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Northwest-trending, middle Cenozoic, left-lateral faults in southern Yunnan, China, and their tectonic significance

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Abstract

The northwest-striking Jianshui, Qujiang, and Chuxiong faults and probably the Zhongdian fault, south China, show evidence for different amounts of middle Cenozoic (pre-Pliocene and post-early Paleogene) left-lateral displacement that range from 6 to 25 km. The age and orientation of the left-lateral faults suggest that the faults are related to a regional deformational event associated with important left-lateral shear on the Ailao Shan shear zone which lies ~50–70 km to the south. Identification of these faults extends left-lateral shear during this deformational event farther to the northeast than previously recognized. Unlike the Ailao Shan shear zone, these faults do not appear to be part of a through-going NW-trending shear zone. These faults are interpreted to be the northernmost part of a NW-trending boundary whose main structure, the left-lateral Ailao Shan shear zone, forms a broad zone of mylonitic rocks bounding a crustal fragment that rotated clockwise around the eastern Himalayan syntaxis.

Following middle Cenozoic left-lateral displacement, only the Jianshui and Qujiang faults exhibited a reversal of displacement in post-Miocene time. This reversal is interpreted to be the result of counterclockwise rotation within the broad, N–S-striking, left-lateral Xiaojiang fault zone. None of the post-Miocene displacement on these two faults appears to be related to post-Miocene right-lateral displacement on the Red River fault system. The Chuxiong fault may have reversed its early left-lateral displacement, but evidence from surface geology for young and active right-lateral displacement is not clear. The Zhongdian fault appears to have undergone only left-lateral displacement, some of which may be middle Cenozoic in age and some post-Miocene in age. Active displacement on the Zhongdian fault is interpreted to mark the eastern boundary for a small crustal fragment that rotates clockwise around the eastern Himalayan syntaxis.

Keywords: Yunnan China; Tectonics; Strike-slip faults; Middle Neogene; Ailao Shan shear zone

1. Introduction

Numerous models have been proposed for the intracontinental deformation in the eastern part of the Tibetan plateau and its adjacent foreland resulting from indentation of Eurasia by the relative northward movement of India during Cenozoic time. The extrusion hypothesis of Tapponnier et al. (1982, 1986) is one of the few hypotheses to propose a kinematic and temporal history of specific structures in support of large scale extrusion. In a recent discussion of the two-stage extrusion hypothesis, Leloup et al. (1995) proposed that during early Cenozoic time (35–17 Ma), Indochina was extruded to the southeast bounded on the northeast by left-lateral displacement on the largely ductile Ailao Shan shear zone. They also proposed that during late Cenozoic time (~4.5–0 Ma) eastern Tibet and part of South China were extruded to the east, bounded on the south by the brittle right-lateral Red River fault zone. Harrison et al. (1992, 1996), Leloup and Kienast (1993) and Leloup et al. (1993, 1995) presented data to support left-lateral shear on the NW-trending Ailao Shan shear zone during early Miocene time and to support the beginning of right-lateral shear on the Red River fault at ~4.5 Ma. Thus, displacement was reversed on the parallel and adjacent Ailao Shan shear zone and Red River fault zone between 17 and 4.5 Ma.

Wang et al. (1998) have suggested the Ailao Shan shear zone and Red River fault zone should be regarded as two independent structures, based on their respective ductile versus brittle character, the difference in their timing, and the unclear spatial relations between them. This temporal

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and spatial separation of the two structures is followed in the discussion below.

Early Cenozoic left lateral shear in Yunnan is not restricted to the Ailao Shan shear zone, but also occurs at the same time on the Chong Shan shear zone that lies ~110 km to the west of the Diancang Shan and XueLong Shan (Wang and Burchfiel, 1997; Akciz et al., 2000). Here we present evidence that demonstrates early Cenozoic, left-lateral shear north of the Ailao Shan shear zone, which indicates broad left-lateral shear across much of Yunnan during early Cenozoic time.

The Jianshui fault is parallel to, and lies 50 km north of, the Ailao Shan and Red River structures (Fig. 1) and shows a reversal of displacement during Cenozoic time. The Qujiang and Chuxiong faults may also show reversal of displacements, but the evidence is less clear. Along strike, and further to the northwest, the Zhongdian fault zone may only show left-lateral displacement. Whereas the early part of the history of this fault may be similar to that of the other three faults, the fault may not have reversed movement direction in late Cenozoic time. Although these faults and the Ailao Shan and Red River faults share a similar history, the tectonic interpretation of the deformation in this region may be different from that proposed for large scale extrusion. Our interpretation suggests that rotation of crustal fragments has played a major role in the deformation.

2. Geological setting

In central Yunnan the NW-trending Ailao Shan–Red River shear zone separates the Yangzi paraplatform to the north and the Three Rivers fold belt to the south (Fig. 1). This part of the Yangzi paraplatform is characterized by three major tectonic units: the Kungdian High, the South China fold belt, and the Chuxiong basin (Fig. 1). The Kungdian High is underlain by Precambrian basement and is characterized by lack of, or very thin incomplete, Paleozoic sedimentary cover. The Chuxiong basin consists of a continuous sequence, more than 8 km thick, of Late Triassic to early Cenozoic sedimentary rocks. The lowermost part of the basin sequence is composed of carbonate strata, and most of the overlying succession consists of coal-bearing, continental clastic rocks (Bureau of Geology and Mineral Resources of Yunnan, 1990). These strata were deposited mainly on Paleozoic rocks west of the Kungdian High as well as on Precambrian rocks forming the western part of the High. The part of the Yangzi Paraplatform lying east of the Kungdian High consists of a sequence of shallow marine and non-marine Sinian (Latest Proterozoic) to Middle Triassic strata intercalated with abundant Permian basalt. A thick marine succession of Triassic limestone and fine-grained clastic rocks that grade eastward into flysch characterize the South China fold belt. Jurassic and Cretaceous rocks consist of terrestrial red beds with limited distribution, except in the Chuxiong basin. Folding and thrusting in the South China fold belt is generally regarded as late Triassic in age (Ren et al., 1987, p. 95). However, the only limits that can be placed on the deformation within Yunnan is after the Late Triassic and before the Early Cretaceous. Structures within the South China fold belt are arcuate, convex north in the east and concave north in the west at the southeastern margin of the Kungdian High (Figs. 1 and 2).

Cenozoic folding and thrusting affected the western part of the Chuxiong basin, parts of the Kungdian High to the east and, to an unknown extent, parts of the Yangzi paraplatform, and South China fold belt. All these tectonic units are cut by younger N-trending, left-lateral faults that form the Xiaojiang fault system and NW-trending mostly right-lateral faults (Fig. 1; for details see Allen et al., 1984; Wang et al., 1998). Because only rare Cenozoic rocks are preserved in the region, the extent of Cenozoic deformation has been very difficult to assess. Late Cenozoic and active right-lateral displacement also is present on the NW-trending Jianshui, Qujiang, and Chuxiong faults. These faults have had an older history of left-lateral displacement and are part of a system of NW-trending left-lateral faults in southern Yunnan.

3. NW-trending faults in the south-central Yunnan

3.1. Ailao Shan shear zone

The Ailao Shan shear zone consists of a NW-trending belt of variably mylonitized metamorphic and igneous rocks that underlie part of the Ailao Shan, Diancang Shan and XueLong Shan in south-central Yunnan (Fig. 1), and extends to the southeast into the DayNuiConVoi in north Vietnam (Leloup et al., 2001). The shear zone has been discussed extensively by Tapponnier et al. (1990), Harrison et al. (1992, 1996), and Leloup et al. (1993, 1995, 2001), and its characteristics are only briefly reviewed here. The mylonitic rocks in the Ailao Shan have kinematic indicators that show a consistent subhorizontal left-lateral shear sense. Leucogranite bodies, formed during high-grade metamorphism and mylonitization, yield U/Pb ages of 22.4 and 26.3 Ma (Scharer et al., 1994; Zhang and Scharer, 1999). The Ar/Ar ages on the mylonitic rocks of the Ailao Shan shear zone lie between 30 and 17 Ma, and indicate rapid cooling to 300 °C during continued left-lateral shear (Leloup et al., 2001). Based on interpretations of how the Ailao Shan shear zone relates to opening of the South China Sea and the radiometric ages within the shear zone, the shear zone is hypothesized to have been active from 35 to 17 Ma (Briais et al., 1993; Leloup et al., 1995, 2001; Gilley et al., 2000). The magnitude of displacement on the shear zone is interpreted to be ~700 ± 200 km (Leloup et al., 1995). Rapid cooling of mylonitic rocks has been interpreted by Harrison et al. (1992) to be related to the transtensional setting of the Ailao Shan range between ~27 and 17 Ma,

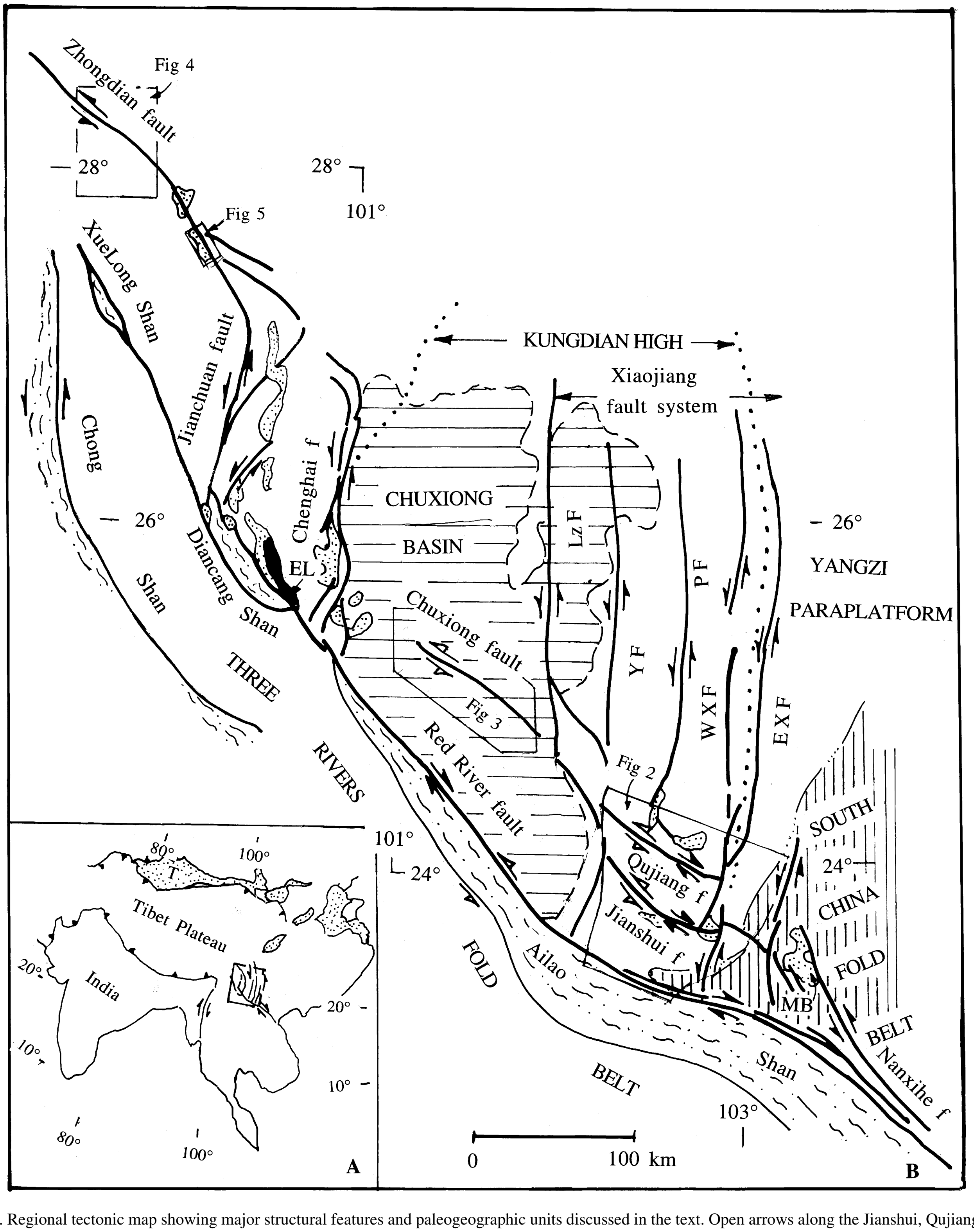
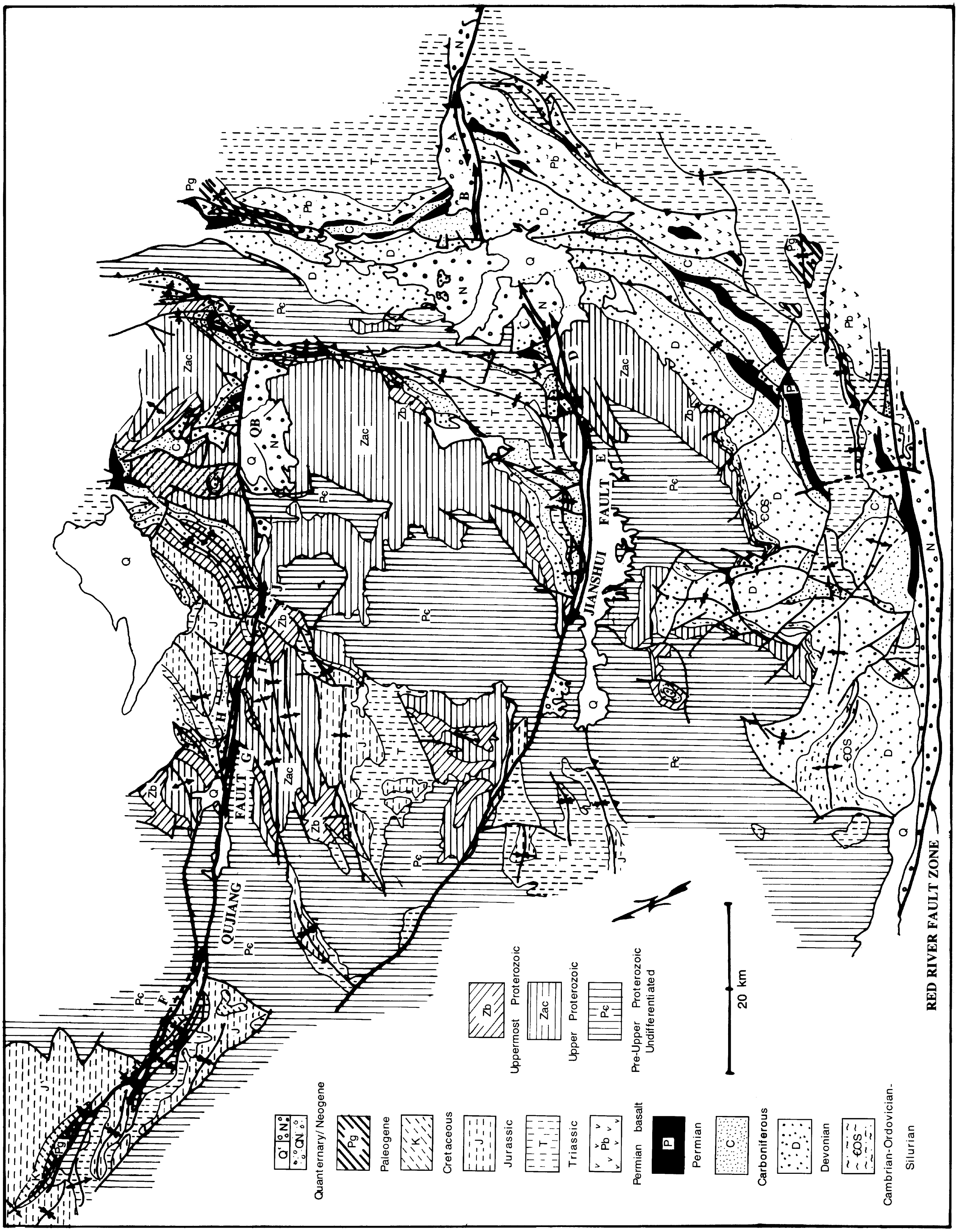


Fig. 1. Regional tectonic map showing major structural features and paleogeographic units discussed in the text. Open arrows along the Jianshui, Qujiang and Chuxiong faults indicate their older left-lateral displacement and solid arrows indicate present right-lateral sense of motion. The Mesozoic strata of the Chuxiong basin overlie most of the western Kungdian High. Inset map A shows the location of southern Yunnan region with respect to India and the Tibetan plateau. Location of other figures are shown. EL = Erhai Lake, MB = Menzi basin. Faults of the Xiaojiang fault system: EXF = eastern Xiaojiang fault, LzF = Luzhijiang fault, PF = Puduhe fault, WXF = western Xiaojiang fault, YF = Yimen fault.



Quanternary/ Neogene
Paleogene
Cretaceous
Jurassic
Triassic
Permian basalt
Permian
Carboniferous
Devonian
Cambrian-Ordovician-Silurian
Uppermost Proterozoic
Upper Proterozoic
Pre-Upper Proterozoic Undifferentiated
20 km
QUJIANG FAULT
JIANSHUI FAULT
RED RIVER FAULT ZONE

which progressively exhumed shear zone rocks from southeast to northwest (Harrison et al., 1996; Leloup et al., 2001).

In contrast, Wang and Burchfiel (1997) have interpreted the Ailao Shan shear zone to be a transpressional transfer structure associated with contemporaneous folding and thrusting during clockwise rotation in the Lanping–Simao belt, part of the Three Rivers fold belt, to the south of the shear zone (Fig. 1). In such a setting, cooling of the shear zone rocks is interpreted to result from vertical extrusion of the high-grade mylonitic rocks within a transpressional shear zone. Folds and thrust faults strike obliquely into the shear zone from the south indicating that shortening is progressively transferred to left-shear along the shear zone causing the displacement to decrease from northwest to southeast (Wang and Burchfiel, 1997).

3.2. Red River fault zone

The Red River fault zone consists of a narrow belt of NW-trending faults with late Cenozoic to active right-lateral displacement (Fig. 1; Allen et al., 1984; Leloup et al., 1995; Wang et al., 1998; Replumaz et al., 2001). One strand of the fault bounds the northeastern side of the northwestern Ailao Shan mylonitic metamorphic rocks where it also shows a component of down-to-the-NE normal displacement. The fault cuts obliquely across and terminates the northwest end of the Ailao Shan metamorphic rocks and continues NW to Erhai Lake separating Mesozoic red beds of the Lanping–Simao fold belt (the easternmost unit in the Three Rivers fold belt) to the south from Mesozoic rocks of the Chuxiong basin to the north (Fig. 1). Geologic relations near the northwest termination of the Ailao Shan suggest the Red River fault had a minimum of ~14–48 km of right-lateral displacement in pre-Pliocene (and presumably post-17 Ma) time and only 5–6 km of displacement in Quaternary time (Allen et al., 1984; Wang et al., 1998). The normal displacement along the northwest part of the Red River fault may be Pliocene to early Quaternary in age (Wang et al., 1998). The Red River fault zone shows clear evidence for active right-lateral displacement (Allen et al., 1984).

A ~100-km-long segment of the Red River fault zone and the Ailao Shan shear zone in southeastern Yunnan trend E–W, a trend interpreted to be the result of left-lateral shear where they are intersected by the Xiaojiang fault system (Fig. 1; Wang et al., 1998; Chen et al., 2000). This part of the Red River fault zone consists of at least two strands. The north side of the Ailao Shan shear zone is bounded by an inactive, south-dipping thrust fault and an active, right-lateral strand of the Red River fault that lies mainly within a narrow belt of Cenozoic rocks along the Red River. The Cenozoic rocks are poorly dated as Oligocene–Miocene and contain conglomerates with Ailao Shan clasts. Work in progress demonstrates that the Cenozoic strata are strongly folded against the S-dipping thrust that we interpret to be related to Ailao Shan shear zone-age transpression and exhumation of the high-grade rocks; thus we regard this fault to be related to Ailao Shan deformation and not part of the Red River fault zone. Other fault strands along the Red River are north- and south-dipping thrust faults, and they may also be related to transpressional tectonism. Active fault strands are near vertical and all show right-lateral displacement. It is these faults we regard as part of the Red River fault zone. The inception of the right-lateral faulting is poorly dated, but may be Late Miocene (post-17 Ma and pre-Pliocene).

3.3. Jianshui fault

The Jianshui fault lies ~50 km north of and parallel to the Red River fault zone and Ailao Shan shear zone. It can be followed for ~150 km and perhaps 200 km (Figs. 1 and 2) from the east side of the Chuxiong basin east to the Menzi basin and possibly to the Chinese border and into Vietnam. The Jianshui fault cuts through the eastern part of the Kungdian High and truncates folds and thrust faults of the South China fold belt. Active right-lateral movement on the fault can be documented by numerous geological (offset structures) and geomorphic (diflected rivers and pull-apart basins) features. The minimum right-lateral displacement on the fault is at least 1–2 km, but probably less than 5–6 km (Wang et al., 1998). From its relation to associated strata, the inception of right-lateral faulting is no older than Quaternary (Wang et al., 1998).

In contrast to the right-lateral offsets of Quaternary and Holocene features, all offsets of pre-Pliocene rock units and structures along the Jianshui fault are left-lateral (Table 1; Fig. 2). Unfortunately, offsets along the fault are all on dipping planar surfaces that do not define unique piercing points, and thus are all left-lateral separations. Since these planar features dip in different directions, they represent true left-lateral offset, but the magnitude of the displacement cannot be uniquely calculated. Measured separations range from 9 to 25 km. From east to west, left-lateral separations (shown by letters in Fig. 2) are present on the eastern boundary of Permian basalt (9 km—A), the eastern boundary of Devonian rocks (10 km—B), a major thrust fault within Devonian rocks (8 km—C), and separation of a Devonian–Late Proterozoic (Sinian) contact (minimum of 12 km—D). Farther west there is a possible 25 km left separation of Late Proterozoic rocks (E), but this possible separation is parallel to the south flank of E-trending folds and very poorly constrained. All these displacements are on the same fault that has Quaternary and active right-lateral

Fig. 2. General geological map of the Jianshui and Qujiang faults. See Fig. 1 for location. Separations of structures and stratigraphic units that define the early left-lateral displacements on the faults are shown by arrows parallel to fault and designated by letters. QB = Quxi basin.

Table 1
Present left-lateral separations on the Jianshui and Qujiang faults—shown by arrows and letter designations in Fig. 2

Jianshui fault		
A	Offset of Permian basalt/Triassic limestone	9 km
B	Offset of Carboniferous/Devonian contact	10 km
C	Thrust contact in Devonian/Carboniferous strata	8 km
D	Precambrian/Devonian contact offset	12 km
E	Pre-Upper Proterozoic/Upper Proterozoic contact	25 km
Qujiang fault		
F	Fold axis in Cretaceous rocks	3–5 km
	Jurassic/Precambrian offset	12 km
G	Pre-Upper Proterozoic/Upper Proterozoic contact	8 km
H	Projected fold axes	11 km
I	Upper Proterozoic contact (Zac/Zb)	3 km
J	Projected fold axes	6 km

displacement. If a right-lateral Quaternary offset of ~5 km (see Wang et al., 1998) is restored, the total left-lateral separation would be 13–17 km, excluding the large separation at E whose significance is uncertain.

3.4. Qujiang fault

The Qujiang fault lies ~70 km north of the Ailao Shan and Red River zones and can be traced ~120 km through rocks of the Kungdian High (Fig. 2). The trace of the fault is slightly concave north, but with less curvature than the Jianshui fault to the south. Active right-lateral displacement is demonstrated by numerous scarps and offset Holocene features (Wang et al., 1998) and seismic activity. An earthquake of M = 7.7 occurred on the Qujiang fault in 1970 (Geodetic Survey Brigade for Earthquake Research, National Seismological Bureau, 1975; Zhang and Liu, 1978), as one of a series of earthquakes recorded on the fault. The 1970 event produced a 60-km-long surface break and with a maximum right-lateral displacement of 2.7 m (Liu et al., 1988; Ma, 1989).

Like the Jianshui fault, all separations of pre-Pliocene units and structures are left-lateral. Along the middle part of the fault Devonian, Late Proterozoic (Sinian) units and numerous fold axes are truncated by the fault (Table 1; Fig. 2—H and J). In all cases left-separation is suggested; however, there are no unique correlations of the folds across the fault. Minimum separations of 11 and 6 km (H and J) are suggested. In the same area the contact between pre-Upper Proterozoic and uppermost Proterozoic rocks shows a 3 km separation (I), and the contact between the pre-upper Proterozoic metamorphic rocks and their overlying sedimentary Proterozoic cover is separated 8 km (G). Along the western part of the fault folds in Jurassic and Cretaceous rocks are offset, but the angle between the fault and folds is very oblique and makes determination of separation very difficult. Separations of between 3 and 5 km can be inferred (F) and a faulted contact between Jurassic and pre-Upper Proterozoic rocks appears to be separated 12 km (F plus its dashed extension to the east; Fig. 2). A complexly faulted syncline of Paleozoic rocks is present north of the eastern part of the fault, but unfortunately rocks on the south side of the fault are covered by Neogene and Quaternary sedimentary rocks of the Quxi basin. East of the Quxi basin a N-trending belt of complexly folded and faulted rocks are not displaced or deflected by the eastern projection of the Qujiang fault (Fig. 2). Like the Jianshui fault, the left-lateral separations are on the same fault showing right-lateral offset of Quaternary and Holocene features. The magnitude of right-lateral displacement is poorly constrained, but is probably no more than ~3 km (Wang et al., 1998). The total left-lateral separation, including the correction for later right-lateral displacement, is approximately 6–15 km, but probably closer to the smaller figure, and is poorly constrained.

3.5. Chuxiong fault

The Chuxiong fault lies ~70 km north of and parallel to the Red River fault zone and the Ailao Shan shear zone (Figs. 1 and 3). The fault is poorly defined by warping and termination of fold axes, but has not been mapped as a continuous surface fault cutting folded Mesozoic rocks of the Chuxiong basin. It lies on strike with the Qujiang fault, but the two faults are not directly connected. Pre-Quaternary left-lateral displacement on the Chuxiong fault was discussed by Leloup et al. (1995) (see also Tapponnier et al., 1990). They point out that the fault cuts obliquely across N-trending folds which bend into the Chuxiong fault from both sides suggesting they were deformed by left-shear. Also folds plunge and terminate along the projected trend of the Chuxiong fault (Fig. 3) Leloup et al. (1995) considered the folding and left-shear to be related and middle Cenozoic in age. They further suggested the left-shear was a northern expression of left-shear on the Ailao Shan shear zone thus making its age 35–17 Ma. No total offset on the fault can be determined by displaced features.

The Chuxiong fault may also have active right-lateral displacement, but the surface evidence is not conclusive. There are two small accumulations of Pliocene and Quaternary rocks along the fault that are faulted, one east of Nanhua and the other northwest of Chuxiong (Fig. 2). The Pliocene rocks are folded, but the folds and surface features along the fault do not yield evidence for the sense of movement or recent activity. Earthquake focal mechanisms for the Chuxiong fault are reported to be right-slip (Ma, 1989). Unlike the Jianshui and Qujiang faults, the reversal of displacement from surface geology is not clear.

3.6. Zhongdian fault

The Zhongdian fault can be traced from the Jinsha River northwest ~120 km to about the Lancang River valley where it appears to end (Fig. 1). Where the fault crosses the

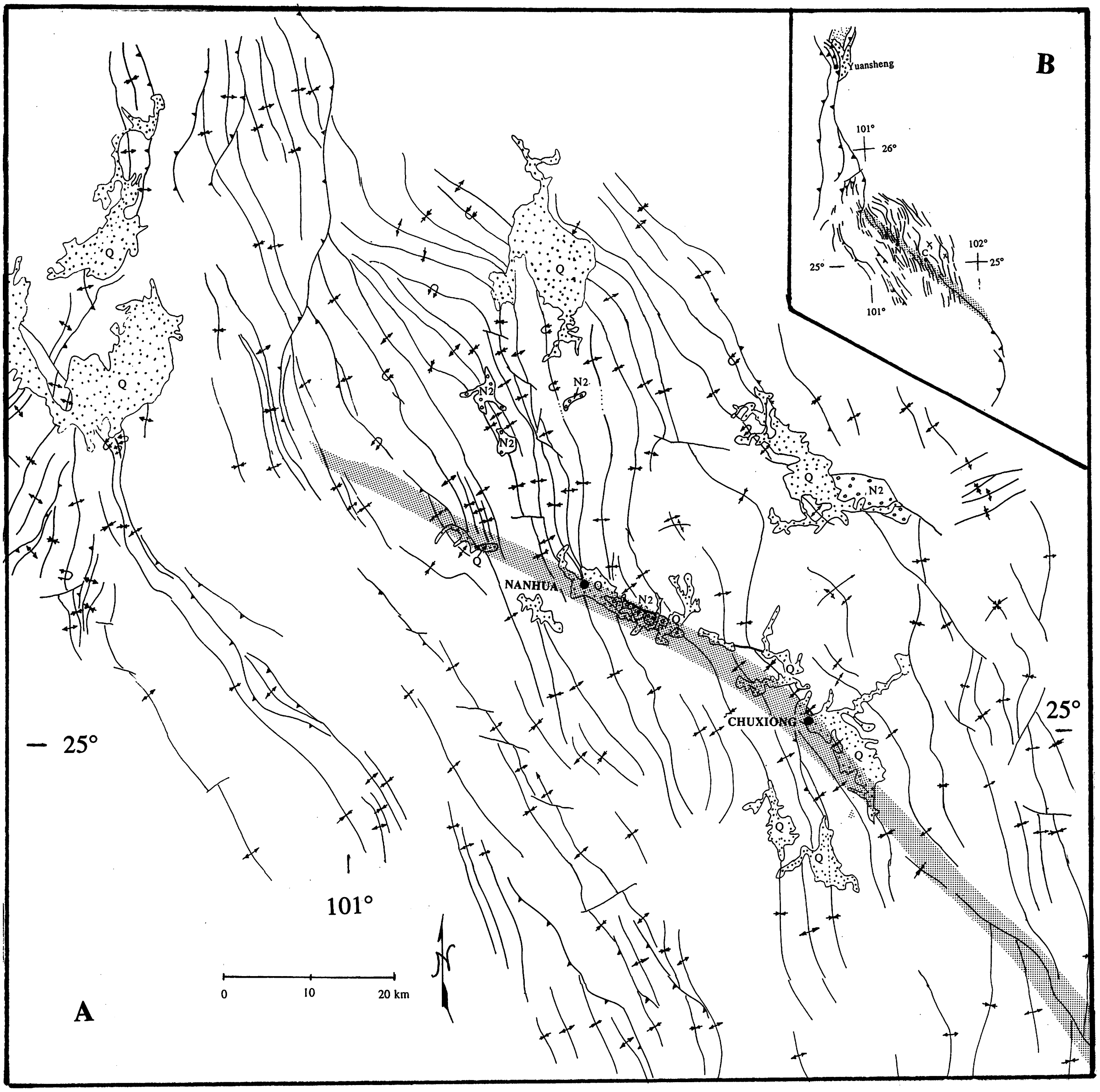


Fig. 3. (A) General structure map along the central part of the Chuxiong basin showing fold axial traces and thrust faults where deflections and terminations of folds mark the trace of the Chuxiong fault. The trace of the fault is shown by broad shaded pattern, but is not shown on geological maps as a through going surface feature. (B) More regional view of Chuxiong fault (shaded) showing its relations to Paleogene rocks to the northwest and areas of shortening at both ends of the fault. At Yuansheng large dots are Eocene strata and small dots are Paleocene strata. See Fig. 1 for location.

Jinsha River the river is deflected left-laterally ~15 km (Fig. 4). All the units in the Jinsha melange belt are offset left-laterally from 10 to 20 km. Shorter parallel faults occur on both sides of the Zhongdian fault with small (<3 km) left-lateral offsets.

Southeast of Zhongdian, the fault passes through a series of basins filled with Quaternary sediments and our analysis suggests left-lateral stream deflections in this area indicate the fault is active (Fig. 5). Some stream channels in this area show apparent right-lateral deflections; however, our analysis indicated that these stream courses are the result of recent stream capture. However, Shen and Wang (2000) suggest active right-slip along this segment of the fault. East of these Quaternary basins the fault can be traced another 50 km to the Jinsha River, but this part of the fault lies in a deeply incised valley and there are no clear left-lateral stream deflections along tributary valleys. The fault bends south at the Jinsha River and merges with the active

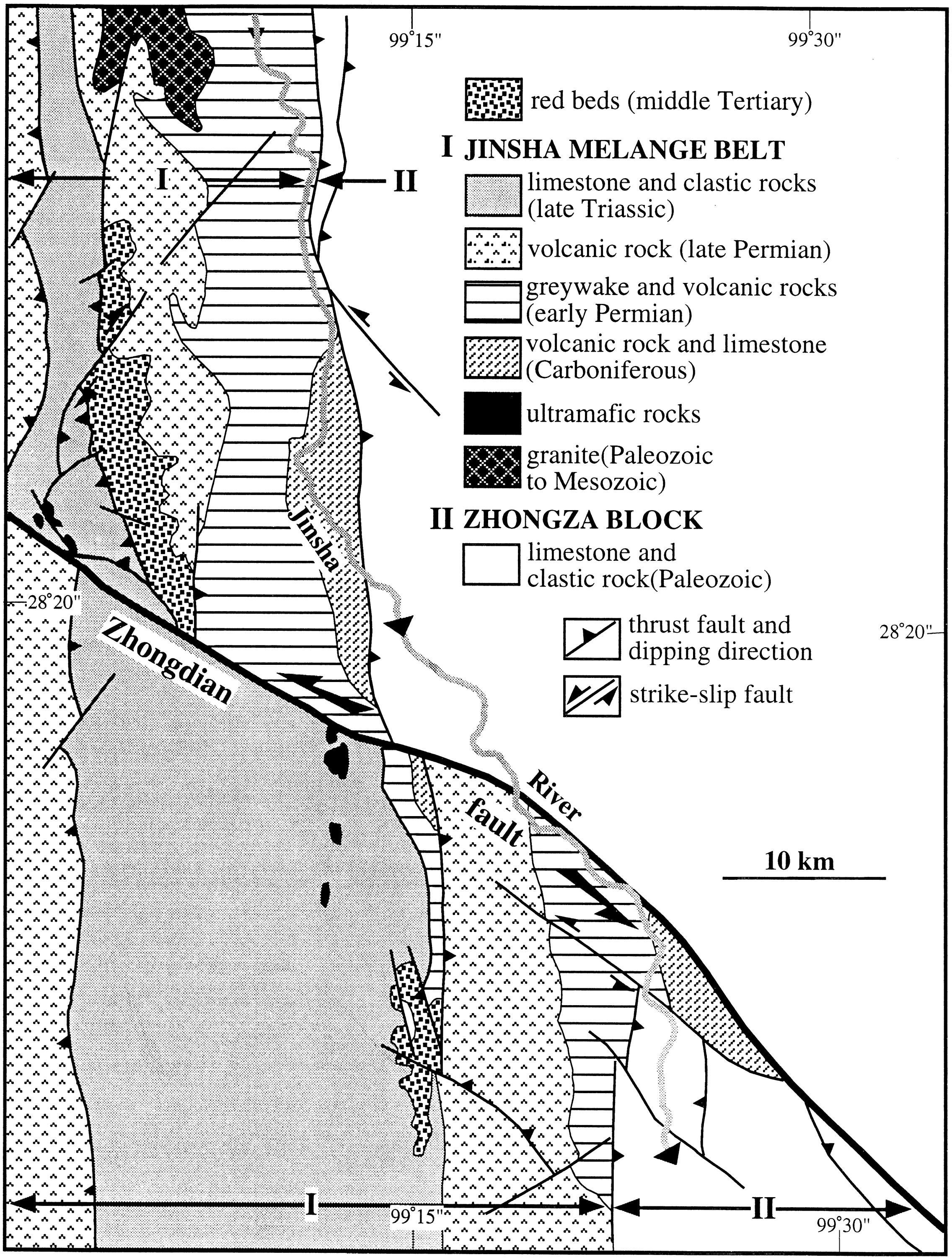


Fig. 4. General geological map along the western part of the Zhongdian fault showing the evidence for the magnitude of left-slip displacement discussed in the text. See Fig. 1 for location.

left-lateral Jianchuan fault (Fig. 1; Wang et al., 1998). The Zhongdian fault is aligned, but not connected, with the other NW-trending faults discussed above, but unlike them, the evidence for active right-slip remains unresolved (Wang et al., 1998; Shen and Wang, 2000).

4. History of fault displacements

Although all four NW-trending faults north of the Red River show recent displacements, the time period of the left-lateral displacements is not well constrained. Left-lateral

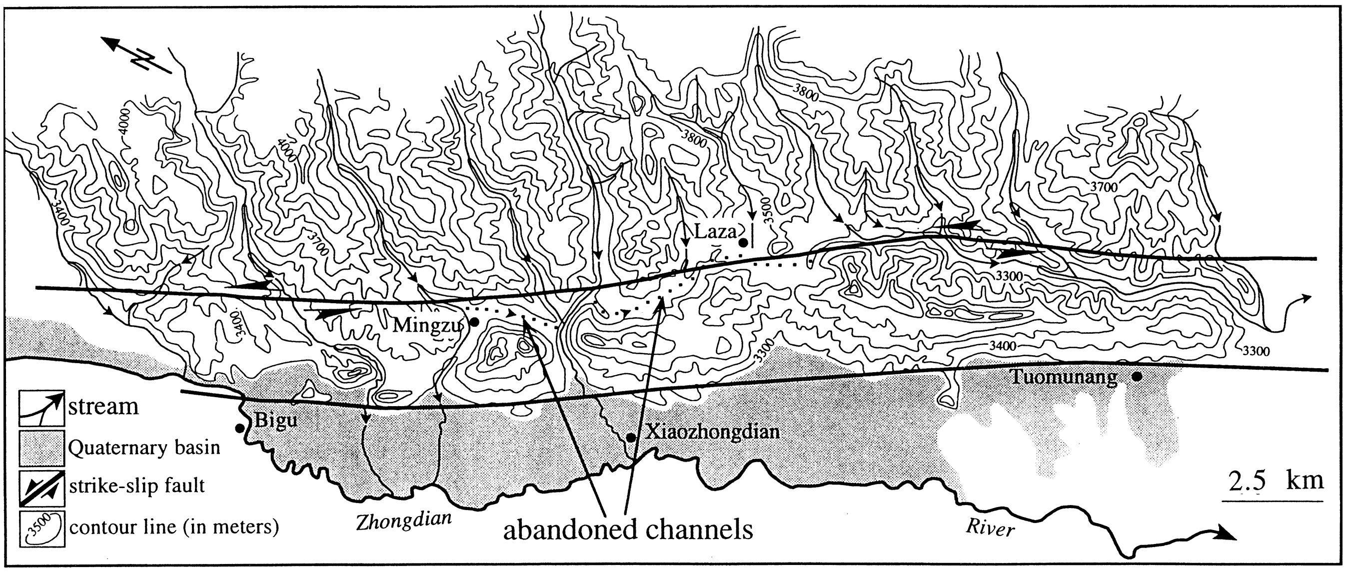


Fig. 5. Trace of the Zhongdian fault east of the town of Zhongdian and north of the Xiaozhongdian basin (see Fig. 1 for location). This is the only place along the Zhongdian fault where there is evidence for active left-slip by the displacement of river channels. Note that at least two of the channels have been modified by stream captures that show apparent right-lateral displacement. Along most of the trace of the fault there is little evidence for the sense of active displacement and some of the evidence is ambiguous (see Wang et al. (1998) for discussion, and also Shen and Wang (2000)).

displacement on the Jianshui, Qujiang and Chuxiong faults, and possible early displacement on the Zhongdian fault, is pre-Pliocene. Pliocene strata rest unconformably on an erosion surface developed mainly on pre-Cenozoic rocks, a surface we refer to informally as the sub-Pliocene erosion surface (Wang et al., 1998). Pliocene strata consist of mainly fine-grained sediments containing lacustrine and coal deposits. They show no evidence of deposition related to either the left-slip or the younger right-slip faulting suggesting left-lateral displacement was pre-Pliocene and the right-lateral displacement post-Pliocene (see Wang et al., 1998).

In the Chuxiong basin there is evidence that displacement on the Chuxiong fault was contemporaneous with folding and thrusting of Eocene/Oligocene age and probably extended into Miocene time. The N-trending fold belt that traverses the central and western part of the basin deforms a conformable succession of Triassic to Paleocene sedimentary rocks (Fig. 3B). A thrust fault involving Paleozoic rocks, reactivated as a Quaternary–Holocene left-slip normal fault (Wang et al., 1998), forms the western boundary of the Chuxiong basin. In the northwestern part of the basin thrust faults and folds parallel to this boundary thrust involve Paleocene and Eocene/Oligocene strata near Yuansheng (Fig. 3B). These folds and thrusts are continuous with the fold and thrust belt that traverses the central part of the basin (Fig. 3A and B). In the Yuansheng area, Paleocene strata rest unconformably on Triassic strata, but consist of fine-grained red sedimentary rocks similar to those in the Chuxiong basin. Although their relation to older strata indicate pre-Paleocene deformation, the character of the Paleocene strata, and the trends of the pre-Paleocene structures indicate that the fold and thrust belt did not form in Paleocene time. In contrast, Eocene/Oligocene strata along the northwestern side of the basin near Yuansheng contain sandstone and conglomerate that unconformably overlie Paleocene and older rocks. In addition, clasts within the Eocene/Oligocene strata are derived from the underlying rocks suggesting deformation began during deposition of these strata. The thrust faults and folds that involve the Eocene/Oligocene rocks are continuous with folds and thrust faults within the central part of the basin suggesting deformation may have begun there in Eocene/Oligocene time. Deformation may have continued into Miocene time, but there are no sediments of this age in the region to confirm this younger age. As pointed out by Leloup et al. (1995), the Chuxiong fault obliquely traverses folds in the fold and thrust belt, and the folds bend into the fault on both sides, indicating left-lateral shear. They interpreted the fault as a tear fault and thus contemporaneous with the folding. We point out that both the western and eastern ends of the Chuxiong fault appear to merge with thrust faults that form part of this fold belt. Thus, we support the interpretation of Leloup et al. (1995) that the Chuxiong fault is intimately related to the formation of the fold and thrust belt and is of Eocene/Oligocene and possibly early Miocene age.

Less convincing evidence is present that suggests the Qujiang fault is also similar in age. The age of the left-lateral separation can only be constrained to lie between Eocene/Oligocene and Pliocene time. Folds containing Eocene/Oligocene rocks are parallel to folds offset by left-lateral separation along the western end of the Qujiang fault (Fig. 2). Pliocene strata in the Quxi basin are unfolded and show only evidence for right-lateral displacement (Wang et al., 1998).

The age of left-lateral displacement on the Jianshui and Zhongdian faults is poorly constrained. The left-lateral displacement on the Jianshui fault is pre-Pliocene as Pliocene rocks do not show a left-lateral offset. The Jianshui fault is parallel to the Ailao Shan shear zone and to the Chuxiong and Qujiang faults, and it is only on this basis that we suggest the age of left-lateral displacement on the Jianshui fault is Eocene/Oligocene and perhaps Miocene in age. Recent movement on the Zhongdian fault appears to be left-lateral (Wang et al., 1998), thus there is no clear separation between younger and possible older left-lateral displacement. Northwest of Zhongdian, north-striking Triassic and Paleozoic rock units are consistently offset left-laterally ~10–20 km, and poorly dated Middle Tertiary red beds may also be offset, but this cannot be unambiguously demonstrated (Fig. 4). The Jinsha River is also left-laterally deflected along the fault and we interpret this deflection as a ~15 km displacement of the river because the deflection is the same magnitude as the structurally determined offsets on the river entrenched in a canyon more than 1 km deep. These data indicate the left-lateral displacement is Cenozoic in age, but over what time period this displacement occurred remains unclear. There are several shorter faults that parallel the Zhongdian fault that also offset geological units left-laterally, thus, the total displacement along all the faults probably exceeds ~25 km. Because the Zhongdian fault is parallel and on strike with the Qujiang and Chuxiong faults to the southeast it may have left-lateral displacement of Eocene/Oligocene to Miocene age, but the sense of younger displacement may not have been reversed. The magnitude of left-lateral displacement on the Zhongdian fault is similar to that on the Qujiang and Jianshui faults and we suggest much of the displacement on this fault may be Eocene/Oligocene–Miocene. If this is true, it follows that the Jinsha River is at least that old as well.

5. Cause of reversal of displacement

Only the Jianshui fault and possibly the Qujiang fault contain evidence for right-lateral reactivation of older left-lateral faults. Wang et al. (1998) show that both the Jianshui and Qujiang faults are cut by and terminate at active N-trending faults of the left-lateral Xiaojiang fault system. We support their interpretation that the right-slip on these two E–W-trending faults is caused by counterclockwise rotation within the wide left-lateral, N-trending Xiaojiang fault system (Fig. 1; Wang et al., 1998). The Xiaojiang fault system is at least 2–4 m.y. old, and possibly as old as 6–8 m.y., which suggests rapid right-slip did not begin on the Quaternary Jianshui and Qujiang faults until left-lateral shear within the Xiaojiang fault system was well underway. Both the Jianshui and Qujiang faults have curved traces, and we interpret the curvature to be due to the continued left-lateral shear within the Xiaojiang fault system after right-slip began on the two faults during Quaternary time. Their curvature is similar to that on the Red River and Ailao Shan fault zones to the south, also interpreted to be the result of through-going left-shear on the Xiaojiang fault system that extends across the Ailao Shan and into southern Yunnan and northern IndoChina (Wang et al., 1998). Thus, in our interpretation the right-lateral displacement is not directly related to the right-lateral Red River fault zone to the south whose main activity is probably older and laterally more extensive (Wang et al., 1998).

Earthquake data suggest right-lateral displacement is present on the Chuxiong fault, but surface expression for right slip is lacking. A young fault trace, expressed as a boundary for low mountains on its south side, can only be followed from Chuxiong 40 km to the southeast. Two small basins, one containing Quaternary and Pliocene strata, are bounded by the Chuxiong fault at Chuxiong and Nanhua. The Pliocene rocks at Nanhua contain open folds and short fault traces, but Quaternary strata are undeformed. Thus, except for the earthquake data, there is no evidence for significant recent right-lateral movement on the Chuxiong fault. This fault lies west of the zone of left-lateral shear within the Xiaojiang fault system, thus right-slip cannot be related to the same cause as for the Qujiang and Jianshui faults. Any current right-lateral displacement, as evidenced by the earthquake data, is probably very small and perhaps can be related to differential E–W extension to the west and east of the fault as suggested for the young and active right-lateral displacement on the Red River fault as proposed by Wang et al. (1998). Their interpretation is supported by a small E–W divergent component in the crustal velocity relative to GPS stations west and east of the Chuxiong basin (King et al., 1997; Chen et al., 2000).

The Zhongdian fault shows possible, but ambiguous, surface features supporting right-lateral displacement and reversal of left-lateral shear from middle Cenozoic to Recent time. The Zhongdian fault merges eastward with the late Cenozoic to active N-trending left-lateral Jianchuan fault (Fig. 1). This curved fault is one of several faults that form the left-lateral Dali fault system of Wang et al. (1998). These faults are interpreted to be part of small crustal fragments that rotate clockwise around the eastern Himalayan syntaxis similar in character, but with a different pole of rotation, from the crustal fragment rotating clockwise relative to South China bounded on the east by the Xianshuihe and Xiaojiang fault system (Fig. 1; Wang et al., 1998).

6. Arcuate structures north of the Ailao Shan shear zone

One of the striking structural features in the area of the Qujiang and Jianshui faults is the concave-north shape of the generally NE-trending fold hinges and thrust faults within the South China fold belt and the Yangzi paraplatform (Figs. 1 and 2). It is the offset of these structures used to demonstrate the left-lateral displacement on the Jianshui and Qujiang faults. Unfortunately the age of these folds and thrust faults is not well constrained in southern Yunnan. Geological relations suggest most of these structures are Mesozoic in age (Wang et al., 1998), unlike the folds and thrust faults associated with the Chuxiong fault to the west. Rare and scattered folds and thrust faults in southern Yunnan, however, deform Eocene rocks. At present it remains unknown if any of the arcuate folds and thrust faults which apparently have been rotated clockwise are directly related to the deformational event that formed the left-lateral Jianshui and Qujiang faults.

7. Conclusions

The Jianshui, Chuxiong faults and probably the Zhongdian and Qujiang fault show evidence for middle Cenozoic (pre-Pliocene and post-early Paleogene) left-lateral displacement. The magnitude of left-lateral displacement is not well constrained, but ranges from 6 to 25 km. The age and orientation of the left-lateral displacement suggests they are part of a regional deformation associated with important left-lateral shear on the Ailao Shan shear zone 50–70 km to the south (Fig. 6). Unlike the Ailao Shan shear zone they do not appear to be part of a through-going NW-trending shear zone, but rather they are a discontinuous series of faults. These faults are interpreted to be part of the northeastern boundary of a crustal fragment that rotated clockwise around the eastern Himalayan syntaxis during middle Cenozoic time. The Ailao Shan shear zone accommodated a large amount (700 ± 200 km according to Leloup et al., 1995) of left-lateral shear relative to rocks north of the shear zone (Wang et al., 1998), and the Chong Shan shear zone accommodated an unknown amount of left-lateral shear farther to the west (Akciz et al., 2000).

Following middle Cenozoic (during Eocene to perhaps early Miocene time) left-lateral displacement, the faults were subjected to different tectonic regimes. Reversal of displacement on the Jianshui and Qujiang faults is interpreted to be caused by counterclockwise rotation within the broad, through-going, left-lateral Xiaojiang fault system. The active left-lateral shear deforms the Jianshui and Qujiang faults as well as the Red River fault zone and Ailao Shan shear zone farther south (Fig. 1; Wang et al., 1998).

The Chuxiong fault may have reversed its early left-lateral displacement, but evidence for recent displacement is not clear. If earthquake data for right-slip on the fault is correct, its small, young displacement may be the result of a small component of active E–W extension shown by GPS velocities and related to a small component of differential east and west extension between regions west and east of the fault (Wang et al., 1998).

The Zhongdian fault may have only left-lateral displacement, some of which may be middle Cenozoic in age. The active Zhongdian fault is interpreted to be the eastern boundary of a small crustal fragment that currently rotates clockwise around the eastern Himalayan syntaxis (King et al., 1997; Wang et al., 1998; Chen et al., 2000).

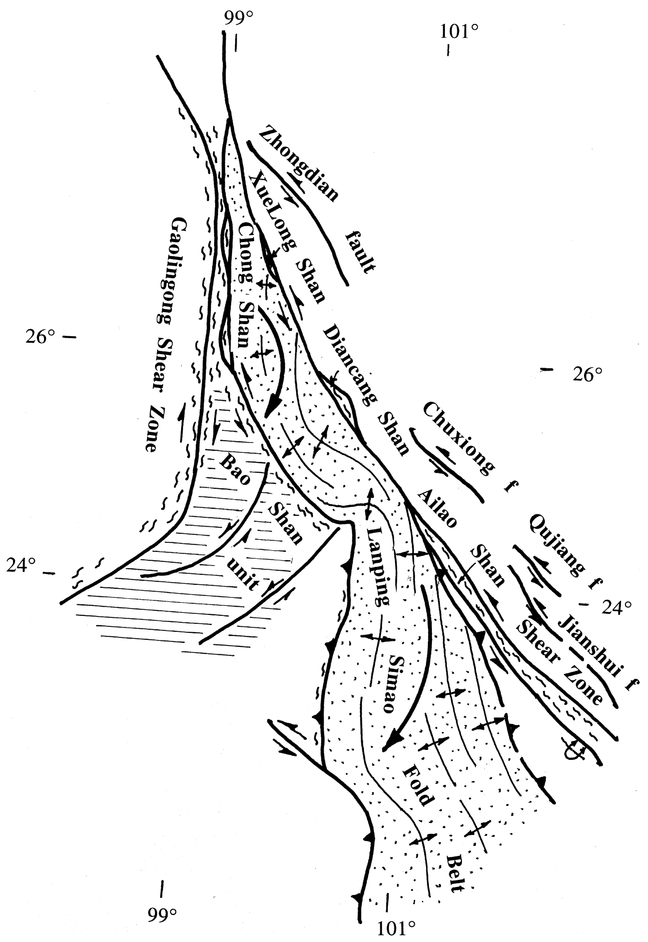


Fig. 6. Interpretation of faults discussed in the text and their relation to regional middle Cenozoic tectonism in southern Yunnan. The Ailao Shan shear zone has been interpreted to form the northern boundary for a crustal fragment that has moved to the SE and rotated clockwise (large curved arrows) relative rocks north of the shear zone and west of the right-lateral Gaolingong shear zone. The four discontinuous faults discussed in the text appear to extend the northern boundary of left-lateral middle Cenozoic tectonism north of the Ailao Shan shear zone.

All the four faults (Jianshui, Qujiang, Chuxiong, and Zhongdian faults) are currently located within crust west of the left-lateral Xianshuihe–Xiaojiang fault system that has been rotating clockwise for at least the past 2–4 m.y. relative to South China. The left-lateral Zhongdian fault is the only one of these faults that bounds a small crustal fragment that is rotating clockwise within the larger region undergoing clockwise rotation (Chen et al., 2000). The Chuxiong fault is probably rotating clockwise with little displacement on the fault. The Jianshui and Qujiang faults lie within the broad left-lateral shear zone that forms the eastern boundary of the clockwise rotating crust and were reactivated as right-lateral faults (Fig. 1). Slow (1–2 mm/yr) right-lateral displacement on the northwestern part of the Red River fault may be caused by a small component of E–W extension shown by the difference in the crustal velocity measured at GPS stations west and east of the Chuxiong basin (Chen et al., 2000). Active right-lateral displacement on the eastern part of the Red River fault zone is interpreted to be caused by a segment of the fault zone being rotated counterclockwise by shear related to the left-lateral Xiaojiang fault system (Wang et al., 1998). We do not regard the right-lateral faulting on the Jianshui, Qujiang and the eastern segment of the Red River fault zone to be related to significant southeastward movement of crust lying north of the Red River fault zone.

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