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Seismotectonics of the 2008 and 2009 Qaidam Earthquakes and its Implication for Regional Tectonics

CHEN Guihua[1, 2, *], XU Xiwei[1], ZHU Ailan[3], ZHANG Xiaoqing[4], YUAN Renmao[1],
Yann KLINGER[5] and Jean-Mathieu NOCQUET[6]

1 *Key Laboratory of Active Tectonics and Volcano, Institute of Geology, China Earthquake Administration, Beijing 100029, China*
2 *Tectonics Observatory, California Institute of Technology, Pasadena, CA 91125, USA*
3 *Earthquake Administration of Shanghai Municipality, Shanghai 200062, China*
4 *Earthquake Administration of Qinghai Province, Xining 810001, Qinghai, China*
5 *Institut de Physique du Globe, CNRS, Paris 75005, France*
6 *Geoscience Azur, Valbonne 06560, France*

Abstract: Three magnitude >6 earthquakes struck Qaidam, Qinghai province, China, in November 10th 2008, August 28th and 31st 2009 respectively. The Zongwulongshan fault has often been designated as the active seismogenic structure, although it is at odd with the data. Our continuous GPS station (CGPS), the Xiao Qaidam station, located in the north of the Qaidam basin, is less than 30 km to the southwest of the 2008 earthquake. This CGPS station recorded the near field co-seismic deformation. Here we analyzed the co-seismic dislocation based on the GPS time series and the rupture processes from focal mechanism for the three earthquakes. The aftershocks were relocated to constrain the spatial characteristics of the 2008 and 2009 Qaidam earthquakes. Field geological and geomorphological investigation and interpretation of satellite images show that the Xitieshan fault and Zongwulongshan fault were activated as left lateral thrust during the late Quaternary. Evidence of folding can also be identified. Integrated analyses based on our data and the regional tectonic environment show that the Xitieshan fault is the fault responsible for the 2008 Qaidam earthquake, which is a low dip angle thrust with left lateral strike slip. The Zongwulongshan fault is the seismogenic fault of the 2009 earthquakes, which is a south dipping back thrust of the northern marginal thrust system of the Qaidam basin. Folding takes a significant part of the deformation in the northern marginal thrust system of the Qaidam basin, dominating the contemporary structure style of the northern margin of the Qaidam basin and Qilianshan tectonic system. In this region, this fault and fold system dominates the earthquake activities with frequent small magnitude earthquakes.

Key words: Qaidam earthquakes, seismotectonics, Xitieshan fault, Zongwulongshan fault, structure style

1 Introduction

On November 10th, 2008, an earthquake of magnitude Ms6.6 (Mw6.3) struck Qaidam, Qinghai province, China, at 1:22 (UTC). The earthquake was located to (N37.66°, E95.91°), with a depth of 16 km (http://www.csndmc.ac.cn/). Two other earthquakes with a magnitude larger than 6 occurred in this area on 28th and 31st of August, 2009. The 28th Ms6.6 earthquake was located at (N37.60°, E95.90°) and the 31st Ms6.1 earthquake is (N37.74°, E95.98°) , with a depth of 7–13 km (Fig. 1). Another group of earthquakes located few tens of kilometers to the east, already struck the region in 2003 with the main shock, Ms6.6, occuring on 17th April 2003. Although a few active faults have been mapped in the northern margin of the Qaidam basin, because of the low population and moderate damages, only limited research ever focussed on the local seismotectonics and the detailed sub-surface active tectonics of this area (Jiang et al., 2006; Sun et al., 2006, 2012; Li et al., 2010). Recently, researchers proposed that the steep Zongwulongshan thrust was a seismogenic fault, based on

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* Corresponding author. E-mail: gh_chen@163.com

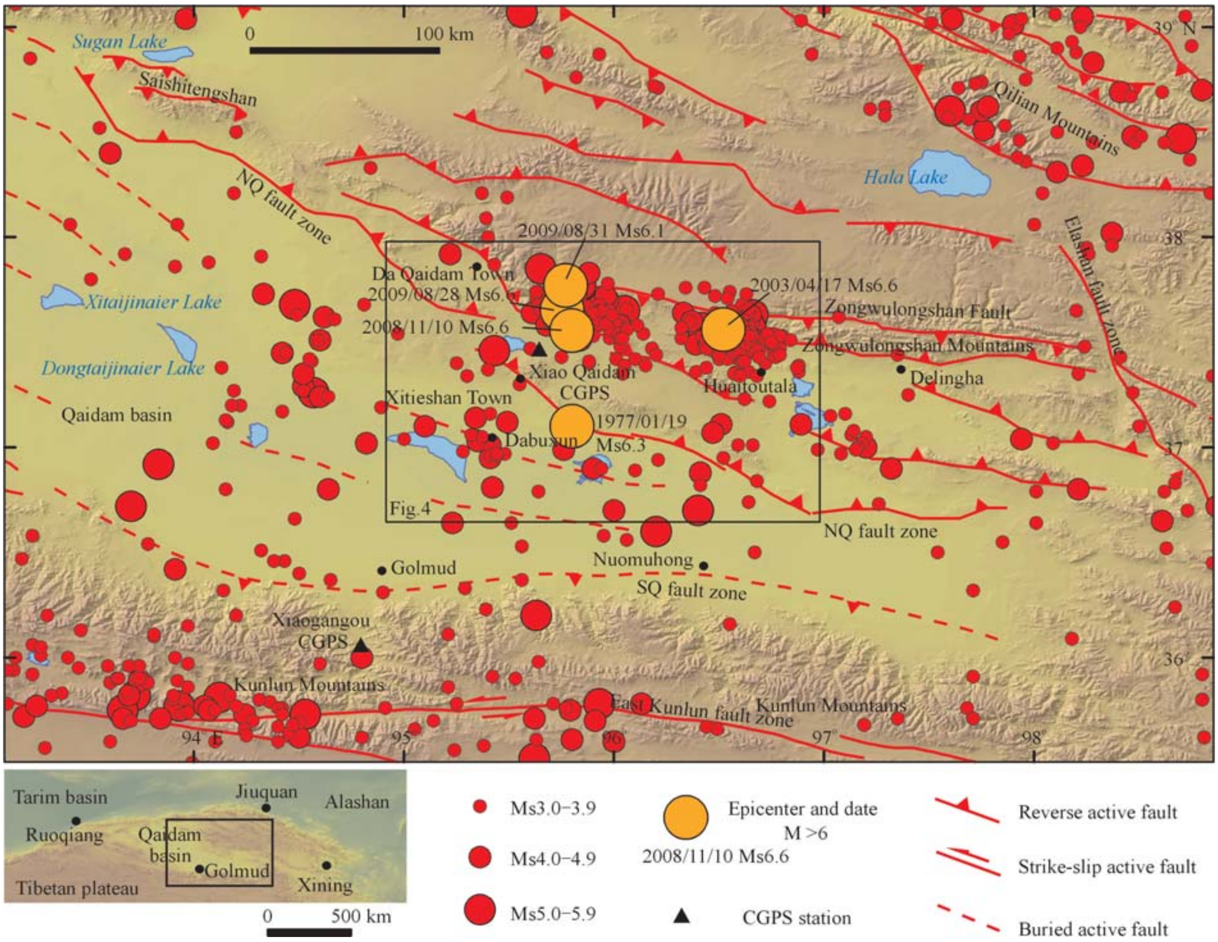

Fig. 1. Regional active faults (Modified from Deng et al., 2003 and Taylor et al., 2009) and seismicity (catalogs from http://www.csndmc.ac.cn) around the northern margin of the Qaidam basin.

the co-seismic deformation measured from InSAR data, associated to the 2008 earthquake (Elliott et al., 2011; Wen et al., 2012) and the 2009 earthquakes (Elliott et al., 2011). The proposed fault model, a right lateral motion for the Zongwulongshan thrust, however, is not incorporating any field measurements, and is at odd with local geological observations（Ye et al., 1996; Wu et al., 2009; Li et al., 2010). In 2007, we set up a continuous GPS (CGPS) profile across the Kunlun Mountains and the Qaidam basin. This local CGPS network recorded the crustal deformation due to the 2008 and 2009 earthquakes. Incorporated with the seismological data and field observations, we have a chance to understand the seismogenic tectonics of these earthquakes and to assess the regional earthquake hazard. This earthquake region is located in the northern margin of the Qaidam basin, close to the active Qilianshan tectonic belt. Hence, the Qilianshan and the northern margin of the Qaidam basin act as the northern boundary of the Tibetan plateau. Active tectonics in northern margin of Qaidam basin is a basic step in research on the Quaternary deformation style and seismogenic behavior. It is also providing constrains on the evolution of the northern part of the Tibetan plateau.

2 Methods

According to the fault dislocation and elastic-rebound model (Reid, 1910), the long-term displacement relates to the inter-seismic displacement and the co-seismic displacement as shown in Fig. 2. Each wall of the fault will have a different inter-seismic and co-seismic displacement pattern. We will have a chance to determine spatial relationships between the seismogenic fault and the survey station, with the inter-seismic and the co-seismic crustal deformation recorded by our local GPS stations.

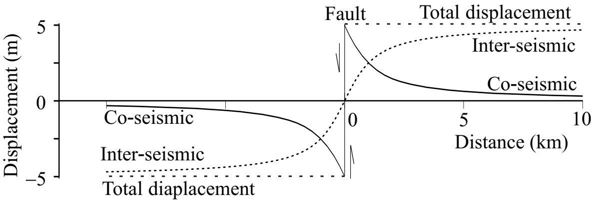

Fig. 2. Sketch of fault dislocation and elastic-rebound model.

We may also derive the kinematic parameters from the inversion of some seismological records. The focal mechanism solution provides fault planes and the associated style of deformation, such as strike-slip or dip-slip, left lateral or right lateral. Only one of these planes represents the active plane that is moving during the earthquake. We usually cannot distinguish which is the active fault plane from the two planes of the focal mechanism solutions with seismology alone. Each plane, however, characterises a different deformation pattern and, in most cases, only one can match the regional crustal stress and the fault attribute, especially for strike-slip faults. Once the seismogenic plane solution has been ascertained, it is easier to know the spatial relationship between the epicenter and the fault trace. Relocated aftershocks are regarded to reflect the stress distributions and strain distributions related to the seismogenic structure.

3 Data and Results

3.1 Co-seismic continuous GPS records

Among our CGPS deployed across the Kunlun Mountains and the Qaidam basin, the Xiao Qaidam station (E95.64, N37.47) is located about 30 km of the epicenter of the 2008 Qaidam earthquake. The other seven stations located to the south of the Qaidam basin are between 190 and 330 kilometers from the epicenter. Our receivers record data with a 30 seconds sampling rate. On average, our CGPS stations have a high proportion of data coverage, although the Xiao Qaidam station lost a lot of data since mid-2009, due to interferences with a newly setup telecom station located very close to our CGPS station.

We processed the CGPS data using the GAMIT and GLOBK packages (Herring et al., 2010) with about 20 neighboring IGS sites included, to provide reference frame stability. The daily time series show that the Xiao Qaidam station experienced obvious offsets during the 2008 and 2009 earthquakes. No identifiable similar signal can be found among our other CGPS stations, located more than 180 km further south across the Qaidam basin.

We took the baseline time series between the Xiao Qaidam station and the Xiaogangou station (Fig. 1), which is located south of the city of Golmud, as a reference. The co-seismic jumps of the Xiao Qaidam station are shown in Fig. 3. The near-field Xiao Qaidam station jumped westward with a displacement of 14 mm, about 9mm southward, and a detectable uplifted of ~10 mm. The most important observation is that the length of the baseline shortened about 14 mm, which means the co-seismic shortening by the seismogenic structures between these two stations. Unfortunately, in 2009 we were not able to distinguish the August 28th earthquake from the August 31st earthquake with our CGPS data due to data missing, and only the integrated deformation is shown in Fig. 3. The Xiao Qaidam station jumped eastward with a displacement about 4 mm, about 15 mm northward, and no obvious uplift. The baseline lengthened back to its initial length before the 2008 earthquake, about 14 mm. Hence, the deformation viewed at the Xiao Qaidam station was almost the opposite during the 2008 earthquake and during the 2009 earthquake. The baseline between the Xiao Qaidam station and the Xiaoganggou station is nearly N-S and it is sub-perpendicular to the northern Qaidam fault and the Zongwulongshan fault. The northern component and the length of this baseline is sensible to the dip slip of these faults, and the eastern component is sensible to the strike slip.

3.2 Focal mechanisms of the main shocks and the relocation of aftershocks

Liu et al. (2010) calculated the quick moment tensor solution for the 2008 Ms6.6 Qaidam earthquake based on seismological records from the regional network. Their result shows that one of the nodal plane strikes 268° with a dip of 37° and a rake of 54°, and the other nodal plane strikes 130° with a dip of 61° and a rake of 114°. The source was located about 10 km deep. The global CMT solution for the 2008 earthquake is similar to the result from Liu et al. (2010) (Fig. 4). One of the nodal planes strikes 252° with a dip of 28° and a rake of 57°, and the other nodal plane strikes 108° with a dip of 67° and a rake of 106° (http://www.globalcmt.org). Although the low density of stations in the seismic network may introduce uncertainties in the determination of the focal mechanisms, these solutions for the 2008 earthquake indicate that the north-dipping plane should have slipped left-laterally and the south-dipping plane should have slipped right-laterally.

The global CMT results (http://www.globalcmt.org) for the August 28th, 2009 earthquake (N37.64°, E95.76°) show that one of the nodal planes strikes 295° with a dip of 31° and a rake of 102°, the other nodal plane strikes 101° with a dip of 60° and a rake of 83°, and that the source is about 12 km deep. The solutions indicate that the north-dipping plane should have slipped right-laterally and the south-dipping plane should have slipped left-laterally. The solution for the August 31st Mw 5.8 (Ms6.1) earthquake shows that one of the nodal planes strikes 277° with a dip of 33° and a rake of 90°, the other nodal plane strikes 98° with a dip of 57° and a rake of 90°, and that the source is about 12 km deep. The seismogenic fault seems to be moving purely as a dip-slip.

We relocated the earthquakes recorded around the study

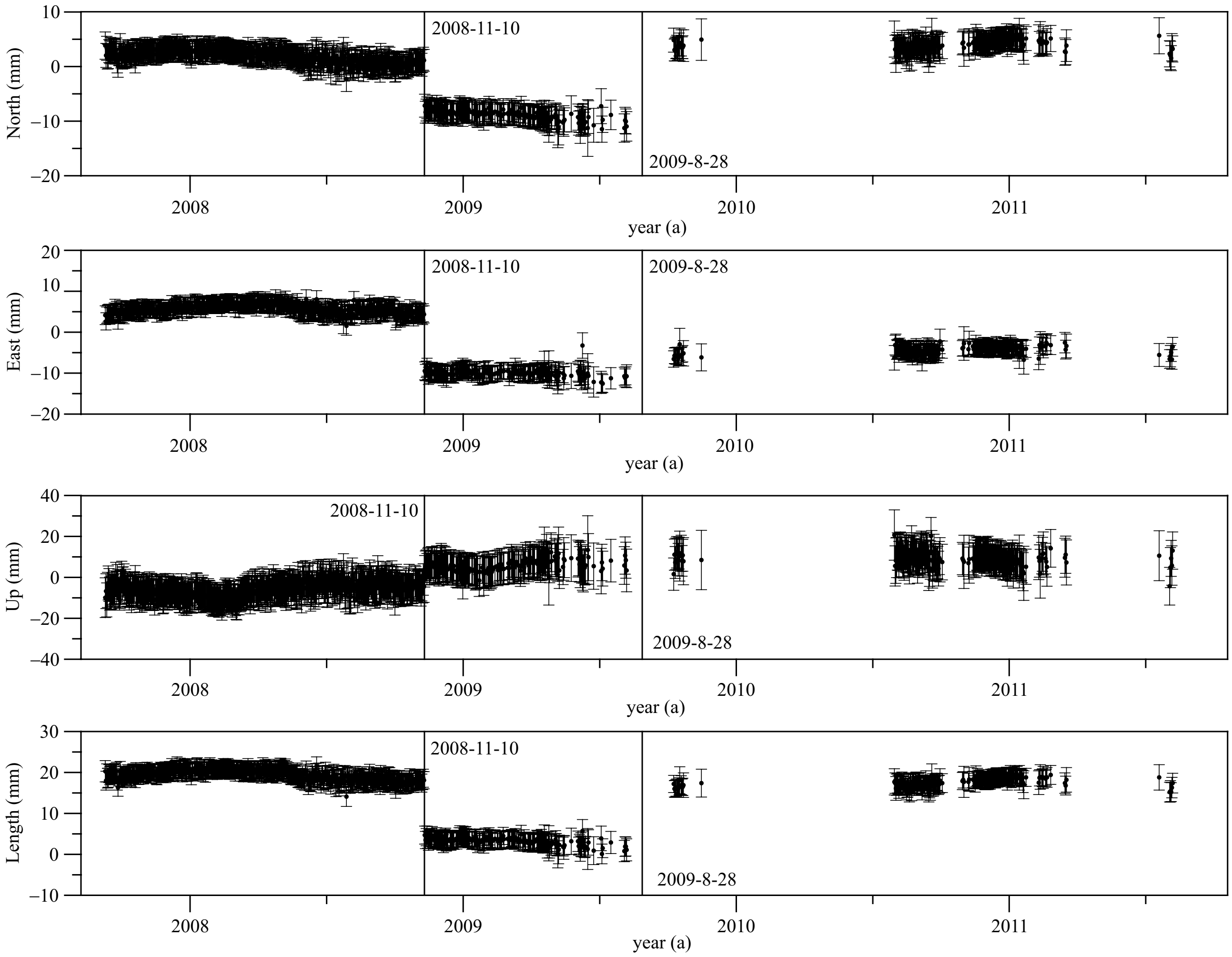

Fig. 3. Time series of the baseline between Xiao Qaidam station and Xiaogangou station.

area using a double-difference algorithm (Waldhauser and Ellsworth, 2000). About 1763 earthquakes were used, which were recorded in 23 stations. We only kept events with no less than 6 P and S wave records. We adopted the velocity – structure model from the Taiwan - Altay geo-section crossing the Qaidam basin and the Qilian Mountains from Wang et al. (2005). About 1490 earthquakes were relocated with a RMS residual of 0.46 s, to be compared to 1.1 s before relocation. The average horizontal standard deviation is 1.3 km, and the vertical deviation is 2.9 km.

In Fig. 5 are plotted the aftershocks following the 2008 Ms6.6 earthquake until August 18th, 2009. The earthquakes mainly concentrate in a narrow region about 5–20 km deep above the main shock, as projected on a NE23° profile that is perpendicular to the tectonic belt (Figs. 5a, 5c), and they distribute to the east, above the main shock, as projected on a SE113° profile (Figs. 5a, 5d). In contrast to the earthquakes following the 2008 earthquake, the earthquakes following the 2009 Ms6.6 earthquake distribute in a belt with a width up to 20 km as projected to a NE23° profile (Figs. 5b, 5e), and are mainly located to the north. They are mostly concentrated between 5 km to 20 km at depth. The earthquakes following the 2009 earthquake also distribute in a wide range as projected to a SE113° profile (Figs. 5b, 5f). The relocated earthquakes show that the aftershocks following the 2009 earthquakes were located to the north of the aftershocks following the 2008 earthquake, with a similar depth, suggesting a horizontal migration. The aftershocks distribute in a rather wide range, which reflects the strain adjustment that the hanging wall of the seismogenic reverse faults experienced.

3.3 Geological and geomorphological evidences of fault activities

3.3.1 The Xitieshan fault

The Xitieshan fault forms the border between the base rocks of the Xitieshan Mountains and the Quaternary sediments of the Qaidam basin (Figs. 4, 6). Several offset landforms recorded the late Quaternary activity of this

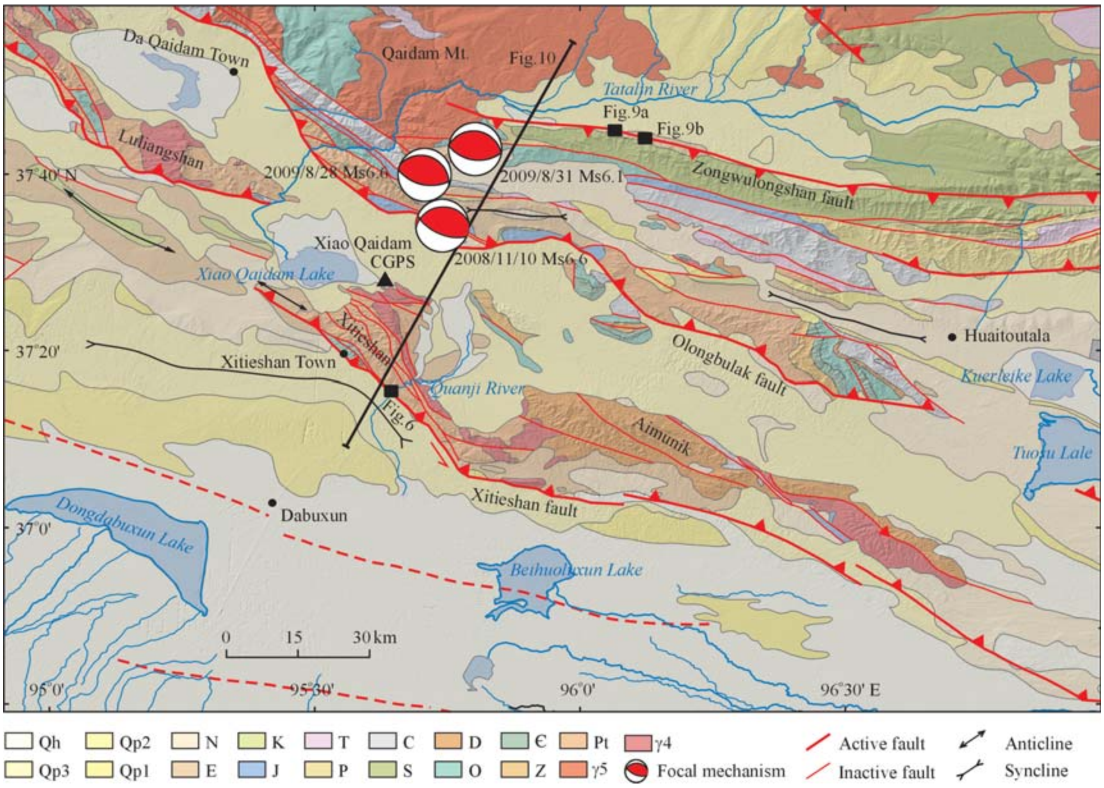

Fig. 4. Simplified Geological map overlying shaded topography with focal mechanism solutions.

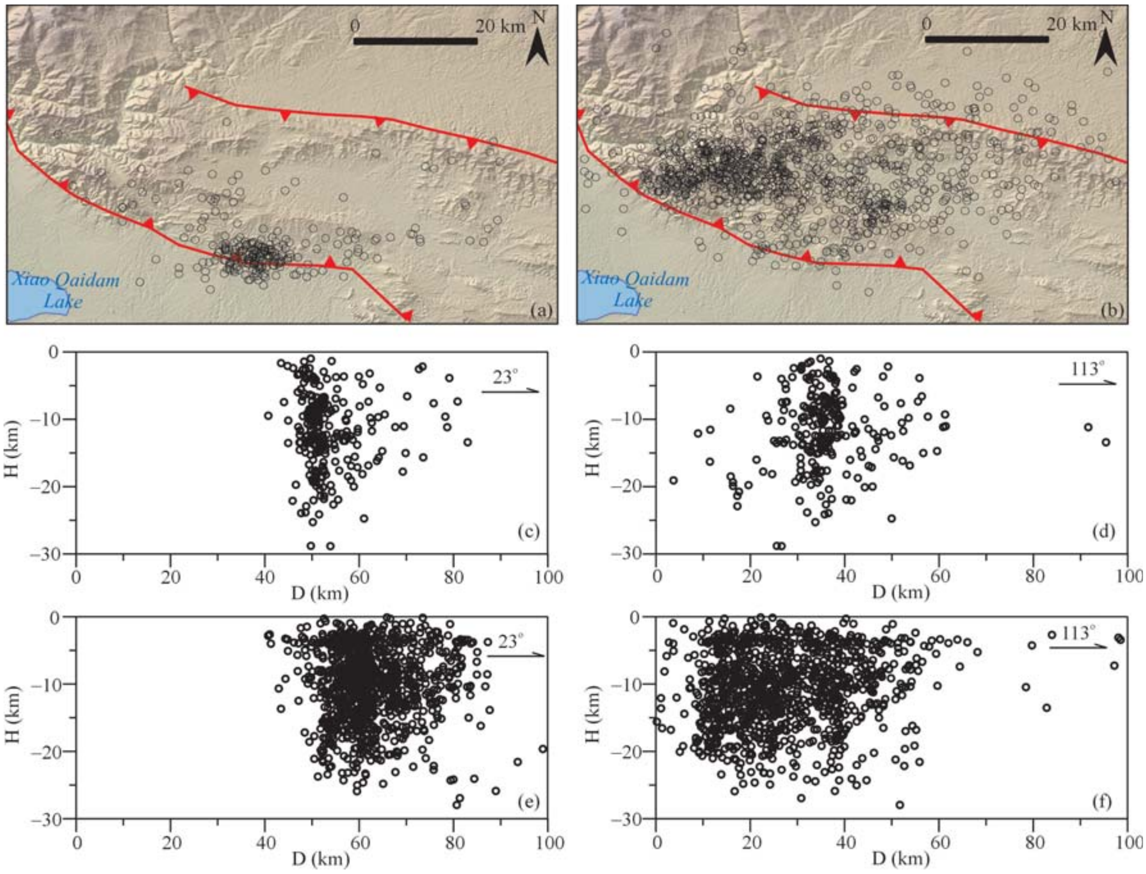

Fig. 5. Relocated aftershocks around the 2008 and 2009 earthquakes.

aftershocks between Nov. 10th 2008 and Aug. 18th 2009: map view (a); NE23° profile (c); SE113° profile (d); aftershocks between Aug. 28th 2009 and Dec. 31st 2009: map view (b); NE23° profile (e); SE113° profile (f).

Fig. 6. Image showing the offset of the Quanji River at the piedmont near the Xitieshan Railway Station.

fault. Ye (1996) reported their field work near the outreach of the Quanji River and we lead ourself detailled field inverstigations along that fault.

To the east of the Xitieshan railway station, the Quanji River cuts through the Xitieshan Mountains and forms a deep-incised valley. The strong incision is related to the strong uplift along the fold and thrust belt of the northern margin of the Qaidam basin. From a southward direction, the river turns to the east at the mountain front, and follows the fault. Then the river goes south again and incises into the alluvial fan surface. The river riser on the highest terrace seems to be offset about 325 m from its initial position. Although the age of this fan is presently unkown, the fact that the Quaternary surface of the fan is offset proves that the Xitieshan fault is still active after the formation of the alluvial fans.

As shown in the cross-section exposed in the incision of the Quanji River (Figs. 7a, 7b), the Neogene sandstone thrusts over the Quaternary loose layers of sands and gravels. The sandstones near the fault in the hanging wall

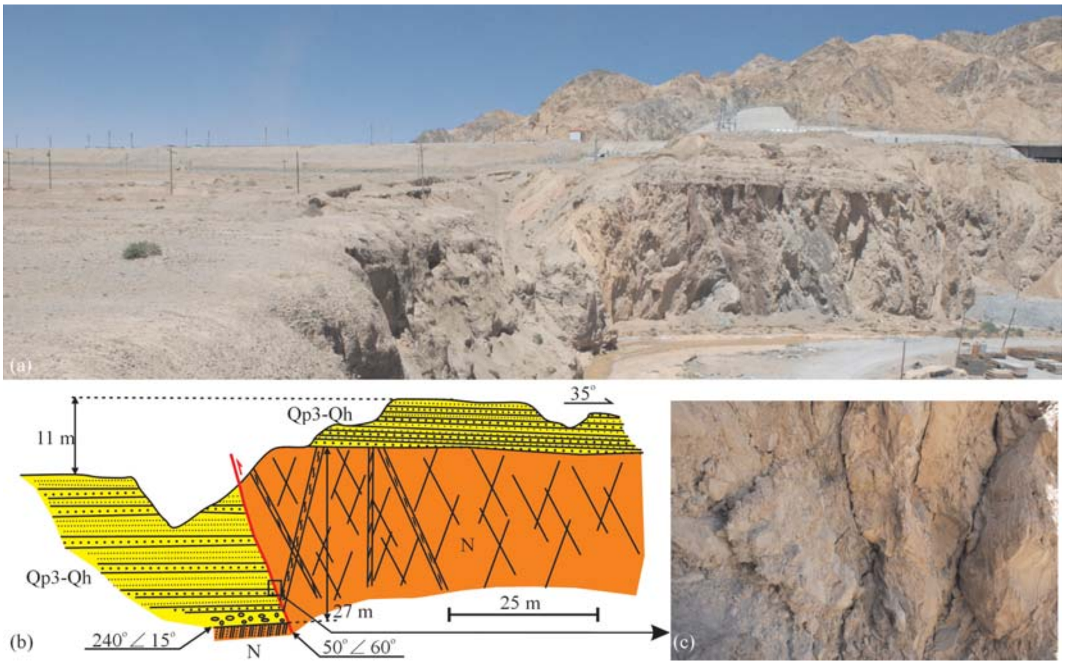

Fig. 7. Field photo (a), profile (b) of the Xitieshan fault excavated by the Quanji River, and foliations along the fault plane (c).

are fractured, and the foliations are developed along and parallel to the fault plane (Fig. 7c). The incising surface of the Neogene is displaced vertically about 27 m, while the old alluvial fan is displaced about 11 m (Fig. 7b). Based on the recent regional climate changes (Wang and Xue, 1998; Owen et al., 2006; Chen et al., 2011; Zheng et al., 2011), the last episode of strong incision, transport and deposition of alluvial sediments in the north of Tibetan plateau took place about 38 ka, associated to the last interglacial, and the end of the major deposition of the main alluvial fans was about 18 ka. If we take account of the vertical offset and the assumed ages for the corresponding landforms, the average slip rate of the Xitieshan fault can be estimated about 0.7 mm/a since 38 ka. More direct dating, however, is in need to constrain this first order estimate.

About 1 km to the east of the site mentioned above, the Xitieshan fault produces a 1.7 m high scarp accross an alluvial fan (Fig. 8a). The Late Pleistocene sands thrust over the loose alluvial sands and gravels along the scarp (Fig. 8b). According to the comparison with the regional alluvial deposition records (Owen et al., 2006; Chen et al., 2011), the offset fan was abandoned about 3 ka. Therefore, it shows the fault was quite active in the past three thousand years.

3.3.2 The Zongwulongshan fault

The Zongwulongshan fault cuts through the southern bank of the Tatalin River. The fault trace is curvy, which is characteristic of reverse faults. When the Tatalin River flows across the Qaidam Mountains southwestward, a deep incising valley is formed without much remnant of terrace. While there are a few terraces, which developed in the broad valley to the northeast of the Qaidam Mountains and on the alluvial fans at the front of the mountains. The recent deformations along the Zongwulongshan fault have made the hanging wall uplifted and incised by the Tatalin River during the late Quaternary.

Along the south bank of the Tatalin River, a few offset landforms indicate that the Zongwulongshan fault moved both verticaly and horizontaly, in a left lateral fashion. The streams perpendicular to the fault record less offset than the streams that have a small angle with the fault. At site a (E96°3'0", N37°45'2") (Fig. 9a) and at site b (E96°6'30", N37° 44'10") (Fig. 9b), many streams were offset systematically and abandoned. Because of the remoteness of these sites, no field mapping or dating is available yet to quantify the activity of the Zongwulongshan fault. Nevertheless, we can infer from these offset streams that the Zongwulongshan fault is currently active.

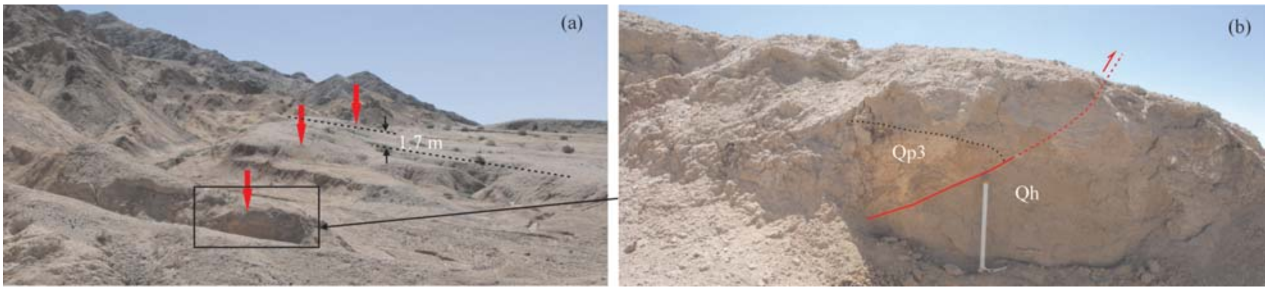

Fig. 8. Offset alluvial fans (a) and fault profile (b) of the Xitieshan fault.

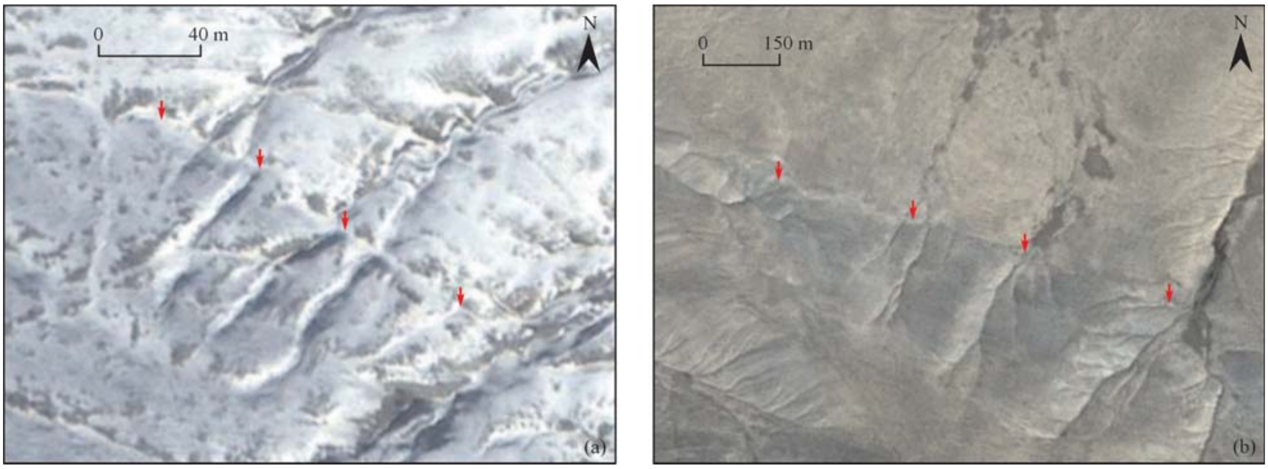

Fig. 9. Offset streams and abandoned channels along the Zongwulongshan fault (See Fig. 4 for location).

4 Discussions

4.1 Seismogenic faults responsible for the Qaidam earthquakes

Previous researches on the 2003 Delingha earthquakes (Jiang et al., 2006; Sun et al., 2006), and about the 2008 and 2009 Qaidam earthquakes (Li et al., 2010; Elliott et al., 2011), all concluded that the NWW striking Zongwulongshan fault was responsible for these earthquakes. If we take into account the fact that the Zongwulongshan fault is located on the north of these earthquakes (Fig. 4), we should have a south-dipping reverse fault. The focal mechanism solution mentioned earlier shows that the south-dipping plane for the Nov. 10th 2008 Ms6.6 earthquake is reverse and right lateral, while the south-dipping plane for the Aug. 28th 2009 Ms6.6 earthquake is reverse and left lateral. According to the geodesy around the Tibetan plateau and its surrounding areas (Gan et al., 2007), and also our 8 CGPS data, the GPS stations in the northeastern Tibetan plateau move in a northeast direction with respect to the stable Eurasia plate, and the vectors decrease to the northeast. Therefore, the NWW and E-W trending faults are reverse with left lateral motion on the northern margin of the Qaidam basin and the Qilianshan - Hexi Corridor area. It is also confirmed by our field geological and geomorphological investigations described above. Hence, it is incompatible with current regional kinematics to infer that the Zongwulongshan fault would be responsible for the 2008 earthquake. As a result, the fault plane for the 2008 Ms6.6 earthquake is the left lateral, north-dipping reverse fault plane, with small dip angle, and the fault trace is located to the south of the epicenter. The 2009 Ms6.6 earthquake fault plane is the left lateral, south-dipping reverse fault plane with a high dip angle, and the fault trace is located to the north of the epicenter.

According to the fault dislocation and the elastic-rebound theory (Reid, 1910), the long-term displacement relates with the inter-seismic and the co-seismic displacement, as shown in fig. 2. As mentioned above, this region is under compression and left lateral shear. Hence, the baseline from the Xiao Qaidam CGPS station to the Xiaogangou station becomes short in the long-term. For the 2008 earthquake, the co-seismic dislocation makes the baseline from Xiao Qaidam station to Xiaogangou station become shorter with the northern component moving southward and the eastern component moving westward. It shows that these two stations are located in different side of the seismogenic fault. Therefore, the seismogenic fault has to be located to the south of the Xiao Qaidam CGPS station. A similar analyses on the co-seismic dislocation of the 2009 earthquakes indicates that the seismogenic fault has to be located to the north of the Xiao Qaidam CGPS station.

We estimated the position of the fault trace based on the source depth (27.2 km) and the location of the epicenter (N37.51°, E95.75°) from global CMT, and we got an approximate nearest fault outcrop about 51 km away from the epicenter with an azimuth of 162°. If we take into account the fact that the dip angle increases when the fault becomes shallower and the variation of the fault plane, the fault would outcrop within 50 km to the south of the epicenter of the 2008 Qaidam earthquake (Fig. 4). With a low density and a poorly distributed seismic network, there are quite large uncertainties in the locations for the 2008–2009 mainshocks, which thereafter affect the inversion of focal mechanisms. But researches from China Earthquake Network Center, USGS and Elliottt et al. (2011) indicate that the 2008 earthquake had a depth of 16–27 km and was about 40–50 km away from the Xitieshan fault. Our Xiao Qaidam CGPS station is located between the epicenter and the Xitieshan fault. In addition, our geological and geomorphological data suggest that the Xitieshan fault is quite active during the late Quaternary and bears potential for strong earthquakes. Hence, the Xitieshan fault is regarded as the most probable seismogenic fault for the 2008 Qaidam earthquake, as one fault part of the active fault system in the northern margin of the Qaidam basin.

According to the CGPS data, the focal mechanism, aftershocks relocation and InSAR data (Elliott et al., 2011), the fault responsible for the 2009 Ms6.6 and Ms6.1 earthquakes is located to the north of the earthquakes, and also to the north of the Xiao Qaidam CGPS station. The offset landforms show that the Zongwulongshan fault is quite active. Therefore, the Zongwulongshan fault could be a good candidate as the source of the 2009 earthquakes. Many regional geological studies show that there is a southward thrusting fault and fold system in the northern Qaidam and southern Qilian area (Cui et al., 1995; Wang et al., 2001; Tang et al., 2002; Liu et al., 2005; Yin et al., 2007, 2008a, 2008b; Wu et al., 2009). Our data also confirm that the Zongwulongshan fault is a back thrust. In Fig. 10 we propose a conceptual model where is shown the relationship between the different faults and the location of the earthquakes of 2008 and 2009. As illustrated, the Olongbulak fault, close to the epicenter of the 2008 earthquake, may be the seismogenic fault of the 2003 Delingha earthquake (Sun et al., 2006, 2012). This fault extends to the south and is active with the Huatoutala fold. Taking into account the stress triggering between the southward thrust and the northward back thrust, the 2009 earthquakes may be regarded as the result of back thrust of the Zongwulongshan fault triggered by thrusting of the

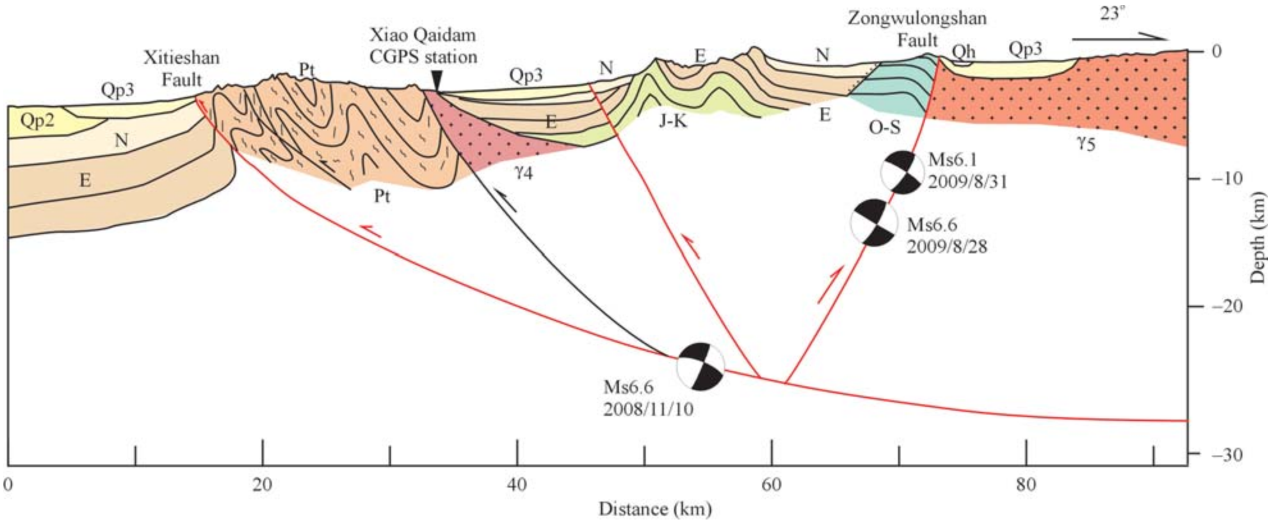

Fig. 10. Geological profile and seismotectonics model of the northern margin of the Qaidam basin (See Fig. 4 for profile line).

Xitieshan fault during the 2008 earthquake.

4.2 Regional tectonics around the northern margin of Qaidam basin

Many researches have published about the Cenozoic tectonic evolution and deformation styles of the northern margin of the Qaidam basin (Cui et al., 1995; Wang et al., 2001; Tang et al., 2002; Liu et al., 2005; Yin et al., 2007, 2008a, 2008b; Liu et al., 2009; Wu et al., 2009; Wu et al., 2012). They documented that the thrust system consists of a series of reverse and left lateral faults and folds, e.g. the Zongwulongshan fault, the Olongbulak fault, and the piedmont faults in front of Saishitengshan – Luliangshan – Xitieshan – Aimunik mountains. The piedmont faults bound the Qaidam basin, which include four en echelon faults, the Saishitengshan fault, the Luliangshan fault, the Xitieshan fault and the Aimunik fault. The Dakendaban Group and early Ordovician thrust over the Neogene and Quaternary strata, at the front of the Xitieshan Mountain Range, and the Neogene and Quaternary strata are folded even in the footwall.

It is worth noting that the late Quaternary deformation along the Xitieshan fault and the Zongwulongshan fault are not large, based only on offset landforms. While the Tatalin River incised deeply into the Qaidam Mountains in the hanging wall of the Zongwulongshan fault, and the Quanji River incised deeply into the Xitieshan Mountains in the hanging wall of the Xitieshan fault (Fig. 4). These uplifting and incising landforms indicate significant deformation in the hanging wall of the thrust during the late Quaternary. There are a series of anticlines in the north of the piedmont faults along the Saishitengshan – Luliangshan – Xitieshan – Aimunik Mountains, e.g. Huaitoutala anticline and Dahonggou anticline, and some synclines in the footwall (Ye et al., 1996; Yin et al., 2008a, 2008b). The uplift and folding absorbed a large part of shortening across the northern margin of the Qaidam basin.

The structure and earthquake activity in the northern margin of the Qaidam basin are supposed to be similar to that in the Tianshan area (Deng et al., 2000; Xu et al., 2006). From the earthquake records in the northern margin of the Qaidam basin, earthquakes usually occurred in swarms with a magnitude smaller than 7, including the 2003 Delingha earthquakes and the 2009 Qaidam earthquakes. This kind of earthquake swarms suggests that the thresholds to shift from stress accumulation to stress release is not as high as for many seismogenic faults. We propose that the ductile folding is actualy relatively significant in investigating the deformation styles and earthquake risks of the northern margin thrust system of the Qaidam basin. This kind of fault and fold system dominates the earthquake activity in such a region with small magnitude earthquakes at higher frequency.

5 Conclusions

We analyzed the co-seismic displacements recorded by our continuous GPS, the focal mechanisms, the relocated aftershocks distribution along with our field geological and geomorphological observations along the Xitieshan fault and the Zongwulongshan fault. We have been able to determine the seismotectonic setting of the 2008 and 2009 earthquakes and we propose that the Xitieshan fault is the fault responsible for the 2008 Qaidam earthquake, which is located to the south of the epicenter and of the Xiao Qaidam CGPS station. The Xitieshan fault is a southward thrust fault with low dip angle and active folding in the hanging wall. The Zongwulongshan fault would be the fault responsible for the 2009 Qaidam earthquakes. This fault is a south-dipping back thrust belonging to the northern margin thrust system of the Qaidam basin.

The Xitieshan fault and the Zongwulongshan fault are fold-related faults, and the shortening and active folding in the hanging wall take a significant part of deformation across the northern marginal thrust of the Qaidam basin. Faulting and its related folding dominate in the contemporary structure style of the northern margin of the Qaidam basin and the Qilianshan tectonic system. This kind of fault and fold system dominates the earthquake activities in such region with small magnitude earthquakes happening more frequently.

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References

Chen Yixin, Li Yingkui, Zhang Yue, Zhang Mei, Zhang Jingchun, Yi Chaolu and Liu Gengnian. 2011. Late Quaternary deposition and incision sequences of the Golmud River and their environmental implications. *Quaternary International*, 236(1–2): 48–56.

Cui Zuozhou, Li qiusheng, Wu chaodong, Yin zhouxun and Liu hongbing, 1995. The crustal and deep structures in Golmud-Ejin qi GGT. *Chinese Journal of Geophysics*, 38(s2): 15–28 (in Chinese).

Deng Qidong, Feng Xianyue, Zhang Peizhen, Xu Xiwei, Yang Xiaoping, Peng Sizhen and Li Jun, 2000. *Active tectonics of the Tianshan Mountains*. Beijing: Seismology Press (in Chinese).

Deng Qidong, Zhang Peizhen, Ran Yongkan, Yang Xiaoping, Min Wei and Chu Quanzhi, 2003. Basic characteristics of active tectonics of China. *Science in China Series D-Earth Sciences*, 46(4): 356–372.

Elliott, J.R., Parsons, B., Jackson, J.A., Shan, X., Sloan, R.A., and Walker, R.T., 2011. Depth segmentation of the seismogenic continental crust: The 2008 and 2009 Qaidam earthquakes, *Geophysics Research Letters*, 38(6), Doi 10.1029/2011gl046897.

Gan Weijun, Zhang Peizhen, Shen Zhengkang, Niu Zhijun, Wang Min, Wan Yongge, Zhou Demin and Cheng Jia, 2007. Present-day crustal motion within the Tibetan Plateau inferred from GPS measurements. *Journal of Geophysical Research-Solid Earth*. 112(B8), Doi 10.1029/2005jb004120.

Herring, T., King, R., and McClusky, S., 2010. GAMIT reference manual and GLOBK reference manual, release 10.4, Mass. Inst. of Technol., Cambridge.

Jiang Mei, Xu Zhiqin, Qian Rongyi, Wang Yajun and Zhang Lishu, 2006. Analysis of deep tectonic activity in the eastern segment of the northern margin of the Qinghai-Tibetan Plateau based on the Delingha earthquake. *Geology in China*, 33(2): 268–274 (in Chinese with English abstract).

Li Zhimin, Tu Hongwei, Tian Qinjian, Zhang Junlong and Li Wenqiao, 2010. The 2008 Ms6.3 earthquake in the Dacaidan region,Qinghai province and its seismotectonic setting. *Progress in Geophysics*, 25(3): 768–774 (in Chinese with English abstract).

Liu Dongliang, Fang Xiaomin, Gao Junping, Wang Yadong, Zhang Weilin, Miao Yunfa, Liu Yongqian and Zhang Yuezhong, 2009. Cenozoic Stratigraphy Deformation History in the Central and Eastern of Qaidam Basin by the Balance Section Restoration and its Implication. *Acta Geologica Sinica* (English edition), 83(2): 359–371.

Liu Chao, Xu Lisheng and Chen Yuntai, 2010. Quick moment tensor solutions for 32 moderate and large earthquakes of October 2008-November 2009. *Acta Seismologica Sinica*, 32 (5): 619–624.

Liu Zhihong, Wan Chuanbiao, Yang Jianguo, Liu ZhenWen and Gao Junyi, 2005. Cenozoic structural features and deformation regularities of the northern Qaidam basin, China. *Chinese Journal of Geology*, 40(3): 404–414 (in Chinese with English abstract).

Owen, L.A., Finkel, R.C., Ma Haizhou, and Barnard, P.L., 2006. Late Quaternary landscape evolution in the Kunlun Mountains and Qaidam Basin, Northern Tibet: a framework for examining the links between glaciation, lake level changes and alluvial fan formation. *Quaternary International*, 154–155: 73–86.

Reid, H.F., 1910. *The Mechanics of the Earthquake, The California Earthquake of April 18, 1906, Report of the State Earthquake Investigation Commission, Volume 2*, Washington, D.C.: Carnegie Institution of Washington, 192.

Sun Changhong, Qian Rongyi, Xiao Guolin and Meng Xiaohong, 2006. The relocation and seismogenic structure of the Delingha earthquake sequence of 2003 in Qinghai. *Geophysical & Geochemical Exploration*, 30(1): 79–82 (in Chinese with English abstract).

Sun Changhong, Xu Feng, Yang Yubo, Qian Rongyi and Meng Xiaohong, 2012. Focal mechanism solutions of 2003 Delingha, Qinghai, M6.7 earthquake sequence and its tectonic implication. *Chinese Journal of Geophysics*, 55(10): 3338–3346 (in Chinese with English abstract).

Tang Liangjie, Jin Zhijun , Dai Junsheng, Zhang Mingli and Zhang Bingshan, 2002. Regional Fault Systems of Qaidam Basin and Adjacent Orogenic Belts. *Earth Science-Journal of China University of Geosciences*, 27(6): 676–682 (in Chinese with English abstract).

Taylor, M., and Yin, A., 2009. Active structures of the Himalayan-Tibetan orogen and their relationships to earthquake distribution, contemporary strain field, and Cenozoic volcanism. *Geosphere*, 5(3): 199–214.

Waldhauser, F., and Ellsworth, W., 2000. A double-difference earthquake location algorithm: method and application to the northern Hayward fault, California. *Bulletin of Seismological Society of America*, 90(6): 1353–1368.

Wang Genhou, Ran Shuming and Li Ming, 2001. The characteristics of Neogene Sertengshan-Xietieshan oblique thrust fault in the northern margin of Qaidam basin. *Journal of Geomechanics*, 7(3): 224–230 (in Chinese with English abstract).

Wang Youxue, Mooney W.D., Han Guohua, Yuan Xuecheng and Jiang Mei. 2005. Crustal P–wave velocity structure from Altyn Tagh to Longmen mountains along the Taiwan–Altay geoscience transect. *Chinese Journal of Geophysics*, 48(1): 98–106 (in Chinese with English abstract).

Wang Sumin and Xue Bing, 1998. Regional environmental differentiation in China since the mid–pleistocene inferred from lake records and its relation with East Asian monsoons. *Acta Geologica Sinica* (English edition), 72(3): 314–320.

Wen Yangmao, Xu Caijun, Liu Yang and He Ping. 2012. Source Parameters of 2008 Qinghai Dachaidan Mw 6.3 Earthquake from InSAR Inversion and Automated Fault Discretization Method. *Geomatics and Information Science of Wuhan University*, 37(4): 458–462.

Wu Zhenhan, Hu Daogong, Wu Zhonghai, Ye Peisheng and Zhou Chunjing, 2009. Quaternary sinistral-slip thrusting in north margin of Qaidam basin. *Quaternary Sciences*, 29(3): 599–607 (in Chinese with English abstract).

Wu Zhenhan, Ye Peisheng, Barosh, P.J., Hu Daogong, Lu Lu and Zhang Yaoling, 2012. Early Cenozoic Mega Thrusting in the Qiangtang Block of the Northern Tibetan Plateau. *Acta Geologica Sinica* (English edition), 86(4): 799–809.

Xu Xiwei, Zhang Xiankang, Ran Yongkang, Cui Xiaofeng, Ma Wentao, Shen Jun, Yang Xiaoping, Han Zhujun, Song Fangmin and Zhang Lanfeng, 2006. The preliminary study on seismotectonics of the 2003 ad Bachu-Jiashi earthquake (ms6.8), southern Tianshan. *Seismology and Geology*, 28(2): 161–178 (in Chinese with English abstract).

Ye Jianqing, Shen Jun, Wang Yipeng and Ren Jinwei, 1996. *The northern marginal active tectonics of Qaidam basin. In: Research on active fault 5*, Beijing: Seismological Press, 172–180 (in Chinese with English abstract).

Yin An, Dang Yuqi, Wang Licun, Jiang Wuming, Zhou Suping, Chen Xuanhua, Gehrels, G.E., and McRivette, M.W., 2008a. Cenozoic tectonic evolution of Qaidam basin and its surrounding regions (Part 1): The southern Qilian Shan-Nan Shan thrust belt and northern Qaidam basin. *Geological Society of America Bulletin*, 120(7–8): 813–846.

Yin An, Dang Yuqi, Zhang Min, Chen Xuanhua and McRivette, M.W., 2008b. Cenozoic tectonic evolution of the Qaidam basin and its surrounding regions (Part 3): Structural geology, sedimentation, and regional tectonic reconstruction. *Geological Society of America Bulletin*, 120(7–8): 847–876.

Yin, A., Dubey, C.S., Kelty, T.K., Webb, A.A.G., Harrison, T.M., Chou, C.Y., and Célérier, J., 2010. Geologic correlation of the Himalayan orogen and Indian craton: Part 2. Structural geology, geochronology, and tectonic evolution of the Eastern Himalaya. *Geological Society of America Bulletin*, 122(3–4): 360–395.

Zheng Mianping, Liu Junying, Ma Zhibang, Wang Hailei and Ma Nina, 2011. Carbon and Oxygen Stable Isotope Values and Microfossils at 41.4-4.5 ka BP in Tai Co, Tibet, China, and Their Paleoclimatic Significance. *Acta Geologica Sinica* (English edition), 85(5): 1036–1056.