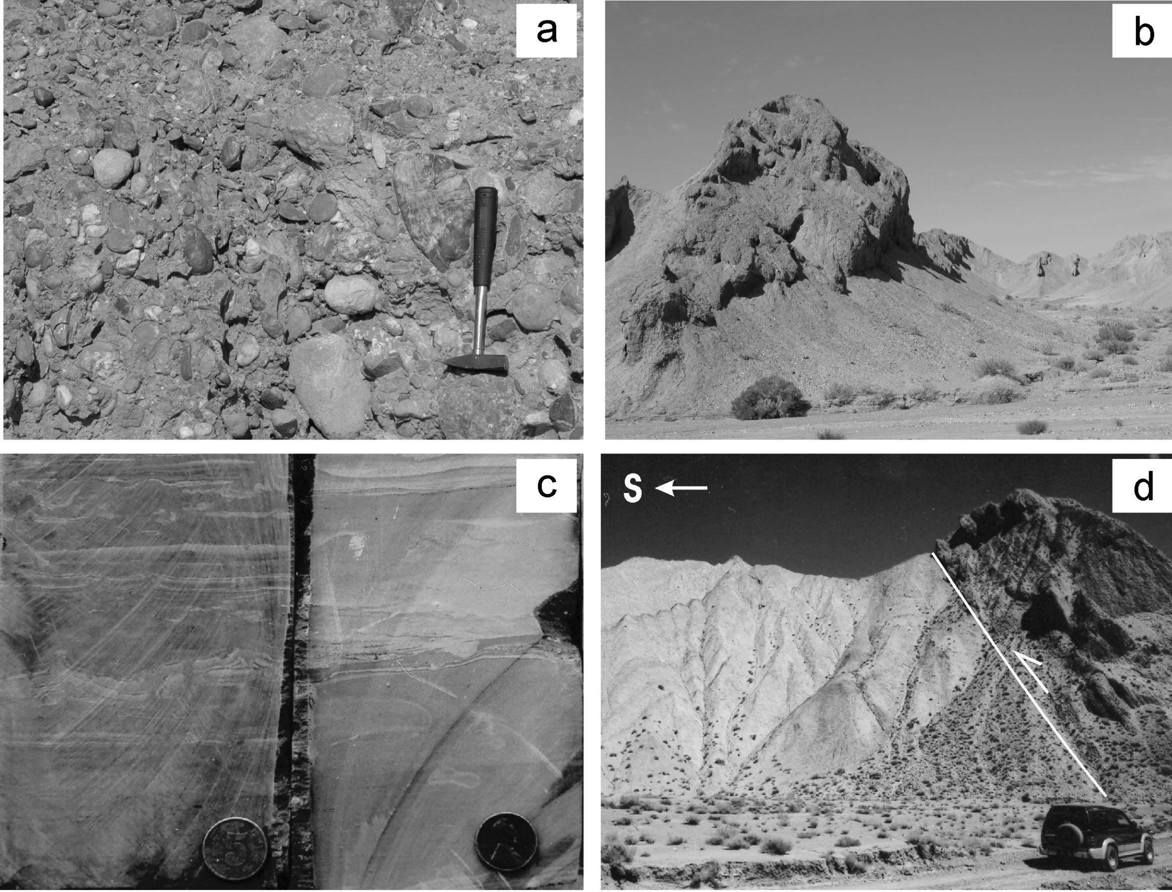

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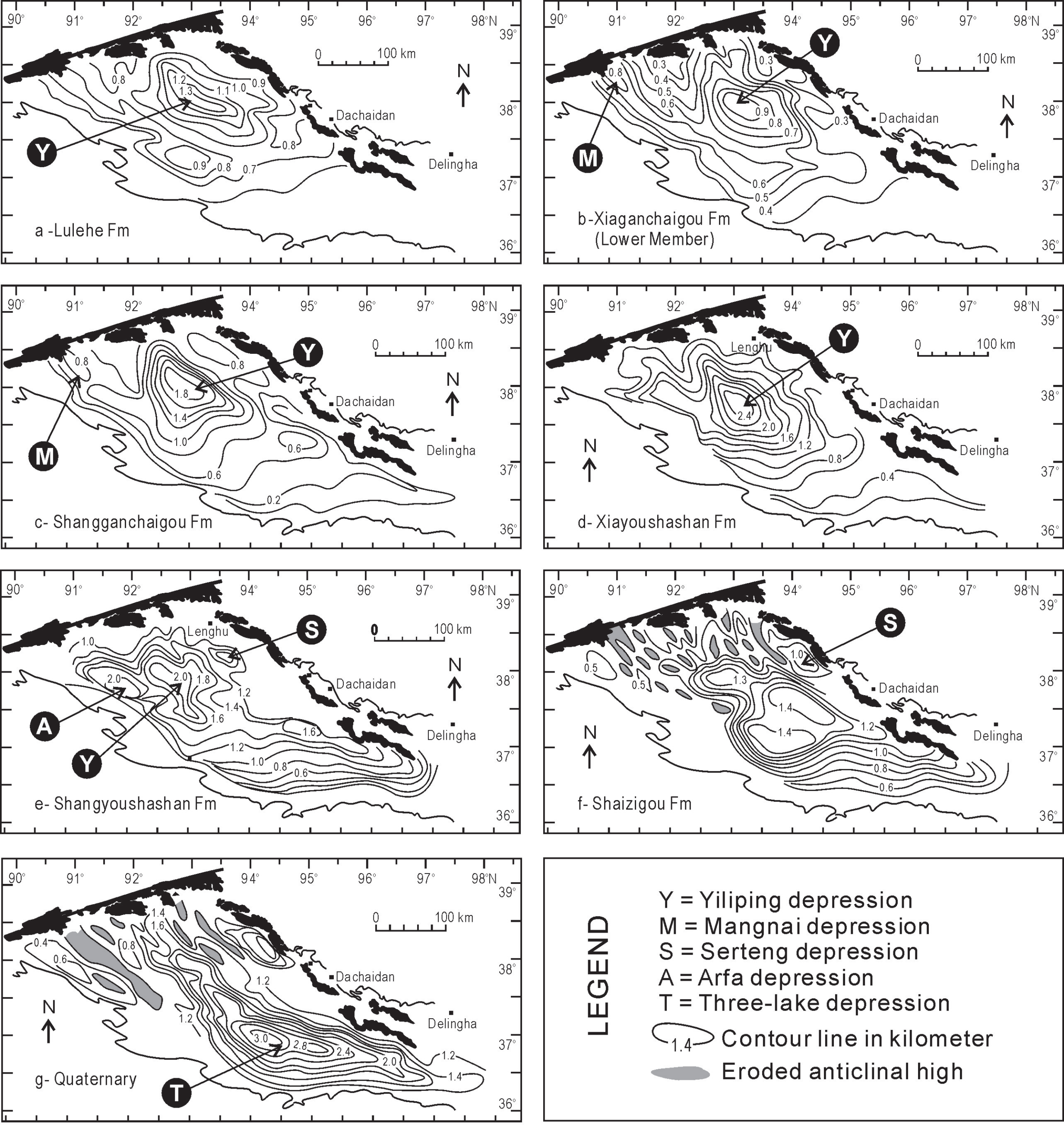

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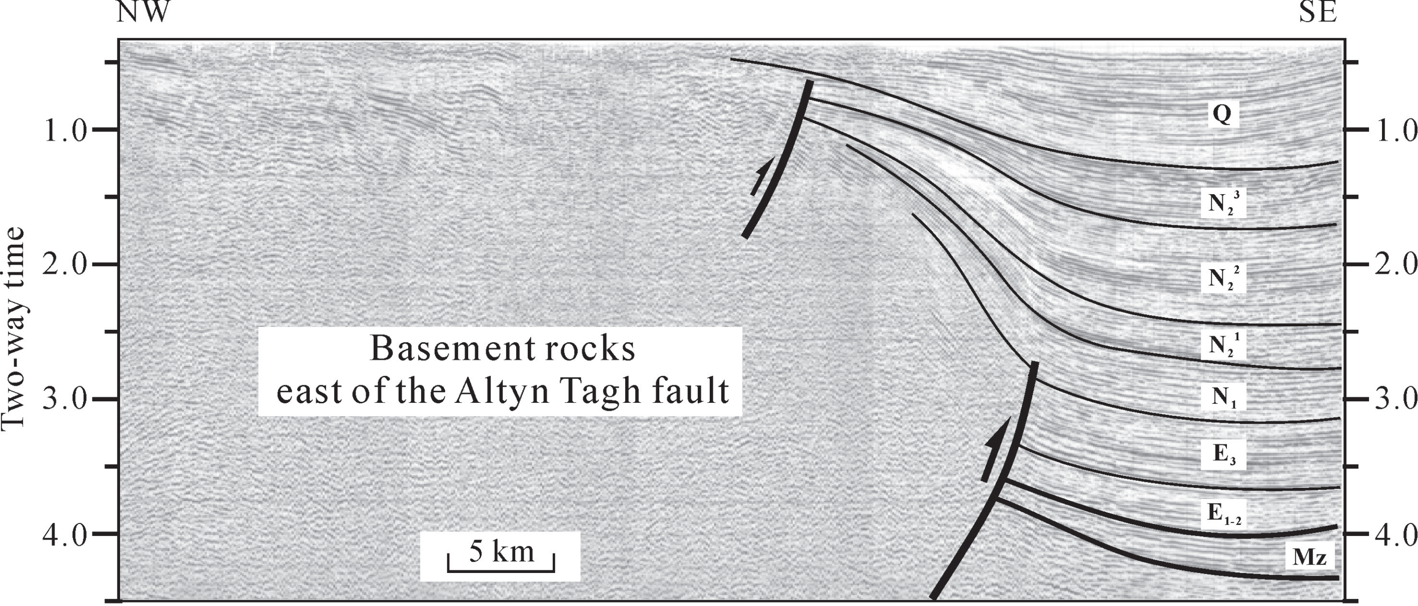


Figure 8 (Meng et al.)

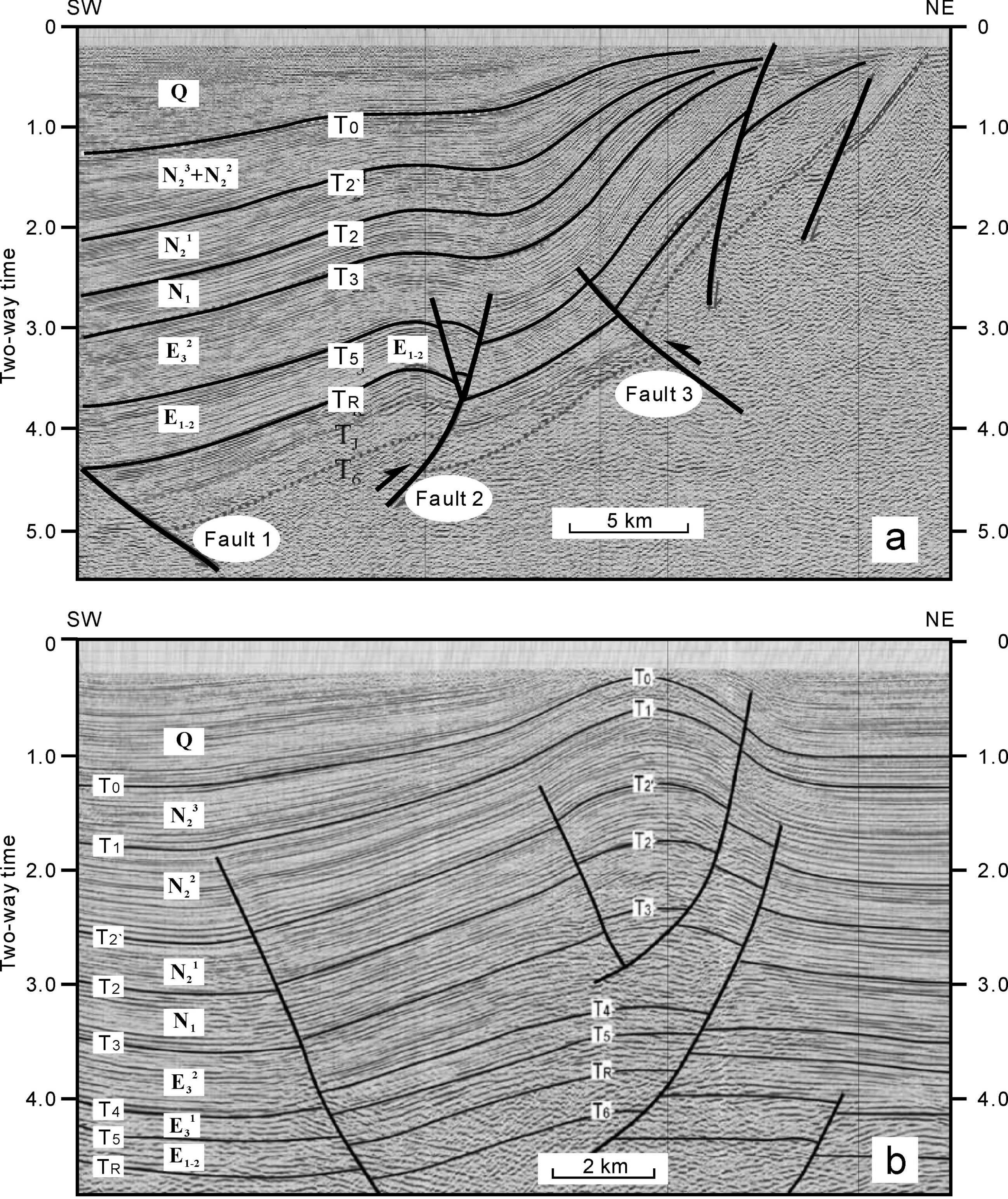


Figure 9 (Meng et al)

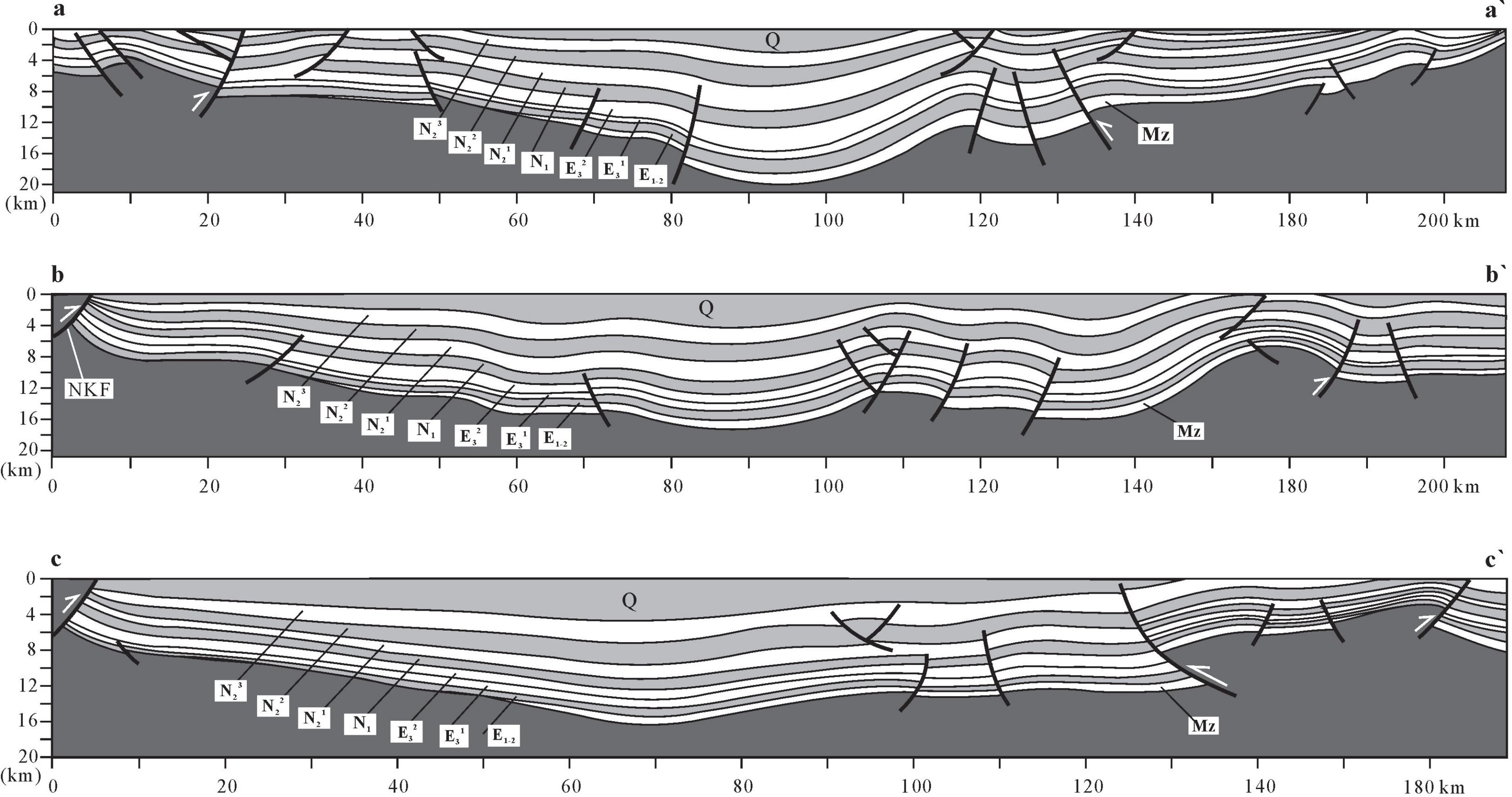
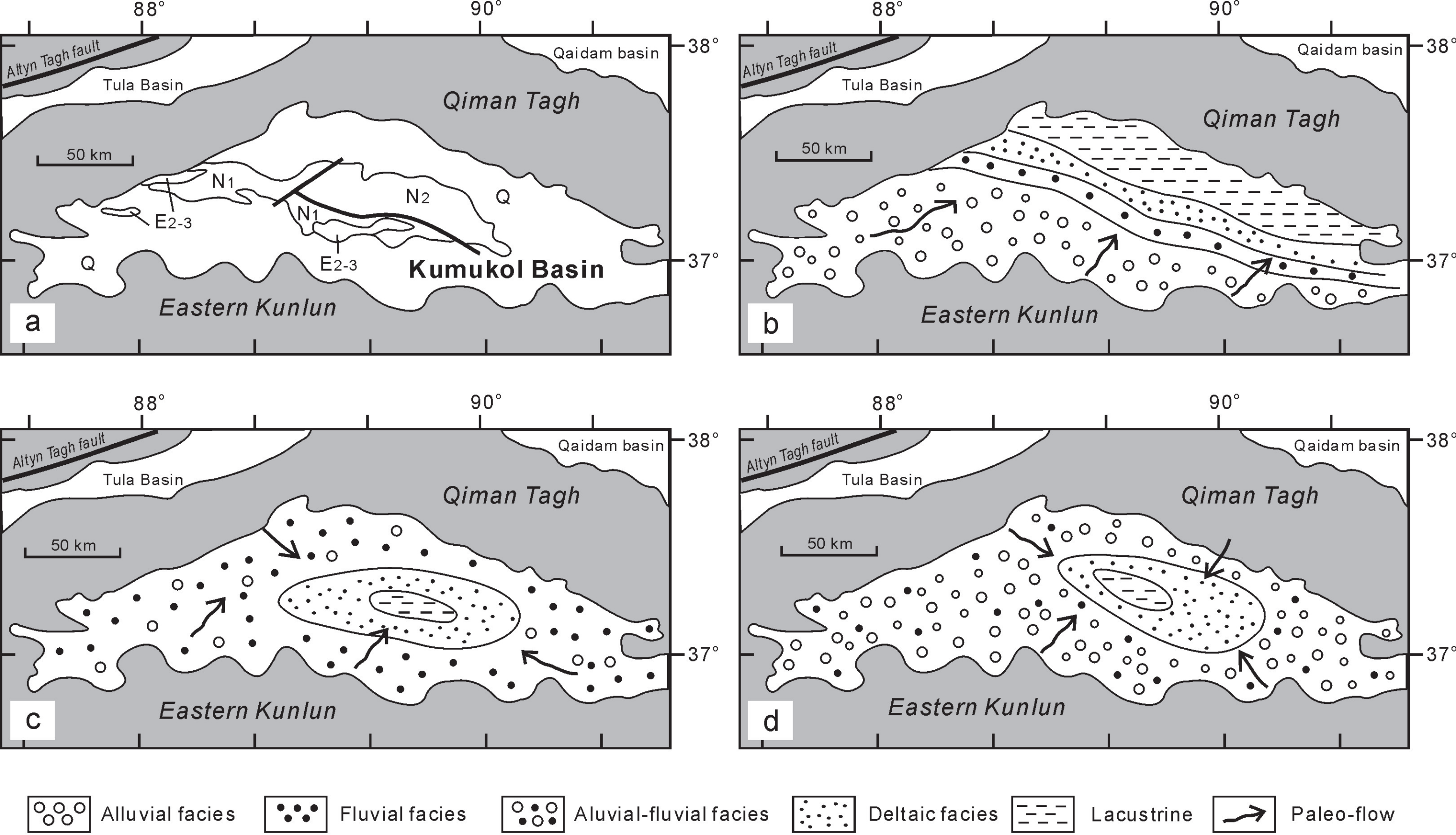


Figure 10 (Meng et al.)



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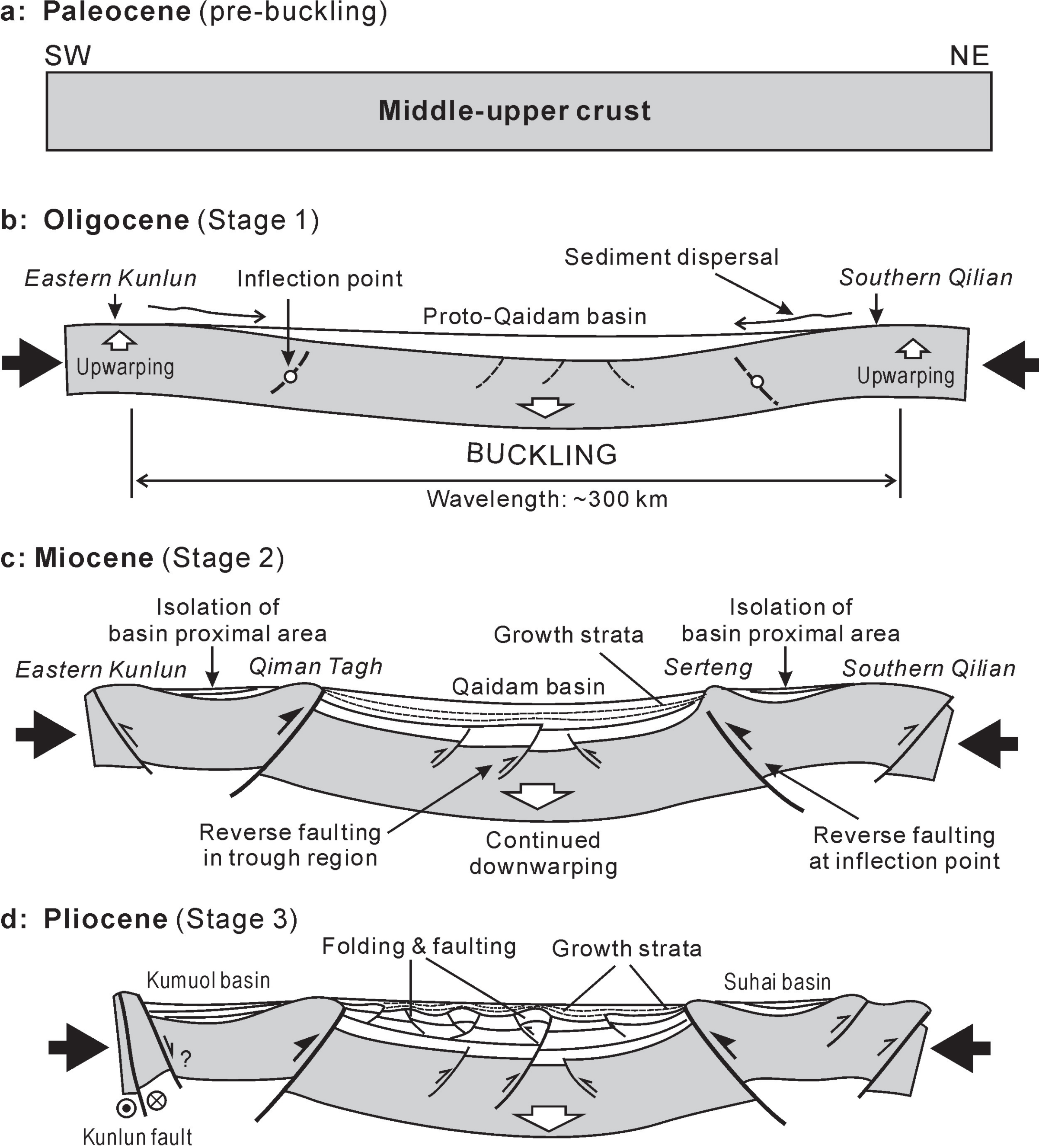

Figure 12 (Meng et al.)

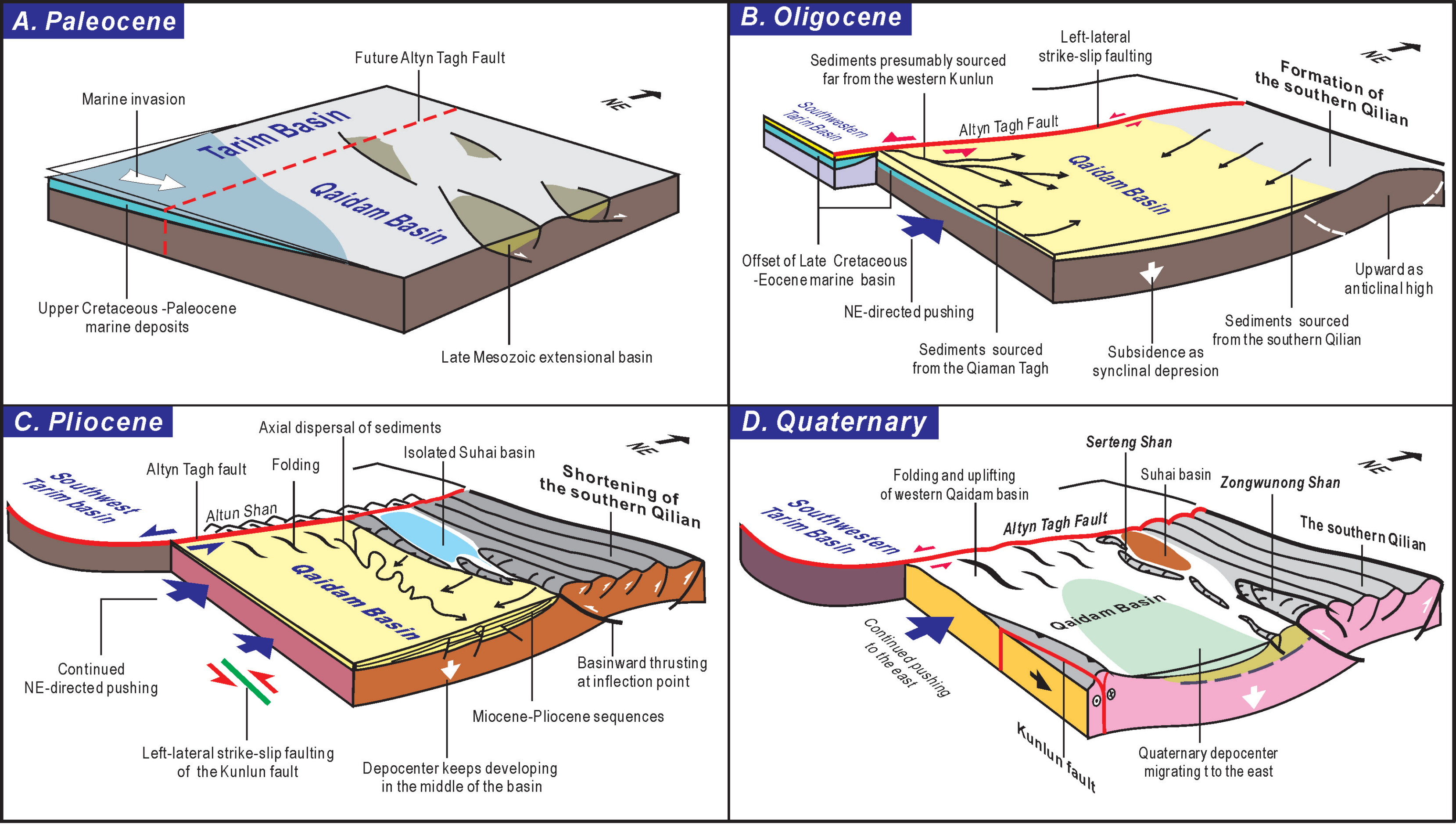

Figure 13 (Meng et al.)