Late Cenozoic deformation along the northwestern continuation of the Xianshuihe fault system, Eastern Tibetan Plateau

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ABSTRACT

The Xianshuihe fault system is a highly active, left-lateral slip fault that has played an important role in accommodating late Cenozoic crustal deformation of the Eastern Tibetan Plateau. The left-lateral displacement on the western portion of the fault system, the Ganzi fault, is ~80 km, based on geologic and geomorphic markers. Left-lateral movement along the fault may have initiated in middle Miocene time (12 Ma), followed by the intensive, brittle, left-lateral movement in late Cenozoic time (2–4 Ma). Lying within the headwater regions of the Jinsha (Yangtze) River in the Yushu region, the northwestern end of the Xianshuihe fault system consists of four branches. These are, from north to south—the Dangjiang fault, the Yushu fault, the Batang fault, and the Xialaxiu fault. Both the Yushu and Dangjiang faults display clear geologic and geomorphic evidence for active, left-lateral slip movement. Several offset markers of Triassic age along the Dangjiang fault suggest ~39 km of left-lateral slip, but the geomorphic evidence along the Dangjiang and Yushu faults suggests only ~16 km and ~25 km of left-lateral slip, respectively. Both the Batang and Xialaxiu faults demonstrate clear evidence for normal dip slip, by an associated series of E-W–trending grabens and horsts that absorb ~9 km of left-lateral movement in early to middle Pleistocene time. About 32 km of left-lateral movement on the fault system was estimated to be absorbed by NE-SW shortening along the rugged North Yushu block in late Neogene time. This is interpreted to have formed as a rhomb-shaped restraining bend, along which the left-lateral movement along the northwestern end of the fault system was partially transferred into crustal shortening.

The westward continuation of the Dangjiang fault is marked by an E-W–trending fault, which can be traced westward for 150 km to central Tibet, where it joins the Fenghuo Shan thrust belt. This thrust belt is interpreted to represent the northwestern continuation of the Xianshuihe fault system, along which 39 km of the left-lateral movement was entirely transferred into the N-S shortening. It indicates that the left-lateral movement within the southeastern part of the Tibetan Plateau along the fault system, either caused by lateral extrusion or by clockwise rotation, is largely restricted to the northwestern end of the fault system. Quaternary extension occurred along the northwestern continuation of the Xianshuihe-Xiaojiang fault was coeval with extension along its southern end, indicating that the southeastern margin of the plateau underwent clockwise rotation.

Keywords: Xianshuihe fault system, stream offset, late Cenozoic time, restraining bend, clockwise rotation.

INTRODUCTION

Plate reconstructions (e.g., Molnar and Tapponnier, 1975; Tapponnier and Molnar, 1977; Patriat and Achache, 1984) indicate that the Indian plate has moved northward for ~2500 km since its collision with the Eurasian plate, 45 ± 5 Ma ago (Rowley, 1996), and has undergone a counterclockwise rotation of ~30° (Dewey et al., 1989; Molnar et al., 1993). Continuing convergence between the Indian plate and Eurasia has mostly been absorbed by intra-continental deformation primarily within the Eurasian plate (Tapponnier et al., 1982; England and Houseman, 1986; Houseman and England, 1993; Avouac and Tapponnier, 1993; Leloup et al., 1995; Royden et al., 1997; Yin and Harrison, 2000). Intra-continental deformation appears to have occurred spatially and heterogeneously, and was concentrated along several large fault zones, including the major strike-slip systems of the Altyn Tagh, Kunlun, Karakorum, Haiyuan, Xianshuihe, and Red River-Ailao Shan fault zones (Molnar and Tapponnier, 1975; Tapponnier and Molnar, 1977), all of which are presently active (e.g., Cowgill et al., 2003; Armijo et al., 1989; Lacassin et al., 2004; Allen et al., 1984, 1991; Replumaz et al., 2001). However, the spatial and temporal evolution of the strike-slip movement along most of these faults remains either unclear or still under debate. For example, the Quaternary left-lateral slip on the Haiyuan fault is interpreted to have been absorbed by transpressional deformation along the Liupan Shan thrust belt (Burchfiel et al. 1989; Zhang et al., 1991). Other studies (e.g., Gaudemer et al., 1995; Zhang et al., 1998), however, argue that the Liupan Shan thrust belt serves as a left-lateral transfer fault, extending eastward into the Qinling belt. Moreover, the left-lateral East Kunlun fault, known as one of the most active structures within the plateau (Van der Woerd et

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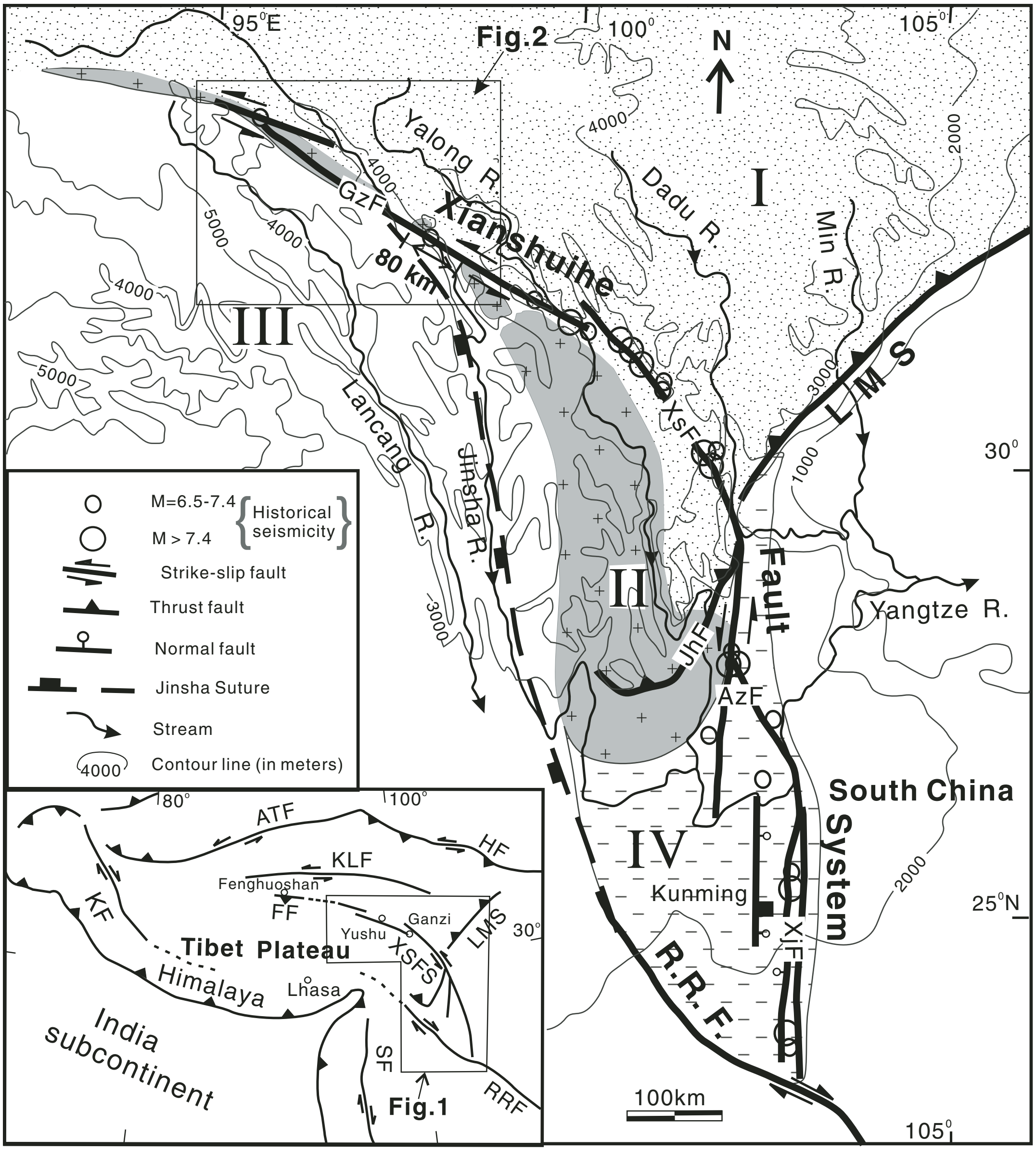

Figure 1. Regional tectonic map shows the trace of Xianshuihe fault system within eastern Tibet. The major tectonic units of the Eastern Tibetan Plateau are: I—Songpan-Ganzi Flysch belt; II—Yidun Volcanic Arc; III—Three River Fold belt; IV—Kungdian High. Abbreviations: ATF—Altyn Tagh Fault; HF—Haiyuan Fault; KLF—Kunlun Fault; KF—Karakorum Fault; LMS—Longmen Shan thrust fault; RRF—Red River Fault; FF—Fenghuoshan thrust fault; SF—Sagaing fault; GzF—Ganzi Fault; XsF—Xianshuihe Fault; AzF—Anninghe-Zemuhe Fault; XjF—Xiaojiang Fault; JhF—Jinghe thrust fault. The box shows the location of Figure 2.

al., 1998, 2002), loses its clear trace around the Yellow River to the east due to a decrease of the left-lateral movement. According to Kirby et al. (2007), this resulted from a horsetail tectonic transformation, whereas Zhang et al. (1995, 1998) propose that the left-lateral movement oversteps easterly into the Qinling belt. In most previous studies (e.g., Allen et al., 1991; Wang and Burchfiel, 1998, 2000), the Xianshuihe fault system was drawn to be ending northwestward in the southeastern corner of the Tibetan Plateau, however, without any explanation of the nature of this termination with respect to other strike-slip faults.

The Xianshuihe fault system has four segments (Fig. 1), which are, from northwest to southeast—the Ganzi, the Xianshuihe, the Anninghe-Zemuhe, and the Xiaojiang faults (Allen et al., 1991; Wang and Burchfiel, 2000). The most prominent geomorphic evidence for the left-lateral movement along the fault system is present at the Ganzi fault, along which the Jinsha River is deflected and a large granite batholith is offset by ~80 km (Wang et al., 1998; Wang and Burchfiel, 2000). Westward of the deflected Jinsha River, the Xianshuihe fault system continues for 200 km into the Yushu area. Presently, no study explains how its 80-km, left-lateral displacement is accommodated farther west. During our recent field study west of the Shango area, where the flat plateau emerges, we found that the northwestern termination of the fault system is not a single structure as most studies indicate. Instead, the Xianshuihe fault system consists of four branching faults separating horst and graben structures and other rugged high mountains (Fig. 2). Little is known about the young and active geologic and geomorphic features of this region. Moreover, the link between these structures and the displacement along the Ganzi fault is uncertain.

This study focuses on the aforementioned active and young fault systems. We elaborate on their genesis and attempt to answer the following questions: (1) Was the basin development in the study area coeval with left-lateral displacement along the northwestern end of the Xianshuihe fault system? (2) What is the tectonic nature of the rugged high mountains in the area? (3) When did these faults that we have identified initiate and how have they evolved with time?

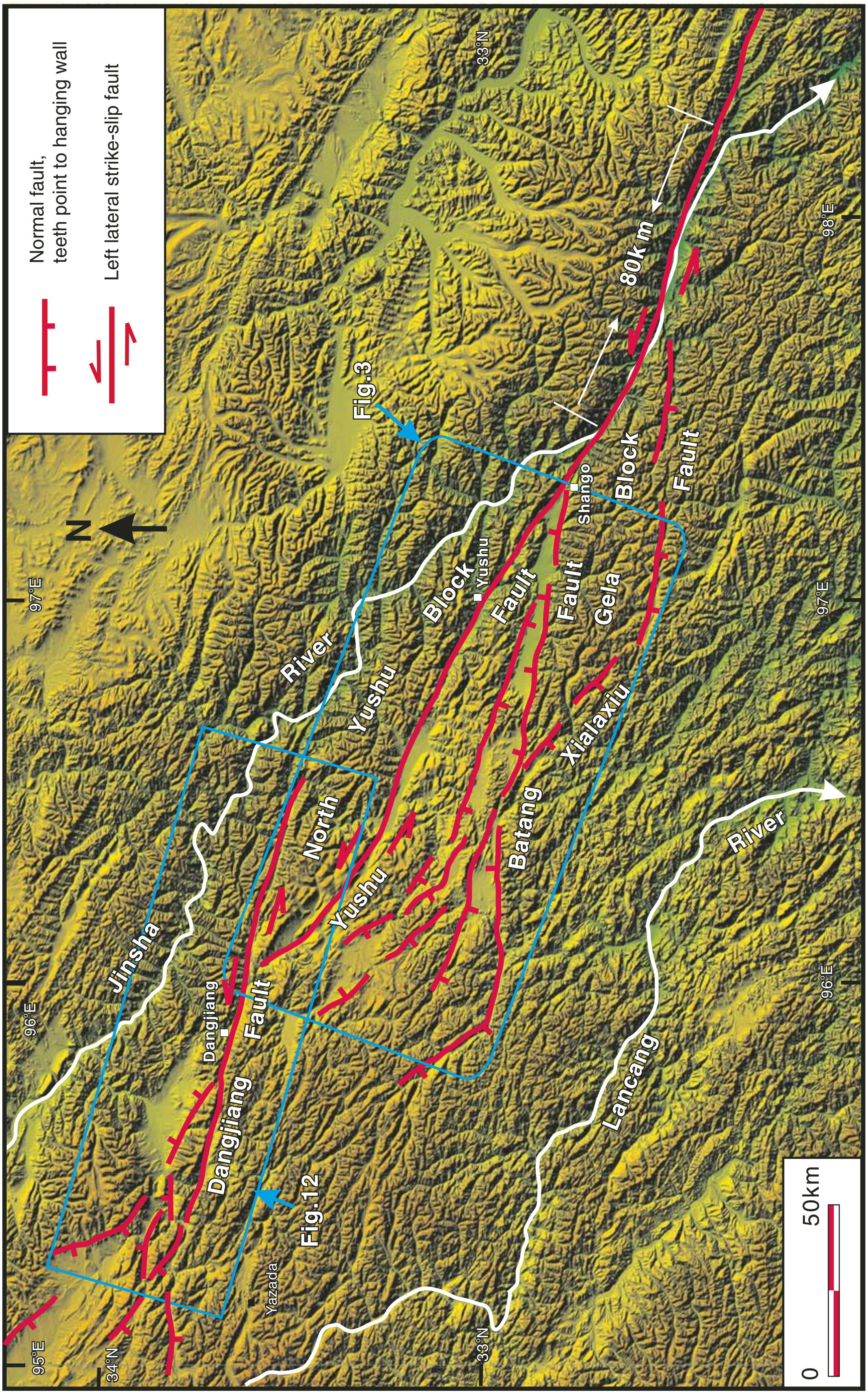

Figure 2. Map of major young and active features at the western continuation of Xianshuihe fault system in the Yushu-Dangjiang area. It shows the 80-km offset of the Jinsha River along Ganzi fault according to Wang and Burchfiel (2000).

GEOLOGIC SETTING OF THE XIANSHUIHE FAULT SYSTEM

The Xianshuihe fault system is a prominent, linear, NW-SE–trending tectonic feature within the southeastern margin of the Tibetan Plateau. Left-lateral displacement along this fault system has trigged 23 strong earthquakes with magnitude >6.5 since 1480 A.D. (Allen et al., 1991; Wen, 2000). The fault system consists of four primary segments, which are from the southeast to northwest—the Xiaojiang (XjF), the Anninghe (AzF), the Xianshuihe (XsF), and the Ganzi (GzF) faults (Wang et al., 1998) (Fig. 1). Some detailed studies on seismology (Holt et al., 1991, 1995; Allen et al., 1991 (Wang et al., 1998; Wang and Burchfiel, 2000), geodesy (King et al., 1997), and thermochronology (Arne et al., 1997; Xu and Kamp., 2000) have been conducted on these fault segments. Both the N-S–striking Xiaojiang and Anninghe faults are located entirely within the South China block. Based on the depositional ages of left-lateral extensional basins that developed along these two faults, the brittle, left-lateral movement was interpreted to have initiated in late Cenozoic times (2–4 Ma) (Wang et al., 1998). However, U-Pb isotopic age dating of granite emplacement cut by the Xianshuihe fault system in the Kangdian area yielded an age of ca. 12 Ma (Roger et al., 1995). Therefore, the emplacement of the granite was interpreted to have occurred in association with fault displacement (Roger et al., 1995). It is possible that the Xianshuihe and Xiaojiang faults formed at a different time, because they occur within a different tectonic setting. The Neogene, left-lateral movement along the Xianshuihe fault was transferred into N-S shortening along the JhF (Fig. 1). The Ganzi fault forms the northwestern continuation of the fault system through a left–step overlap near Ganzi, approximately along the Yidun magmatic belt. The Yidun magmatic belt is interpreted as a Triassic magmatic arc northeast of the Jinsha suture and is composed mainly of an assemblage of intermediate-acid intrusive and volcanic rocks, locally referred to as the Batang group in the study area. North of the Yidun belt is the Songpan-Ganzi fold belt, which consists mainly of Triassic flysch deposits with local exposures of upper Paleozoic rocks. The folds in this unit trend generally northwest-southeast, but contain complex interference patterns and arcuate axial trends (Burchfiel et al., 1995). The Three River fold belt southwest of the Jinsha suture is characterized as a tectonic mélange consisting of many elongated lithological and structural units of different ages and characters. In the Yushu area, the Three Rivers fold belt is dominated by upper Triassic strata composed of clastic rocks and limestone of the Jiezha group and volcanic rocks and limestone of the Batang group.

These three tectonostratigraphic units are unconformably overlain by a series of Cenozoic sedimentary rocks of Paleogene to Quaternary age. The Paleogene strata have a very limited distribution and consist of a thick succession of purple, coarse-grained sediments, which are mostly distributed along some NW-trending transpressional faults. Deformation along the transpressional structures was associated with K-rich intrusions dated at 38–29 Ma (Wang, et al., 2001; Horton et al., 2002). Subhorizontal Neogene strata are characterized by purple, fine-grained lacustrine sediments. Quaternary sediments are widespread within grabens, but their age is poorly constrained because of a lack of fossils. Ages are mainly based on related geomorphic features. Quaternary strata exposed along terraces are usually assigned to a Pleistocene age.

From the deflected Jinsha River, the northwestward continuation of the Ganzi fault is called the Yushu fault, which is generally considered as the northwestern continuation of the Xianshuihe fault system. However, our field study has shown that the Yushu fault is joined by three east-trending, linearly aligned faults—the Dangjiang, Batang, and Xialaxiu faults (Figs. 2 and 3)—which are related to historic earthquake activity. According to historical records (Zhou et al., 1997), two earthquakes occurred along this fault alignment since 1738; one occurred along the Dangjiang River, 100 km northwest of Yushu, the other near Dengke, 100 km southeast of Yushu. These four active faults (the Yushu, Dangjiang, Xialaxiu, and Batang faults) delineate the northwestern end of the Xianshuihe fault system as a complex fault system that forms a key area in our study of the evolution of the fault system.

YUSHU FAULT

The Yushu area, with an average elevation of 4500 m, forms a broad water divide between the Jinsha River and the Lancang River drainage systems (Fig. 2). The NW-SE–oriented Yushu fault cuts obliquely through the Yidun magmatic belt and can be traced for 200 km. The fault terminates against the Dangjiang fault to the northwest, and both faults and the Jinsha River outline the rhomb-shaped, rugged, North Yushu Mountain area (Fig. 2). The Yushu fault shows evidence for active young transtensional deformation with stream offsets, fault scarps, pull-apart basins, and shutter ridges. The fault is divided into an eastern and western segment based on deformational and geomorphic features.

The eastern segment, termed East Yushu fault, stretches between Shango and Longshida (Fig. 3). The east end of the fault cuts through a rhomb-shaped divide, separating the Jinsha River to the east and the Batang River to the west (Figs. 4A and 4B). The top of the drainage divide is covered by sands and gravels that are interpreted as stream-channel deposits. We suggest that the eastern branch has a shortening component that causes the formation of a push-up rising above the Jinsha River. The East Yushu fault consists of two E-trending, arcuate, en echelon, normal faults (Fig. 4B). The faults dip 65° S and juxtapose two high mountains formed by Triassic limestone in their footwalls and Quaternary sediments within the eastern margin of the Batang basin in the hanging wall of the western fault (Fig. 4B). The rocks along the fault scarps are breccias (Fig. 5), most of which formed as landslide deposits. In contrast to the steep fault scarps, the northern slope of the mountains gently dips to the north, along which the Jinsha River is bent to the north, implying that uplift of the mountain was associated with northward tilting and was accommodated by normal slip along the East Yushu fault. From this location and beyond, the East Yushu fault expresses an extensional component. The shear sense of these two faults and their geometric relation clearly indicates that they were formed in a broad zone of left-lateral shear.

The Batang River, a large tributary of the Jinsha River, intersects the NW-SE–striking East Yushu fault near Yushu (Fig. 6). A 3-m–high terrace west of the Jinsha River can be discontinuously traced northwestward for 3 km parallel to the trace of the East Yushu fault running through a narrow gorge. This alluvial terrace is composed of gravel deposits. We suggest that this is an abandoned stream channel of the Batang River (Fig. 6), along which the river flowed westward along the East Yushu fault until the Batang River was captured upstream. If so, the westward deflection of the paleo-Batang River can be attributed to left-lateral movements along the East Yushu fault with an estimated displacement of ~3 km (distance between points C and D in Fig. 6). The age of these channel deposits is unclear; presumably, they are late Pleistocene in age. We interpret the large-scale, westward deflection of the Batang River along the East Yushu fault to be caused by the left-lateral movement along the fault. Since the Batang River is a large tributary of the Jinsha River, its deflection reflects an extended history of left-lateral movements on the East Yushu fault. Its upper part consists of two branches that run to the east and west along the Batang basin. Using both branches gives an estimated offset of 14 km to 30 km (minimum/maximum). Thus, their deflection results in an average left-lateral offset of 22 km (Fig. 4B), while total left-lateral offset of the Batang River course is estimated to be 25 km.

Toward the northwest, the East Yushu fault extends along the southern margin of a deeply incised valley, along which a tributary of the Batang River flows to the east. At this location, the East Yushu fault dips northeast 55°, juxtaposing the Triassic flysch in the hanging wall and white limestone of the Batang group in the footwall. Where exposed, the fault surface contains slickenlines that show the upward displacement of the hanging wall. There are two rhomb-shaped shutter ridges along this fault, the larger of which is 3 km long and 200 m high, aligned NW-SE in an en echelon pattern (Figs. 7F and 7G). The fault and morphological features indicate that they formed in a zone of left-lateral shear. Wherever we can find stream deflection, the offset is consistently left-lateral. All deflected streams point in an up-river direction, which is strong evidence that the stream deflection is caused by left-lateral movement of the fault. Near Chesheda, both large and small streams are offset left laterally by several hundred meters to several kilometers (Fig. 7). Longer drainage systems tend to exhibit larger displacements, suggesting that the offsets have been progressive. Offsets of small streams are evidence for active left-lateral slip on the fault. A series of small streams are consistently offset left laterally for 300–600 m, as indicated by the distances between C and D and between A and B (Figs. 7 and 8). The largest offset is indicated by a 3-km deflection of a large river between E and F (Fig. 7). All stream offsets are younger than the Batang River and, therefore, record only the most recent movement of the East Yushu fault.

The western fault segment can be traced between a deeply incised valley in the southeast and a flat plateau in the northwest. It extends along the boundary between the rugged North Yushu mountain range in the east and a flat plateau in the west (Fig. 3). Although this fault marks a geomorphic boundary, the rocks on either side are similar and are characterized by dark-green volcanic rocks interbedded with greywacke of the Batang Formation. Near Longshida (Figs. 3 and 9A), the western fault segment, dipping northeastward at 50°, is clearly exposed along the eastern slope of a pass and juxtaposes Neogene red beds in its footwall and Triassic, dark-green, volcaniclastic rocks in its hanging wall (Figs. 9 and 10). Both the Neogene red beds and the Triassic volcanic rocks are strongly sheared along the fault as a result of south-directed thrust movement along the fault.

West of Longshida, the western fault segment cuts into the plateau, where it bifurcates

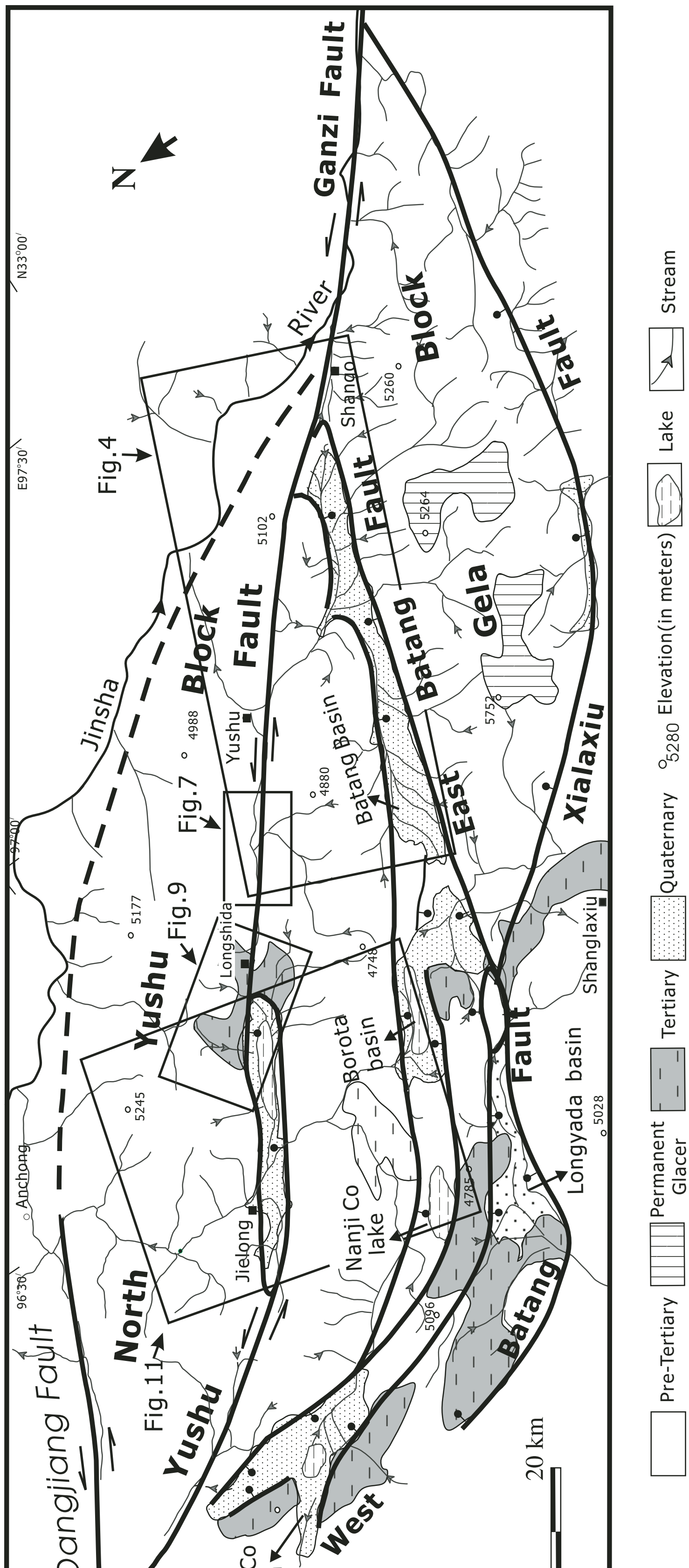

Figure 3. Tectonic map shows the main features of the Yushu fault zone, the transpressional structures between the Yushu and Dangjiang faults, and the transtensional structures related to the Yushu and Batang faults.

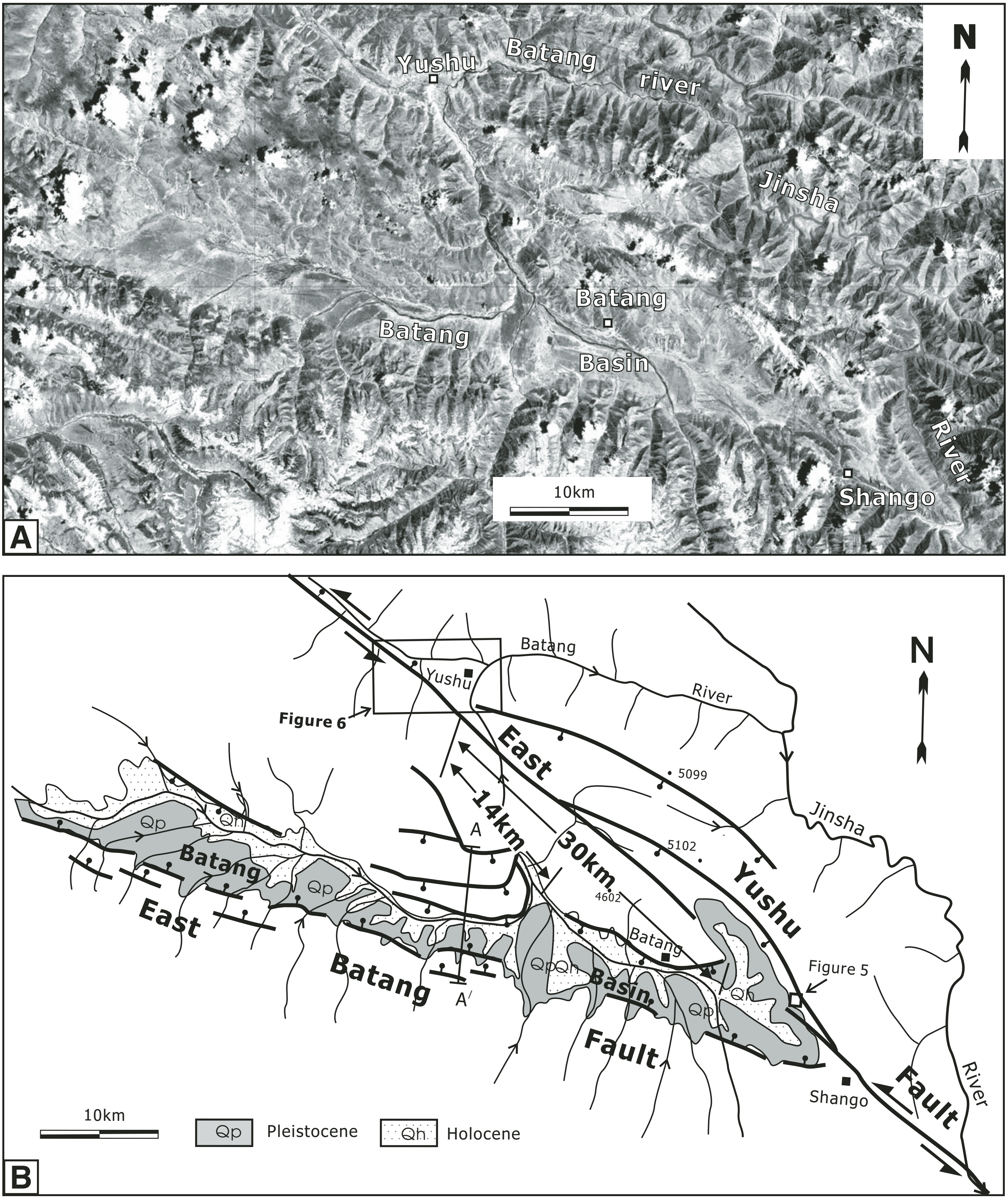

Figure 4. (A) ETM (Enhanced Thematic Mapper) remote imagery shows the area of the eastern Yushu fault. (B) The 14- to 30-km offset of the Batang River and the normal fault related to the Yushu fault along the East Yushu fault segment. The extensional Batang fault and Batang basin are located at the southwestern side of Yushu fault.

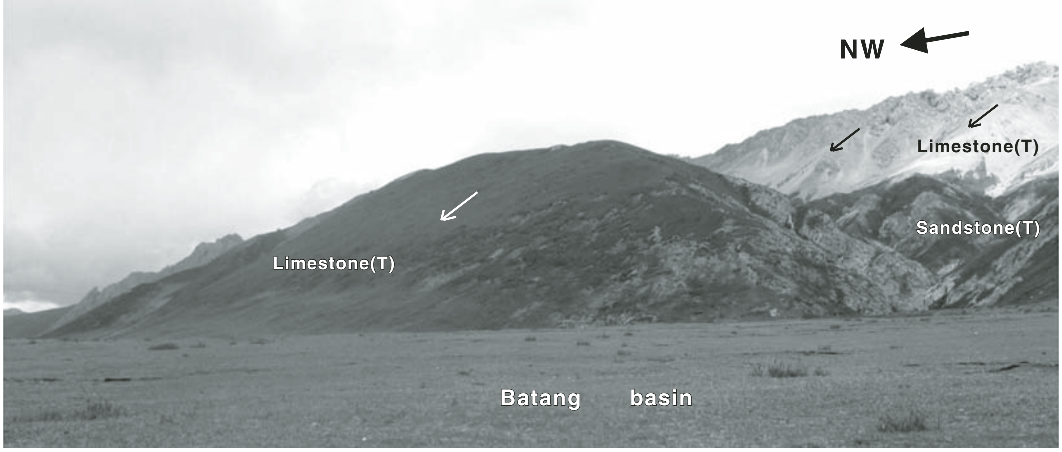

Figure 5. The triangular facet and fault scarp shows the normal fault character of the East Yushu fault segment. Triassic limestone and sandstone form the footwall of the fault; landslided limestone block and Quaternary sediment in Batang basin lie in the hanging wall of the fault. The location in the photograph is northeast of the town of Batang in Figure 4.

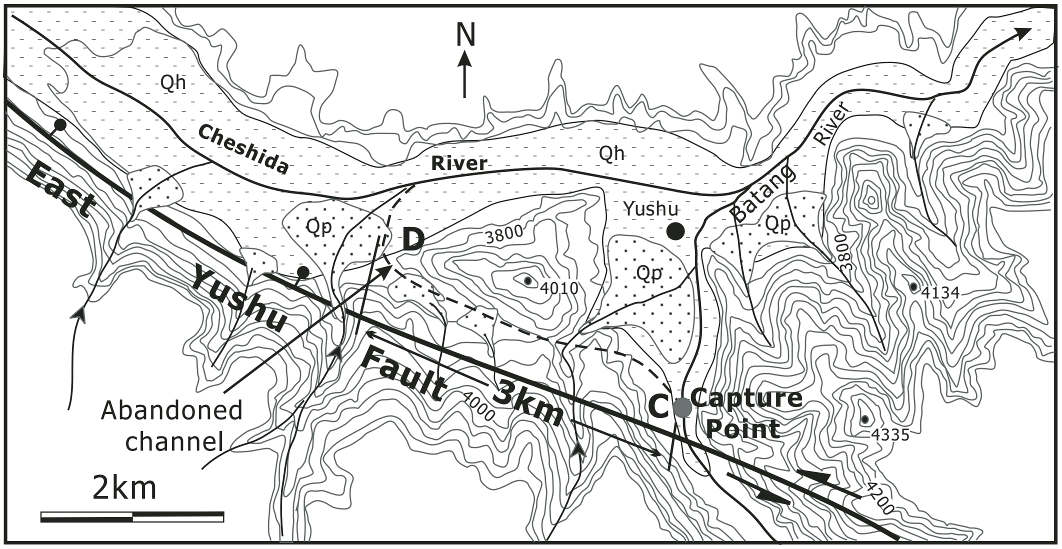

Figure 6. River capture along Batang River by the left-lateral slip of Yushu fault at Yushu town. The dashed line is the abandoned river channel, and the amount of river offset reaches 3 km.

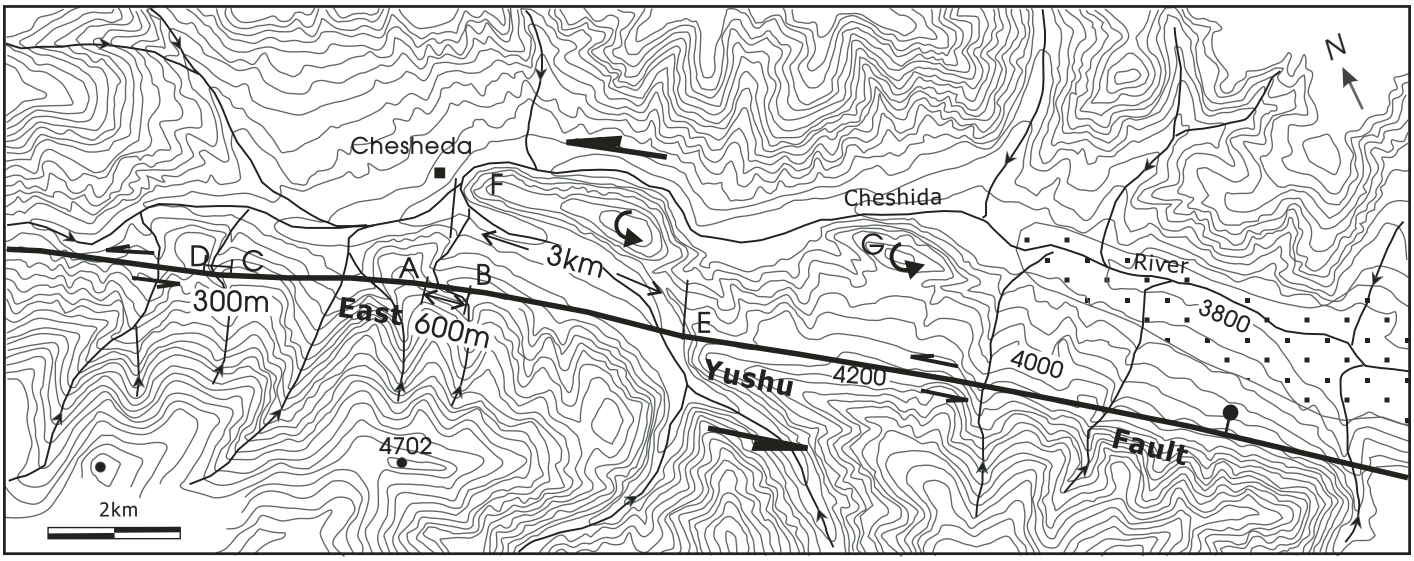

Figure 7. Consistent, left-lateral disruption of drainage, development of shutter ridges (A, B, C, and D) and side-hill ridges (F and G) along the Yushu fault in the Chesheda area. The amount of stream offset ranges from 300 m (C and D) to 600 m (A and B) and to 3 km (E and F).

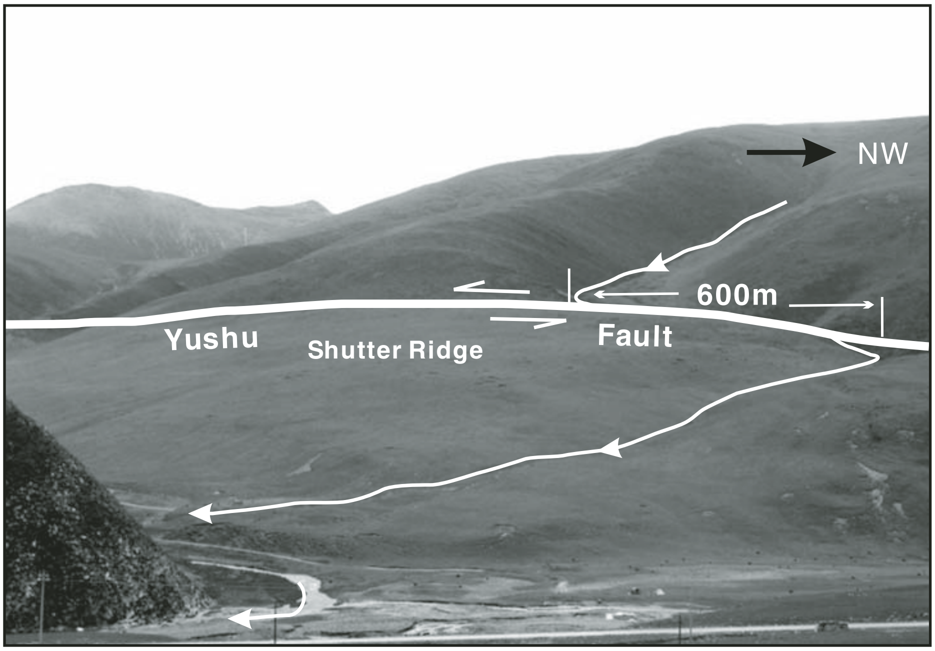

Figure 8. Left-lateral bend of a stream and shutter ridge along west side of East Yushu fault segment. The amount of stream offset reaches 600 m. The photo is taken between points A and B in Figure 7.

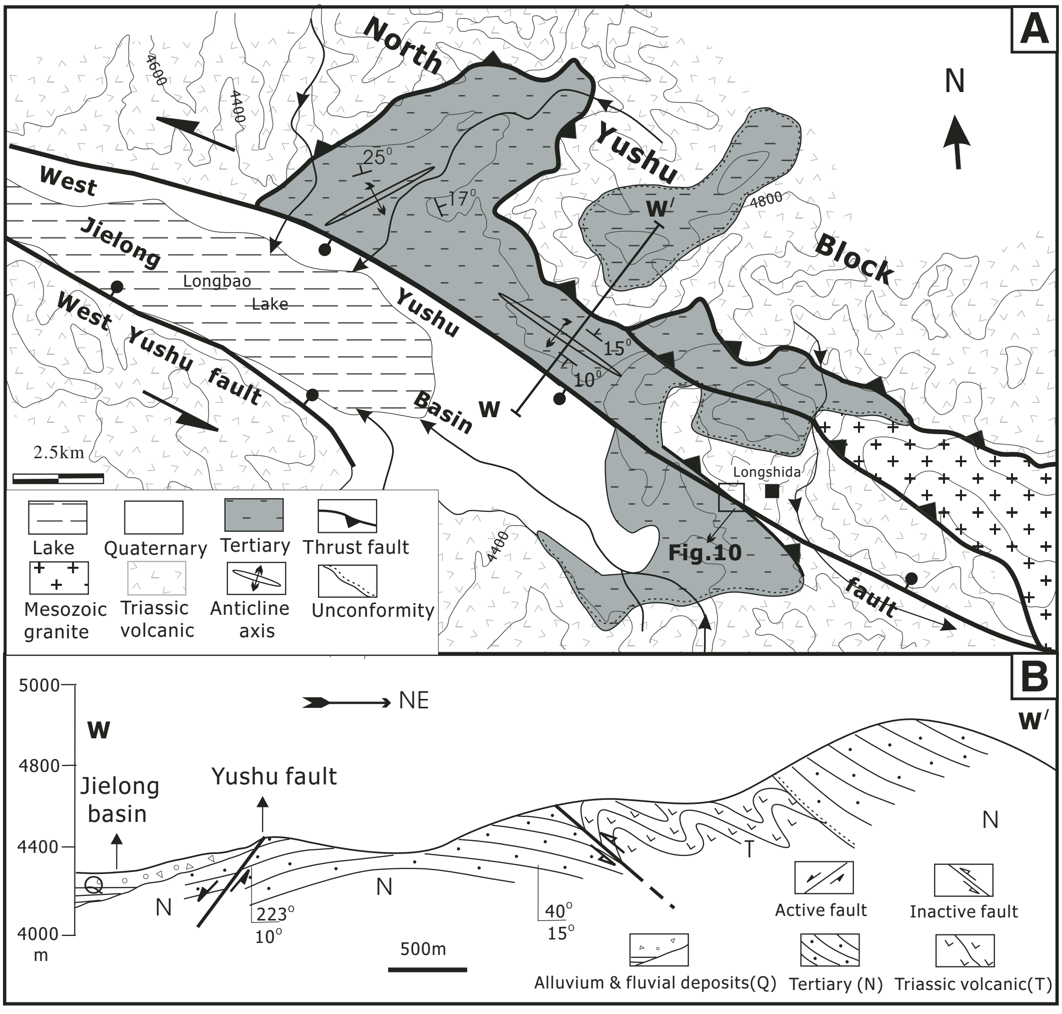

Figure 9. (A) Map shows the trace of the thrust fault along the West Yushu fault segment. Square near Longshida is the location of Figure 10. (B) Triassic rocks thrust on folded Neogene strata. See line of section W-W′ in (A).

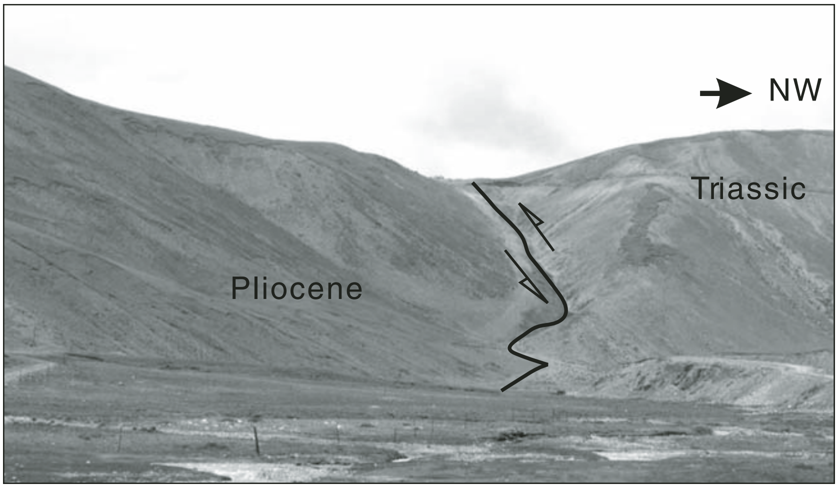

Figure 10. Fault trace of a thrust along the West Yushu fault segment, where Triassic rocks are thrust upon Neogene strata.

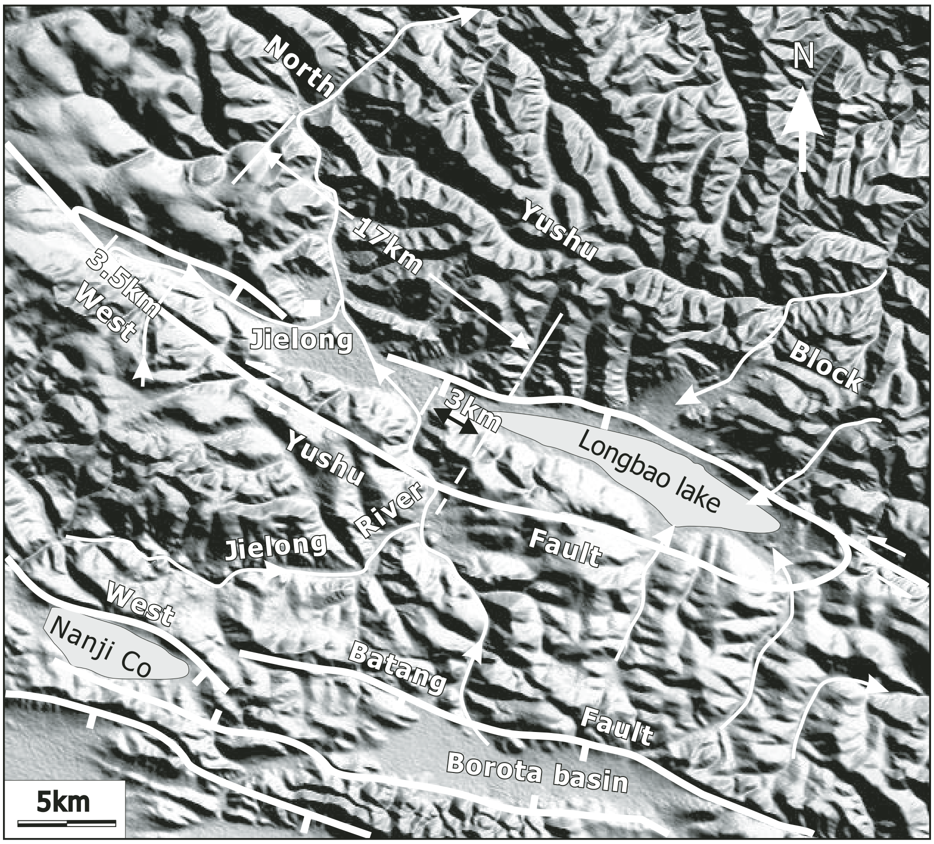

Figure 11. Map of structural and geomorphic features along the West Yushu fault segment. The Jielong basin is a pull-apart basin along two branches of the fault. Young stream offsets are between 3 km and 3.5 km; the Jielong river shows 17-km deflection in the sense of fault movement.

with faults bounding the Jielong basin. At the southern basin margin, the fault branch dips northward at 60°, while in the north, the fault branch is characterized as a north-dipping thrust fault, placing brecciated, Triassic volcanic rocks above Neogene red beds (Fig. 10). Triassic volcanic rocks are, in turn, unconformably covered by Neogene red beds, which are similar to those in the footwall, indicating that thrusting probably occurred in post-Neogene time (Figs. 9 and 10). North of the Jielong basin, the Neogene red beds in the footwall of this thrust fault are exposed at the surface due to erosion, thus forming a large structural window, in which the red beds are shortened along a series of E-W–trending folds (Figs. 9A and 9B). According to the width of the structural window, the south-directed thrust displacement is estimated to be at least 10 km. Farther to the west, both the Neogene rocks and the thrust fault are truncated by the southern branch of the western Yushu fault.

The southern strand of the western Yushu fault continues to the western boundary of the rugged North Yushu range in the east. This part of the western fault segment consists of two faults that bound the elongated shallow Jielong basin (Fig. 11). The Jielong basin is ~35 km long and 7 km wide and is occupied by a lake and marshes that are drained by the Jielong River. Along the basin margins, the strata appear to onlap onto bedrock, except along the western part of the southern basin margin, where a series of steep, northward-dipping, triangular facets are present, suggesting normal fault displacement. Normal faulting is the likely cause of basin subsidence, similar to the Batang basin. The left-lateral displacement along the western fault segment is also documented by stream offsets. A stream offset of ~3.5 km is present along a large, elongated shutter ridge (Fig. 11). The Jielong River course is offset by ~3 km, where it is cut by the western fault segment. These offset rivers are young and have only recorded the most recent movements of the western fault segment. The sense of deflection of the Jielong River is also left lateral. The left-lateral displacement ~17 km (Fig. 11), which is similar to the 25-km displacement of the Batang River. Based on the spatial relationship of these two fault branches, we interpret this basin as a pull-apart basin formed by left-lateral movement of the West Yushu fault .

From the Jielong basin to the northwest, the western fault segment continues 40 km to Yazada (Fig. 3), where it terminates against the E-W–striking Dangjiang fault. This part of the Yushu fault still marks the boundary between the rugged North Yushu mountain range to the east and the flat plateau to the west.

Although the southern and northern strands of the western Yushu fault contain different deformation features, they mark the northwestward continuation of the eastern Yushu fault. Thus, it is likely that these two fault strands represent different generations of the Yushu fault: the southern strand is younger and takes up the present-day left-lateral movement of the Yushu fault, whereas the northern strand is older and accommodated the thrust component of the Yushu fault that is no longer active. The North Yushu structural block is positioned in the hanging wall of the northern branch, so that its uplift must have been coeval with the thrust movement.

Dangjiang Fault

The strike of the Dangjiang fault is more east-west–oriented (~290°-110°) than the Yushu fault and can be traced for ~140 km (Fig. 12; see Fig. 2 for location). It terminates the northwest end of the Yushu fault along its middle part. The two faults define the southern and northern margins of the North Yushu block. The Dangjiang fault obliquely truncates the boundary between the Songpan-Ganzi and Yidun belts. The trace of the fault is a prominent linear feature on satellite images and in the field. It is marked by a deeply incised valley, along which several tributaries of the Jinsha River flow to the north. Based on geomorphic and geologic features, the Dangjiang fault is divided into two segments.

The eastern fault segment is confined within a narrow valley, along which two tributaries of the Jinsha River, the Dangjiang River to the west and the Jielong River to the east, flow along the fault, and then to the north. This fault segment was activated during a historical, magnitude-7.5 earthquake in 1783. The epicenter was located south of Dangjiang, and the earthquake caused a 50-km–long surface rupture (Zhou et al., 1997). The trace of the fault is marked by a zone of fractured rocks and a series of lens-shaped blocks, ~100 m long and 50 m wide, that are exposed as isolated hills. The sheared rocks consist of Triassic volcanic rocks of the Yidun belt. The left-lateral movement is demonstrated by the consistent offset of rivers and ridges. The largest left-lateral displacement along the fault is indicated by the 16 km offset of the Dangjiang River (Fig. 12). Along the eastern end of the fault in the Anchong area, active left-lateral movement is demonstrated by measurable offsets of a series of stream channels, gullies, and terraces. The course of the Jielong River, which drains the basin into the Jinsha River, is offset left laterally for ~5 km (Fig. 12). Along this river offset, a lens-shaped hill made up of Triassic, acidic volcanic rocks lies to the north of the fault trace. Similar rocks south of the fault

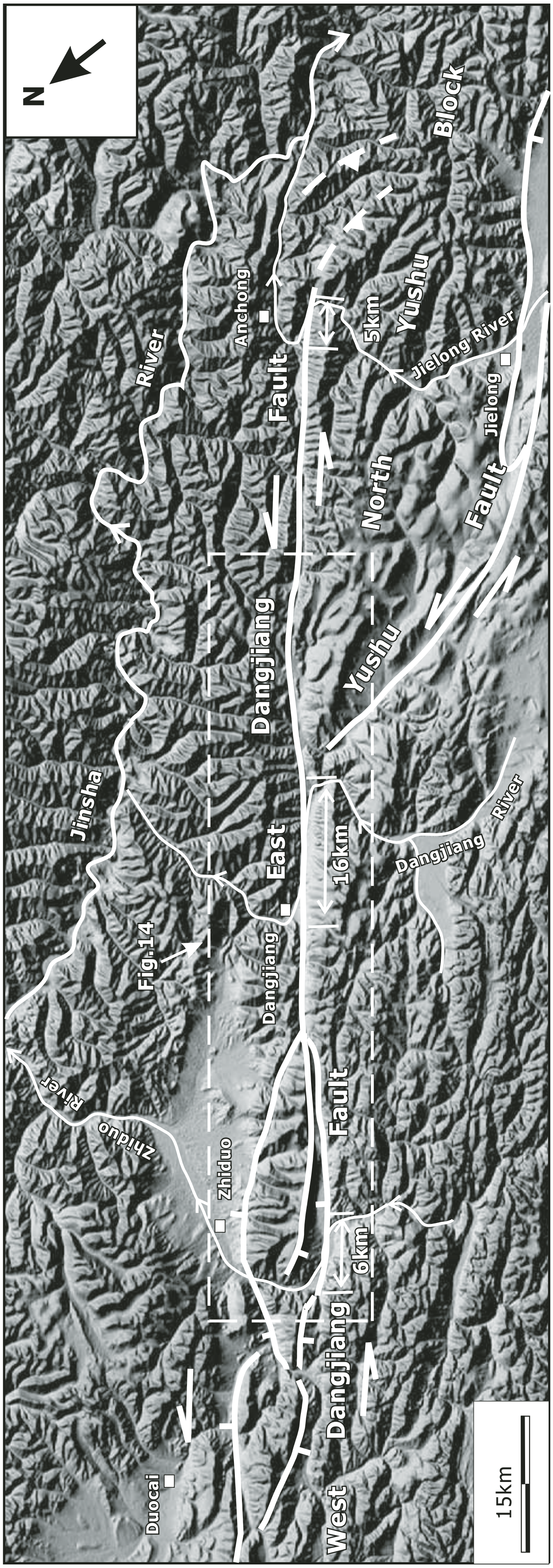

Figure 12. Topographic map showing the trace of the Dangjiang fault. The stream offsets are 5 km and 16 km along the East Dangjiang fault segment. Stream offset decreases to 6 km along the West Dangjiang fault segment. Displacement is finally absorbed by a normal fault related to two branches of the Dangjiang fault.

trace indicate 4 km of left-lateral displacement. Moreover, the ridges south of the fault commonly show a right-stepping, en echelon pattern that also indicates a left-lateral sense of shear.

The western fault segment consists of two parallel branches bounding a wide E-W–trending valley, along which the Zhiduo River flows to the north. The left-lateral movement along this fault segment is clearly indicated by the offset of two main tributaries of the Zhiduo River, by which a left-lateral displacement of 6 km can be determined. About 10 km southwest of Dangjiang, a NW-striking, north-dipping, arcuate branch (Duocai fault) of the Dangjiang fault juxtaposes Triassic volcanic rocks in its footwall and the Neogene red beds of the Zhiduo basin in its hanging wall (Fig. 12). Besides the dip-slip movement, this fault also shows a left-lateral movement by the consistent offset of the rivers along the fault. A rhomb-shaped block is defined between this fault and the western fault segment of the Dangjiang fault to the south.

The Dangjiang fault strikes more easterly than the regional tectonic units within the Eastern Tibetan Plateau, which allows its left-lateral movement to be determined by the offset of tectonic units, particularly the Yidun belt. This belt in the study area is made up of intermediate-acidic volcanic rocks and intercalated slate and sandstone, which are intruded by an elongated dioritic pluton. These rock units can be matched across the Dangjiang fault, revealing offsets of 39 km and 29 km, respectively (Fig. 13). The geological evidence demonstrates a larger amount of displacement than that of the geomorphic evidence, indicating that the left-lateral movement along the Dangjiang fault has an older history than the rivers.

North Yushu Block

Both the Yushu and Dangjiang faults, as well as the Jinsha River, bound the NW-SE–trending North Yushu block, which is ~150 km long and 30 km wide. In contrast to the surrounding plateau, the North Yushu block is characterized by a rugged surface topography and contains some of the highest peaks in the region (Figs. 2 and 3). It is mainly composed of Triassic intermediate-acidic volcanic rocks and intercalated limestone of the Yidun arc. This block has suffered contractional deformation, resulting in a series of NW-SE–trending folds and faults. Despite the fact that this block has an evolutionary history since the Triassic, its uplift and internal deformation history must have been modified and enhanced in late Cenozoic time. This is indicated by the deformed Neogene red beds at the southern margin along the western fault segment of the Yushu fault. The eastern end of the Dangjiang fault, with 5 km of left-lateral displacement, appears to abruptly terminate at short distance to the east. The Jinsha River follows the southeastward prolongation of the Dangjiang fault and along the eastern range front of the North Yushu block. We suggest that the fault continues by transferring left-lateral displacement to distributed shortening along the Jinsha River and the eastern front range of the North Yushu block. However, its Cenozoic deformation has been erased by the extensive river erosion. Neogene strata, consisting of purple, fine-grained conglomerates, sandstones, and mudstones, are exposed along the southern flank of the North Yushu block. The strata were strongly shortened in a NE-SW direction along the Yushu fault (Fig. 9). Clasts found in Neogene conglomerates are composed of dark-green volcanic rocks and gray sandstones and slates similar to the underlying Triassic rocks. These clasts suggest that sedimentation was associated with shortening deformation of the North Yushu block along the Yushu fault. Based on the shape, pattern of deformation, associated sedimentation, rugged landform and intimate relationship with the Yushu and Dangjiang faults, we interpret that the North Yushu block experienced strong shortening in Neogene time, which was associated with the left-lateral movement along the Yushu and Dangjiang faults.

Batang Fault

The Batang fault strikes E-W and joins with the Ganzi fault to the east near Shango, where it splits into several fault strands that bound several basins to the west (Fig. 3). The fault follows the contact between the Yidun magmatic belt to the north, formed by Triassic, dark-green

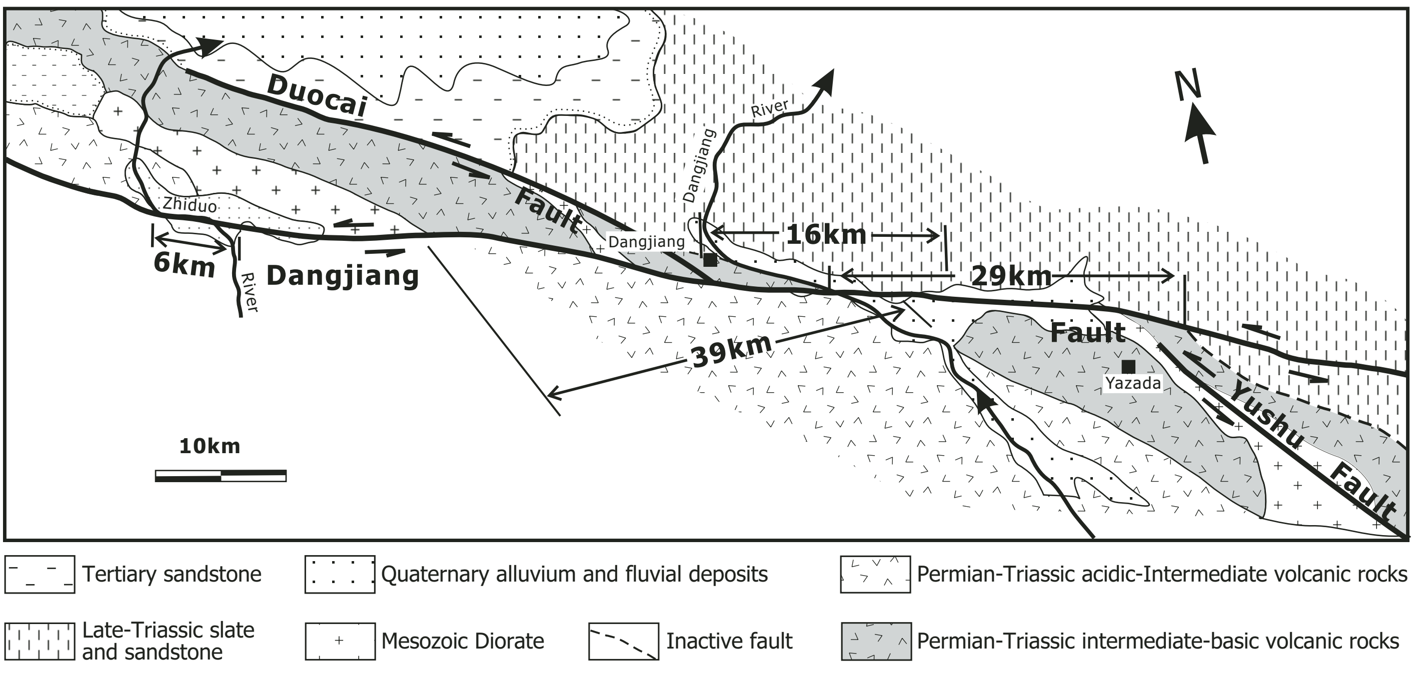

Figure 13. Geologic map showing the 39-km offset of Mesozoic volcanic rocks, and a 16-km stream offset in the Dangjiang area.

volcanic rocks, and the Three River fold belt to the south, composed of late Triassic limestone. Based on the geometric features of the fault, we divide the Batang fault into two segments, the East and West Batang faults.

The East Batang fault bifurcates into the northern and southern boundary faults of the Batang basin, a 75-km–long and 5-km–wide prominent linear basin that is well expressed both in the field and on satellite images (Figs. 4A and 4B). The basin is drained by the north-flowing Batang River. The faults that bound the Batang basin in the south dip to the north at ~40° and juxtapose Triassic clastic rocks in the footwall with Quaternary sediments in the hanging wall (Fig. 14A). The fault is composed of a series of steeply north-dipping fault steps, along which a series of fault blocks were dropped down to form bedrock terraces. Fault surfaces typically depict well-developed triangular facets. Where exposed along the fault, the Triassic clastic rocks, mostly sandstone, are strongly sheared and form cataclasites and breccias that are ~5–10 m thick and are penetrated by well-developed shear surfaces that dip steeply northward. Slickensides on the shear surfaces indicate down-dip, hanging-wall displacement. Along the southwest end of the Batang basin, purple Neogene sediments are truncated by the southern boundary fault and yield a lower time limit to the normal faulting. Along the southeastern margin of the basin, a terrace developed on Triassic bedrock is bounded by a north-dipping normal fault. This fault is overlapped by coarse-grained alluvial deposits, which have been assigned to a late Pleistocene age (Bureau of Geology and Mineral Resource of Qinghai Province, 1991), which gives an upper time limit to the normal faulting along the southern boundary of the Batang basin.

The northern fault strand of the eastern fault segment dips south at 60°–70° and forms the northern boundary of the Batang basin. The footwall rocks are characterized by late Triassic, dark-green volcanic rocks and an overlying white limestone that is strongly deformed, presumably in late Triassic time (Fig. 14A). The land surface on these deformed rocks is shallowly dipping, similar to the plateau surface, and dips toward the Batang basin at 9°. Along the northern margin of the basin, the surface is truncated by the northern fault strand of the Batang fault. The dip-slip movement along this fault strand is taken up by a series of fault steps, along which the late Triassic white limestone and the overlying flat surface are sharply truncated to form a series of terraces that dip toward the basin. The middle segment of the northern boundary fault is characterized by a turtle-back structure with three arcuate, stepped, normal faults (Figs. 4A and 4B).

The upper part of the sedimentary fill of the Batang basin is assigned a middle Pleistocene age (Bureau of Geology and Mineral Resource of Qinghai Province, 1991) and is characterized by coarse-grained alluvial deposits (Fig. 15). They are mostly composed of purple sandstones and white limestones, similar to the strata of the Jiezha group that crop out along the mountain to the south. The Jiezha group is the probable source of the alluvial deposits within the Batang basin. The alluvial fans are aligned along the southern margin of the Batang basin, and their

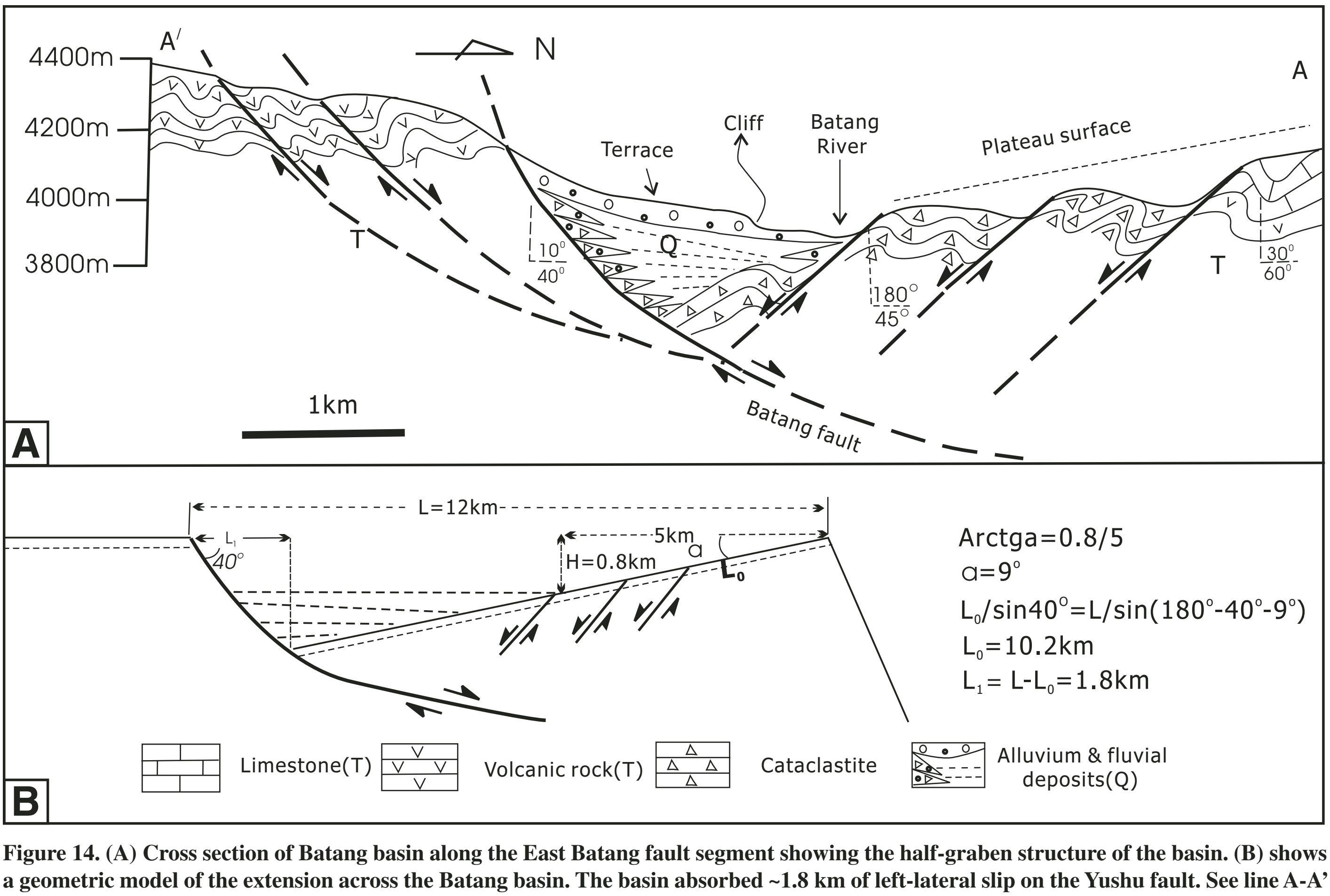

Figure 14. (A) Cross section of Batang basin along the East Batang fault segment showing the half-graben structure of the basin. (B) shows a geometric model of the extension across the Batang basin. The basin absorbed ~1.8 km of left-lateral slip on the Yushu fault. See line A-A' in Figure 4B for location.

surfaces dip gently to the north. The fan tips encroach on the northern margin of the basin and have pushed the river in a northern direction. In contrast, the northern margin of the basin is very narrow and lacks alluvial deposits. This indicates that the normal faults along the north side of the basin are presently the most active and that they have tilted the southern block toward the north. The structure and sedimentation discussed in this paper suggest that the north-dipping normal fault bounding the southern Batang basin margin is the major feature of the East Batang fault and that the Batang basin is still active with a prominent normal component along the East Batang fault. Based on the asymmetric pattern of sedimentary fill, the basin is interpreted to have formed as a half graben, linked to the southward tilting of the block in the hanging wall (Fig. 14). The southern fault strand may be a listric normal fault dipping north beneath the northern fault strand of the East Batang fault. Based on the tilt angle of the flat surface of the hanging wall and the width of the basin, the amount of N-S extension can be estimated to be ~1.8 km (Fig. 14B). Movement along a listric detachment along the southern Batang fault strand is also corroborated by the average elevation difference between the mountains on its footwall and hanging wall, reaching 5500 m and 4800 m, respectively. Based on the geometric model in Figures 4 and 14, the maximum thickness of the Batang basin infill may be as much as 1000 m, so that it is possible that even older sediments exist beneath the middle Pleistocene strata. Thus, we infer that deformation and basin subsidence could have initiated at least in early Pleistocene time, and perhaps somewhat earlier.

The development of the Batang River is genetically linked with the deformation of the young and active structures in the Yushu area because the lower part of the river is offset by the Yushu fault in the north, whereas its upper part developed along the Batang basin. This spatial and temporal relationship implies that an average, 25-km, left-lateral offset occurred in the early Pleistocene.

From the Batang basin westward, the regional N-S extension becomes partitioned between several faults grouped together as the West Batang faults (Fig. 3). These fault branches traverse the flat, grass-covered plateau, which is underlain by Neogene fine-grained sandstones and mudstones. Where these fault strands are visible, the plateau surface composed of Neogene red beds is tilted in various directions and forms many basins, including the Chala Co basin in the west, the Borota basin in the east, and the Longyada basin in the center. The Chala Co basin is bounded to the north and south by two steeply dipping normal faults that dip toward each other. The footwall Neogene red beds along the southern boundary are tilted to the south and mark a local water divide. The Longyada basin is bounded to the south by the western continuation of the southern fault strand of the Batang faults and to the north by two, steeply south-dipping, normal faults. Along these stepped normal faults, the Neogene red beds are offset vertically and are exposed on the fault scarps. The northernmost fault of the West Batang faults is characterized by several stepped normal faults, which define a series of terraces with different elevations, separating two grabens to the north and south. The Borota basin is separated from the Longyada basin by a horst composed of late Triassic white limestone. This basin is bounded on the north and south by the northern and southern fault strands of the Batang faults and is divided into two parts by a horst in its central part. This horst consists of Neogene red beds that are tilted to the west at 35°. Fresh fault scarps are well preserved along the northern edge of the basin, along which the stream flows within a relatively steep valley, suggesting a young age of the normal fault. Because of the complicated geometry of the West Batang faults, the total amount of the extension cannot be estimated.

Figure 15. The 8-m–high terrace of alluvial fans of middle Pleistocene age in the Batang basin. Facing to east.

Xialaxiu Fault

The Xialaxiu fault lies in the southernmost part of the Yushu area and forms an arcuate feature (Figs. 2 and 3) that can be followed for 130 km. It merges with the Ganzi fault to the east and the West Batang fault segment to the west. The Xialaxiu fault lies within a remote area of high elevation, and, thus, only limited field observations were made. It bounds a large, rhomb-shaped mountain in the south and is bounded by the East Batang fault basin in the north. The Xialaxiu fault is exposed along the southern margin of a linear valley and dips to the north at various angles. There is no direct evidence for horizontal motion along the fault. The mountain north of the fault marks the highest part of the Yushu area, is capped by permanent glaciers, and reaches an elevation of 5750 m. The northern and southern slopes of this mountain range are asymmetric, with the steepest gradient on the north, suggesting that the mountain has been tilted to the south. Based on this observation, we tentatively suggest that the Xialaxiu fault is a young, north-dipping, normal fault, and both this fault and the Batang faults were formed by regional N-S extension and associated southward tilting of the intervening mountain block.

INTERPRETATION OF DEFORMATION HISTORY

Geologic and geomorphic evidence presented in this paper demonstrates that late Cenozoic deformation associated with the left-lateral movement along the northwestern end of the Xianshuihe fault system was taken up by the Yushu fault, the Xialaxiu fault, the Dangjiang fault, and the North Yushu block. Different units of Triassic strata can be matched across the Dangjiang fault and yield 39 km of left-lateral displacement (Fig. 13). This suggests that the Xianshuihe fault system has lost as much as 41 km (80 km − 39 km = 41 km) of its left-lateral displacement at its northwestern end in the area between the Yushu and Dangjiang

TABLE 1. OFFSETS OF GEOLOGICAL BODIES AND STREAMS ALONG THE XIANSHUIHE FAULT SYSTEM

Locations	Offset features	Magnitudes	Life span
Ganzi fault			
Figure 1	Granite batholith	80 km	Late Tertiary
Figure 2	Jinsha River valley	80 km	Late Tertiary
Yushu fault			
Figure 6	Stream channel	400 m	Holocene
Figure 6	Stream channel	600 m	Holocene
Figure 6	Abandoned stream channel	3 km	Late Pleistocene
Figure 4	Batang River valley	14 km	Early Pleistocene
Figure 4	Batang River valley	30 km	Early Pleistocene
In article	Batang River channel	25 km	Early Pleistocene
Figure 7	Stream channel	300 m	Holocene
Figure 7	Stream channel	600 m	Holocene
Figure 7	Stream channel	450 m	Holocene
Figure 7	Stream channel	3 km	Late Pleistocene
Figure 8	Stream channel	600 m	Holocene
Figure 11	Stream channel	3.5 km	Late Pleistocene
Figure 11	Jielong River valley	3 km	Late Pleistocene
Figure 11	Jielong River valley	17 km	Early Pleistocene
Dangjiang fault			
Figure 12	Jielong River valley	5 km	Early Pleistocene
In article	Volcanic body	4 km	Early Pleistocene
Figure 12	Dangjiang River valley	16 km	Early Pleistocene
Figure 12	Zhiduo River valley	6 km	Early Pleistocene
Figure 13	Volcanic body	29 km	Late Cenozoic time
Figure 13	Volcanic body	39 km	Late Cenozoic time

faults. Both the Batang and Xialaxiu faults were dominated by extensional deformation and the development of a series of grabens and horsts. Among the graben basins, the early Pleistocene Batang basin is the largest. It is interpreted to have formed as pull-apart basin in map view and as half-graben in N-S profile, resulting from NW-SE extension across the Batang fault. The amount of NW-SE extension across the Batang basin is calculated to be 1.8 km. Both the Batang and Xialaxiu faults join with the Ganzi fault to the east. This indicates that these two structures absorbed a part of the left-lateral movement on the Ganzi fault. Although there is a lot of controversy on the use of river offsets for assessing tectonic offsets, particularly for long-term offset (e.g., Gaudemer et al., 1989; Lacassin et al.,2004; Replumaz et al., 2001), the river offset that occurred along the northwestern continuation of the Xianshuihe fault system is consistently left lateral (Table 1). Thus, we use the river offset as the base for determining the left-lateral movement of the fault. The Batang River is a key feature within this region because its development is probably genetically associated with these faults. The river is deflected ~25 km by the east segment of the Yushu fault at the same time its upper part was controlled by the opening of the Batang basin, initiated in early Pleistocene time. This suggests that the NW-SE, left-lateral movement and NW-SE extension along the northwestern continuation of the Xianshuihe fault system fault were coeval and initiated in early Pleistocene time. No fine-grained lacustrine deposits are present within the Batang basin, suggesting that the Batang River did not enter the previously closed Batang basin. Based on geomorphic evidence, the left-lateral displacement along the Yushu and Dangjiang faults occurred since early Pleistocene time and is estimated to be 25 km and 16 km, respectively. Therefore, ~9 km of the left-lateral displacement were absorbed in the area between the Yushu and Dangjiang faults (Fig. 16): ~5 km were absorbed by the crustal shortening along the North Yushu block, ~1.8 km were absorbed by the extension across the Batang basin, and the remaining 2.2 km were absorbed by extension across the Xialaxiu fault and other extensional basins since early Pleistocene time.

The cross-cutting relationship between the southern branch of the Yushu fault, with left-lateral movement, and its northern branch, with thrust movement, indicates that the crustal shortening across the North Yushu block and associated left-lateral movement along the Yushu and Dangjiang faults may have initiated in Neogene time, probably in middle Miocene (ca. 12 Ma), as indicated by the timing of emplacement of the granite along Xianshuihe fault in Kangding area (Roger et al., 1995). The Yushu fault obliquely joins with the Dangjiang fault to the northwest along the North Yushu block, which experienced significant shortening in middle Neogene time. Based on the shape and the spatial and temporal relationship of the North Yushu block with the Yushu and Dangjiang faults, we interpret this block to lie within a restraining bend (Fig. 16), along which the left-lateral movement along the Xianshuihe fault system was partially transferred into crustal shortening. Shortening sums up to ~32 km (41 km – 9 km = 32 km), of which, ~10 km of shortening were taken up by thrusting along the west segment of the Yushu fault.

Despite the fact that the Dangjiang fault loses its geomorphic expression at its western end, its westward continuation is also an east-striking fault (Fig. 16), separating Permian rocks to the north from Triassic rocks to the south. This fault can be traced northwestward into the Fenghuo Shan area in central Tibet, where it runs into a thrust belt with a prominent topographic expression, along which a thick succession of Tertiary red beds (Liu and Wang, 2001) was shortened in a N-S direction by 40% along a series of thrust faults and folds (Coward et al., 1988). Global Positioning System (GPS) measurements (Zhang et al., 2004) demonstrate that the northward movement of the plateau decreases across this thrust-fold belt, suggesting that the Fenghuo Shan thrust fault may still be active. We speculate that the Fenghuo Shan thrust belt was previously the westward continuation of the Xianshuihe fault system in late Neogene time, along which the left-lateral displacement of ~39 km was gradually transferred westward into the N-S shortening through the Dangjiang faults. Correspondingly, the fault dip changes from high angle to low angle, which may have led to the fault losing its clear identity on the satellite image and in the field. Thus, the left-lateral movement within the southeastern part of the Tibetan Plateau along the fault system, which was caused either by lateral extrusion or clockwise rotation, is largely restricted to the northwestern end of the fault system. Cenozoic deformation history along the northwestern part of the Xianshuihe fault system includes left-lateral strike slip, and normal and reverse dip slip. The left-lateral movement is mainly taken up by the Yushu and Dangjiang faults, whereas the NW-SE extension occurred along the Batang and Xialaxiu faults.

DISCUSSION AND CONCLUSIONS

The northwestern continuation of the Xianshuihe fault system lies within a transitional area between the main part of the Tibetan Plateau to the west and its southeastern margin to the southeast. While the Tibetan Plateau experiences east-west extension by conjugate strike-slip faults (Molnar and Tapponnier, 1978; Taylor et al., 2003), the latter area is rotated clockwise around the northeastern syntaxis of the Himalayas with a component of southeastward extrusion (Holt et al., 1991; Wang et al., 1998). The transfer mechanism from north-south shortening and east-west extension to oblique rotation is an important, unanswered question. For example, it has not yet been determined whether the left-lateral motion along the northwest-southeast–trending faults, including the Xianshuihe fault within this transitional zone, was caused by rotation or lateral

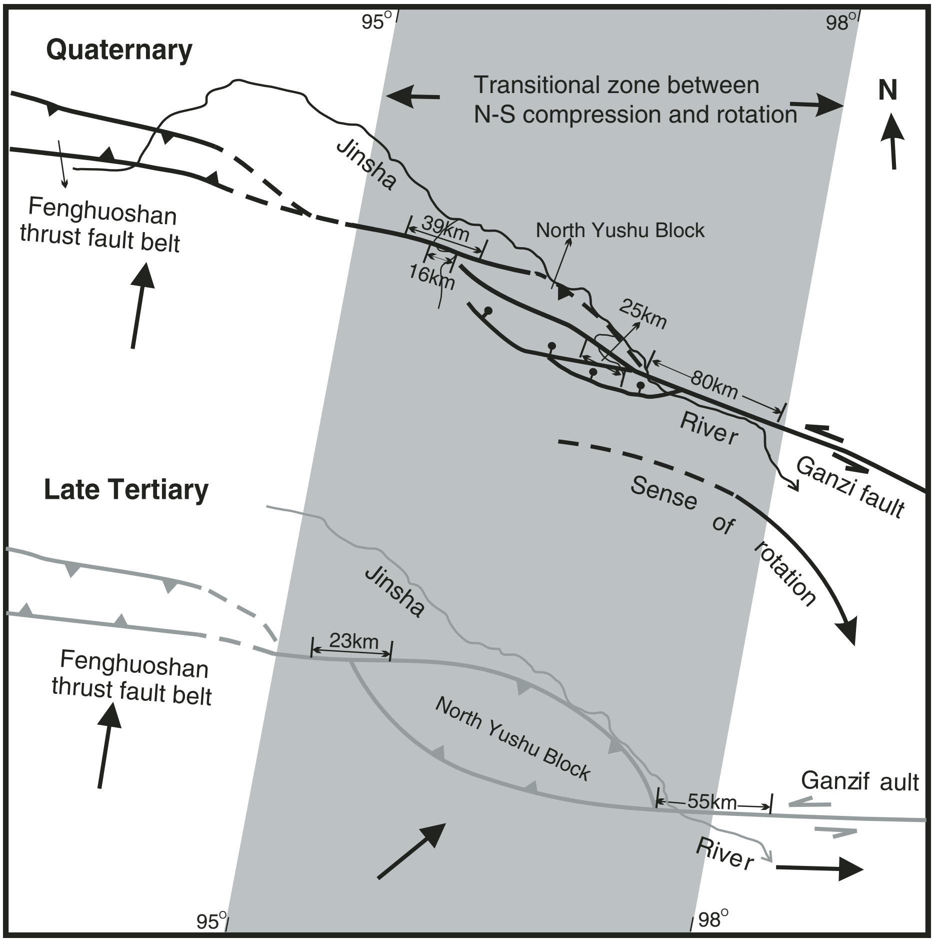

Figure 16. The northwestern continuation of the Xianshuihe fault system lies within the transitional zone between the central Tibetan Plateau, undergoing N-S compression, and the southeastern margin of the plateau, experiencing clockwise rotation. The change in strike of the fault is interpreted to have been the main cause for the occurrence of deformation transformation changing from transpression to transtension. A two-stage evolutionary model of the northwestern continuation of the Xianshuihe fault system shows that ~41 km (80 km – 39 km) of the left-lateral displacement was lost in the Yushu-Dangjiang area, and the rest of the displacement, ~39 km, was absorbed by the Fenghuoshan thrust fault.

extrusion (Tapponnier, et al., 1986; Molnar and Lyon Caen, 1989). As shown in this paper, the late Cenozoic deformation along the northeastern continuation of the Xianshuihe fault can offer an interpretation of how such transfer process occurs.

Our observations on field relations and Landsat imagery suggest that the northwestern continuation of the Xianshuihe fault has had a complex evolutionary history. Fault evolution was dominated by transpressional and transtensional deformation, initiated in the middle Miocene (12 Ma) and the early Pleistocene, respectively. Fault trend change is possibly the main reason for the transfer system changing from compression to extension. Through these transfer structures, the left-lateral displacement that accumulated on the northwestern part of the Ganzi fault was largely absorbed. The Quaternary extension occurred along the northwestward continuation of the Xianshuihe fault and was coeval with extension that occurred along its southern end in central Yunnan, implying that the southeastern margin of the plateau underwent clockwise rotation. The northwestern continuation of the Xianshuihe fault may have extended farther west to the Fenghuo Shan thrust belt, where the left-lateral movement was completely transferred into N-S shortening. The existence of transfer structures described in this paper suggests that either extrusion or rotation of southeast Tibetan crust was constrained in the eastern part of the Yushu fault and does not shift toward the center of the Tibetan Plateau.

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