Hairpin river loops and slip-sense inversion on southeast Asian strike-slip faults

Robin Lacassin*
Anne Replumaz
P. Hervé Leloup
Laboratoire de Tectonique, Mécanique de la Lithosphère, UMR 7578 Centre National de la Recherche Scientifique, Institut de Physique du Globe de Paris, 75252 Paris cedex 05, France

ABSTRACT

In the Golden Triangle region of southeast Asia (northern Thailand, Laos and Burma, southern Yunnan), the Mekong, Salween, and neighboring rivers show hairpin geometries where they cross active strike-slip faults. Restoration of young, left-lateral offsets of these rivers leaves residual right-lateral bends of many kilometers. We interpret these hairpins as evidence of late Cenozoic slip-sense inversion on these faults, about 5 to 20 Ma. Near the Red River fault, stress field and slip-sense inversion occurred ca. 5 Ma. This implies that the present course of these large rivers has existed for at least several million years. Pliocene–Quaternary slip rates, possibly on the order of 1 mm/yr, are inferred on each of the strike-slip faults of the Golden Triangle.

INTRODUCTION

River courses, alluvial fans, shorelines, and glacial valleys are geomorphological markers that can record offset along active strike-slip faults. Of these markers, rivers are the most durable and active. The presence of bayonet-shaped (i.e. "dog-leg") deflections generally enables an assessment of the slip sense on the fault. Determination of timing and rate of offset is, however, more difficult. This is because the magnitude of offset of any particular river course depends on the age of the river course, the ability of the river to erase deflections induced by fault motion, and the eventual occurrence of stream captures. Furthermore, regional landscapes are usually diachronous, so individual faults commonly display a variety of offset sizes (Wallace, 1968; Gaudemer et al., 1989). Precise determination of slip rates from such river offsets requires measurement of the age and offset of individual streams (Sieh and Jahns, 1984). In the absence of direct age measurement, one must infer relationships between amounts of offset, river course geometry, and age of the course (Gaudemer et al., 1989).

The active character of river courses, especially in regions of low relief, means that channel offsets will usually be less than the total amount of slip along a fault. Nonetheless, the largest rivers in deeply incised regions of strike-slip faulting are commonly offset by tens of kilometers and might be good markers of long-term displacements (Gaudemer et al., 1989). We draw attention here to the largest rivers of the eastern Himalayan syntaxis. In the Golden Triangle region, these rivers (Mekong and Salween Rivers and their tributaries) cross active strike-slip faults and are offset by several kilometers (Fig. 1). Rather than the classical bayonet shape, these offset rivers often have a peculiar hairpin loop geometry that we will argue is due to a change in sense of lateral slip millions of years ago.

*E-mail: lacassin@ipgp.jussieu.fr.

TECTONICS OF THE GOLDEN TRIANGLE REGION

Southeast of the eastern Himalayan syntaxis, the penetration of India into Asia has induced deformations in a rapidly changing stress regime (Le Dain et al., 1984; Tapponnier et al., 1986). The U/Pb and $^{39}Ar/^{40}Ar$ ages of sinistrally sheared rocks imply that southeastward extrusion of Indochina occurred between ca. 35 and 17 Ma along the Red River fault zone (Tapponnier et al., 1990; Schärer et al., 1994; Leloup et al., 1995). After that major tectonic event, as India was moving north, an inversion of the stress directions (from east-west compression to east-west extension) occurred in the Indochina block (Leloup et al., 1995). Slip sense on the left lateral Red River fault thus changed to right lateral (Fig. 1). The age of this inversion, inferred from thermochronometry, seems to have occurred ca. 5 Ma close to the Red River fault (Leloup et al., 1993), and perhaps as early as 23 Ma, near the Wang Chao fault of central Thailand (Lacassin et al., 1997) (Fig. 1).

The Golden Triangle region (northwestern Thailand and Laos, northeastern Burma, southern Yunnan) lies within the triangle-shaped northwestern corner of Indochina. It is bounded by two major strike-slip boundaries: the Red River and Sagaing fault zones (Fig. 1). Between these zones, numerous lesser strike-slip faults cut a region of rugged relief that ranges in elevations from 500 to 3000 m (Fig. 1). Most of these lesser faults strike northeast-southwest and are arcuate (Fig. 1). The clear geomorphologic expression of these faults on satellite images (e.g., Figs. 2 and 3) and topographic maps attests to their recent activity (Le Dain et al., 1984). The most recent sense of slip along these faults may be deduced from kilometer-scale deflections of river courses along them and from the focal mechanisms of earthquakes (Fig. 1). These present-day slip senses are opposite to the finite offsets that have been inferred from geological markers (Le Dain et al., 1984; Lacassin et al., 1997). We document here the geometry of the most recent offsets on the basis of topographic maps and images taken by SPOT satellite (Figs. 2 and 3).

HAIRPIN LOOPS OF LARGE RIVERS

Left-lateral river offsets, compatible with the present-day stress regime, are obvious on most of the northeast-southwest–striking faults of the Golden Triangle, attesting to long-term sinistral movement on these faults (Figs. 2 and 3). Despite the clearness of these left-lateral deflections, the river courses commonly display more complex geometries than the bayonet-shaped offsets generally observed along active faults. Near some Golden Triangle faults, the deflected river courses form unusual hairpin loops near the fault traces. Three clear examples of this geometry are given by the courses of the Mekong, Nam Loi, and Salween Rivers as they cross the Nam Ma, Mengxing, and Wanding faults (Figs. 1, 2, and 3).

Geometry of Mekong, Nam Loi, and Salween River Offsets

North of the Nam Ma fault, the Mekong River, flows toward the south-southwest. After meeting the fault at point A (Fig. 2), it turns N75°E and follows the trace of the fault for ~12 km to point B, thus defining a clear left-lateral offset. South of point B, it turns back to a south-southwest direction for a short length and completes its hairpin loop by flowing toward the west-southwest, nearly parallel to the fault.

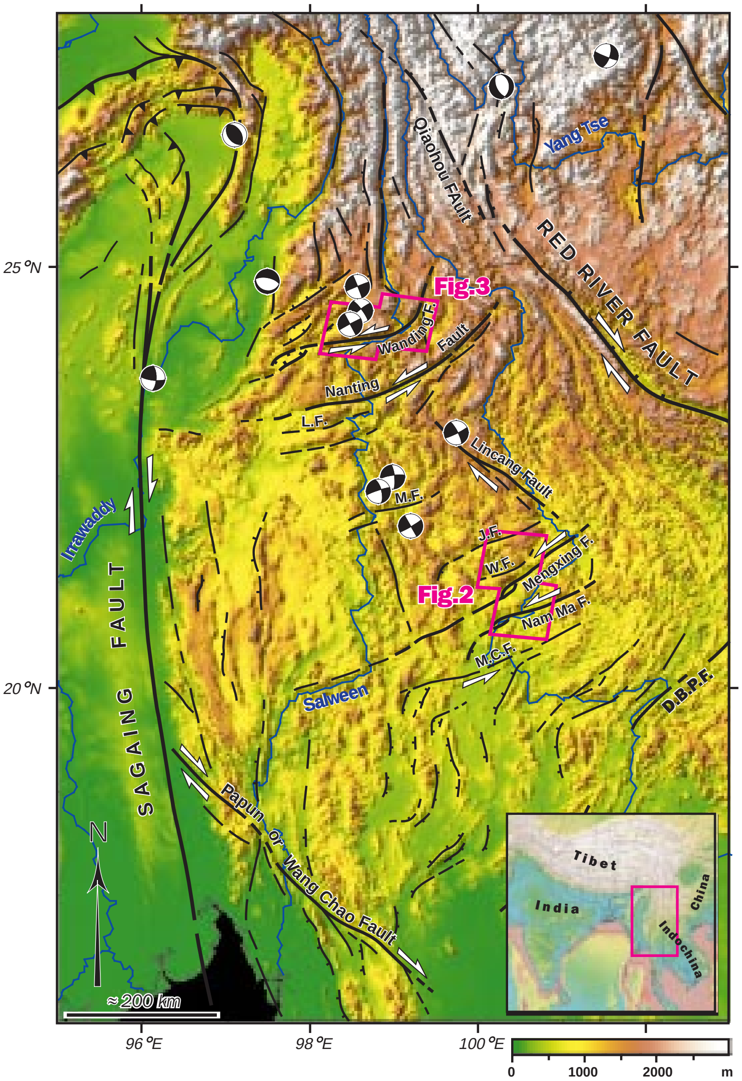

Figure 1. Active faults of northwest Indochina. Fault traces from interpretation of Landsat and SPOT satellite images and of topographic maps. Arrows show Pliocene-Quaternary sense of motion along faults. Focal mechanisms (1976–1997, M_s or $M_w \geq 6$) from Harvard database. Shaded topography from Digital Chart of the World elevation model. D.B.P.F.—Dien Bien Phu fault; M.C.F.—Mae Chan fault; W.F.—Wan Ha fault; J.F.—Jinghong fault; M.F.—Menglian fault; L.F.—Lashio fault.

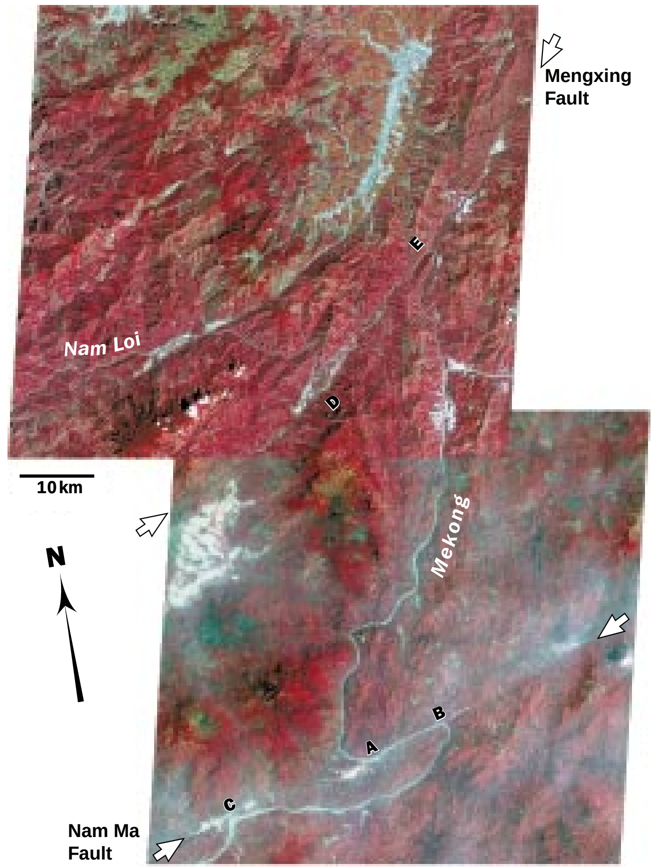

Figure 2. Mosaic of SPOT multispectral images of Nam Ma, Mengxing, and Wan Ha faults. Arrows point to Nam Ma and Mengxing fault traces, along which Mekong and Nam Loi Rivers form hairpin loops. A–B and D–E mark contemporary left-lateral offsets. C marks point where Mekong River impinges upon Nam Ma fault downstream from a large loop that may reflect an earlier 30 km offset.

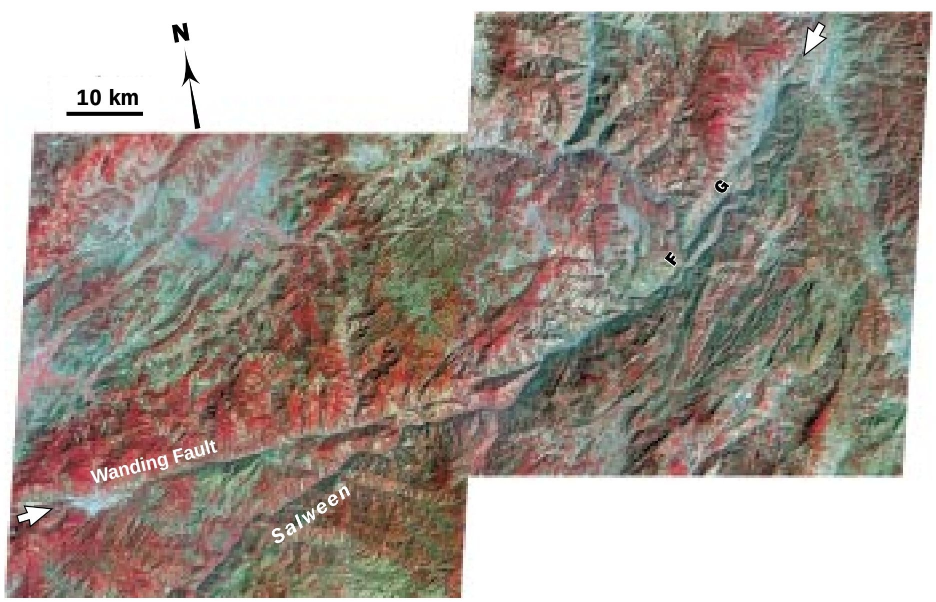

Figure 3. Mosaic of SPOT images of Wanding fault. Recent left-lateral offset of Salween River appears to be ~9.5 km (F–G), and 38 to 58 km length of river along fault may indicate large, prior, right-lateral displacement.

It flows tangentially to the fault at point C (Fig. 2), ~30 km west of point B, and then resumes its south-southwestward flow away from the fault.

About 60 km farther north, the Nam Loi River is also deflected left-laterally by two faults (Fig. 2). Along the Mengxing fault, the offset river follows the fault trace for ~24 km from point D to point E (Fig. 2). However, on both sides of the fault, the Nam Loi River draws two unusual hairpin loops resembling that drawn by the Mekong south of point B.

The Salween River flows in a deeply entrenched valley and its course presents several kinks as it is offset by strike-slip faults (Fig. 1). For example, it is deflected left laterally by the Wanding fault, flowing northeastward along the fault trace for ~10 km between points F and G (Fig. 3). Then, after a sharp hairpin loop, it flows back toward the southwest, parallel to the fault trace, for several tens of kilometers before returning to its original north-south trend.

Interpretation of River Hairpin Loops

As they cross northeast-southwest–striking faults, the Mekong, Nam Loi, and Salween Rivers thus present left-lateral offsets, flowing exactly along the fault traces for several kilometers (Fig. 4, A and C). However, rather than exhibiting a simple bayonet-like kink at the fault, these rivers form hairpin loops on one or both sides of the fault.

If one restores the left-lateral offsets, defined by the distance between the points where the rivers meet and leave the fault trace (A–B, D–E, F–G, Figs. 2 and 3), the rivers are not restored to nearly straight courses, but present deflections in an opposite right-lateral sense (Fig. 4B and 4C). Apparent opposite offsets and river course geometries resembling that of the Nam Loi River, might theoretically result from a complex interplay between tectonic offset and river captures (Wallace, 1968; Gaudemer et al., 1989). However, the major rivers in this region flow through deeply incised valleys and, near their hairpin loops, there are no other valleys of comparable size that could have been recently abandoned after a capture event. The occurrence of the hairpin loop geometry at several fault crossings and the lack of evidence for regional river captures lead us to believe that this geometry is not coincidental. The shape of the courses of the Mekong, Nam Loi, and Salween Rivers appears to result from two superposed offsets of opposite sense, the contemporary left lateral movement on the fault overprinting a former right-lateral bend. The left lateral river offsets measured on the different faults of the Golden Triangle range between 5 ± 3 and 24 ± 1 km (Table 1). There is geomorphic evidence of former right lateral offsets on some of these faults. The residual right lateral bends that remain after restoring the left lateral offsets seem to be ~30 km on the Nam Ma fault (Mekong offset) and at least 38 km on the Wanding fault (Salween offset) (Fig. 4). On the Mengxing fault, the apparent residual bend of the Nam Loi River is only 10 to 12 km, less than the 24 km left lateral offset (Fig. 4B), but an abandoned course of this river could exist farther southwest, implying the possibility for a right lateral deflection of ≈50 km (Fig. 4B). On the Menglian fault, a small hairpin loop affects a Salween tributary, the Nam Hka River (left lateral offset ~2.5 km, Right lateral bend ~5 km). The Salween River, offset left-laterally 7 km by the Nanting fault, shows a ~30 km right-lateral bend on the Lashio fault ~20 km to the south.

DISCUSSION

We interpret the hairpin-loop shape of the Golden Triangle rivers as traces of the two major tectonic phases that affected the region in the Cenozoic (e.g., Leloup et al., 1995). The left lateral offsets would be due to the contemporary motion on the active faults, whereas the older right lateral deflections would correspond to "fossil" offsets due to the Oligocene–Miocene strike-slip motion (Fig. 4). Other structural evidence confirms the right-lateral sense of Tertiary offsets: geometry of foliations or bedding fabric on satellite images (Le Dain et al., 1984), and offsets of rock units inferred from geological maps (Lacassin et al., 1997). If our interpretation of the hairpin river loops is correct, the large river courses have recorded the inversion of the slip-sense on the faults.

This interpretation, together with the large amplitude of the left-lateral offsets, implies that the courses of these rivers kept nearly the same trace for at least several million years, and have recorded a long-term history of the fault motion. On the Wanding, Mengxing, and Mengla faults, both fossil right-lateral, and active left-lateral offsets are still visible in the river shapes. We thus infer that the large river courses are antecedent to the onset of the present-day stress regime and slip-sense. It follows that the left lateral offsets correspond to the total amount of upper-Cenozoic sinistral motion on these faults.

Offsets measured on other faults of the Golden Triangle region are of the same order of magnitude as on the Wanding, Mengxing, and Mengla faults, and probably also correspond to total upper Cenozoic offsets. That some of these faults show only left-lateral offsets could imply that they are new Pliocene–Quaternary faults, or that the rivers changed their courses after the end of the first Cenozoic phase of strike-slip motion. It is also possible that right lateral deflections existed but have been eliminated by later left-lateral offsets. Note that in the three examples presented above, fossil deflections are still visible because on one branch of the hairpin loop, the river has been shifted out of the active fault zone.

The river offsets give the values of total slip due to contemporary motion on the faults and may be used to put bounds on the slip rates. Let us first assume that the onset of left-lateral motion on the Golden Triangle faults occurred coevally with the right-lateral reactivation of the Red River fault ca. 5 Ma (Leloup et al., 1993). This would imply average Pliocene–Quaternary slip rates of 1 to several mm/yr on each fault (Table 1). Tectonic inversion could have occurred significantly before 5 Ma in the Golden Triangle; we thus take these rates as upper bounds for the slip rates. If we now consider that tectonic inversion occurred ca. 20 Ma, an age compatible with that proposed for the Wang Chao fault (Lacassin et al., 1997), we obtain lower bounds for the slip rates ranging between less than 0.1 and 1.2 mm/yr (Table 1). The actual rate could be significantly different

TABLE 1. ACTIVE OFFSETS AND RESIDUAL LATERAL BENDS MEASURED ON NORTHEAST–SOUTHWEST–STRIKING FAULTS OF GOLDEN TRIANGLE

Fault	River	Left-lateral active offset (km)	Maximum slip rate (mm/yr)	Minimum slip rate (mm/yr)	Residual bend (km)
Wanding fault	Salween	9.5 ± 0.5	1.9 ± 0.1	≈0.5	≈ 38 to 58
Nanting fault	Salween	≥8	≥1.6	≈0.4	No detected bend
Menglian fault	Nam Hka	≈2.5	≈0.5	≈0.12	≈5
Lashio fault	Salween	No detected offset	N.A.*	N.A.*	≈30
Wan Ha fault	Nam Loi	5 ± 3	1.0 ± 0.6	≈0.25	No detected bend
Mengxing fault	Nam Loi	24 ± 1	4.8 ± 0.2	≈1.2	≈12 (≈50 ?)
Nam Ma fault	Mekong	12 ± 2	2.4 ± 0.4	≈0.6	≈30
Mae Chan Fault	Mekong	≈1.5	≈0.3	≈0.075	No detected bend
Faults between Mae Chan and Dien Bien Phu fault	Mekong	6 to 15	1.2 to 3	≈ 0.3 to 0.75	No detected bend

Note: Estimates of upper and lower bounds for average slip rates are deduced from left-lateral offsets with hypotheses of fault reactivation since 5 Ma and since ca. 20 Ma, respectively. Residual bends are right-lateral deflections that remain after restoring left-lateral offsets.
* Not applicable.

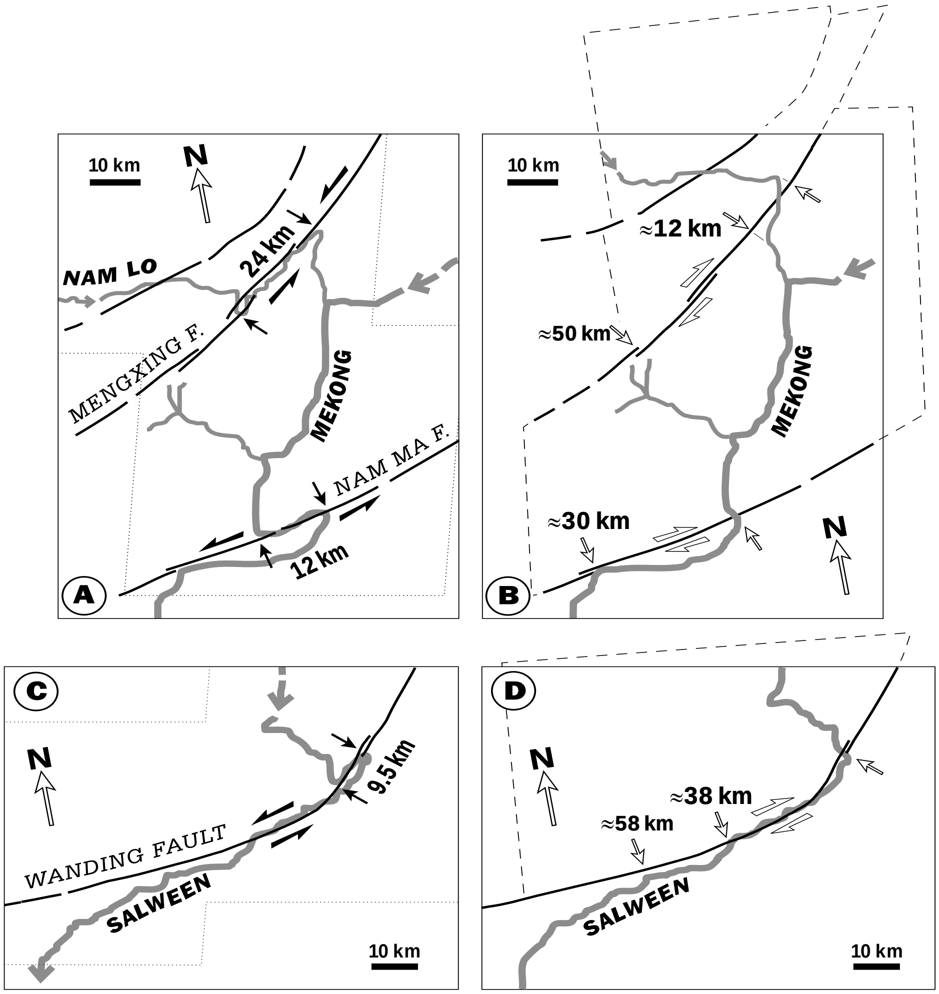

Figure 4. A: Nam Ma and Mengxing fault traces and contemporary left-lateral offsets. B: Geometry of courses of Nam Loi and Mekong Rivers after restoring left-lateral offsets. C: Wanding fault trace and contemporary left-lateral offset. D: Geometry of Salween River course after restoring left-lateral offset. On A and C, dotted frames show limits of SPOT mosaics (Figs. 2 and 3). On B and D: Dashed lines correspond to offset borders of sketches A and C; white arrows outline residual right-lateral deflections of river courses.

than the average rate calculated over time spans of several million years. In any case, these bounds on the slip rates confirm that the northwest corner of Indochina presently undergoes significant deformation (Armijo et al., 1989; Holt et al., 1991), probably by block rotation between the Sagaing and Red River faults. The slip rates estimated for each of the Golden Triangle faults are at most comparable to (upper bounds), and at least one order of magnitude less than, the ca. 5 mm/yr slip rate estimated for the Red River fault (Allen et al., 1984; Replumaz and Lacassin, 1997).

The large rivers incising the rugged relief of the Golden Triangle were thus emplaced during the Tertiary, at least before 5 Ma, and have been offset subsequently by fault motion. This confirms that large rivers may be excellent tectonic markers for measuring long-term strike-slip displacements. Deeply incised river courses may be stable for periods of several million years, and behave as nearly passive markers for horizontal tectonic offsets. Some of the Golden Triangle rivers, affected by the first Tertiary phase of strike-slip motion, already existed before the end of left-lateral motion on the Red River fault ca. 15–17 Ma (Leloup et al., 1995). This might imply that the incision of the large rivers of southeast Asia had already started in the middle to late Tertiary, and that important relief existed in eastern Tibet in the Miocene.

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