

Propagation of surface uplift, lower crustal flow, and Cenozoic tectonics of the southeast margin of the Tibetan Plateau

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ABSTRACT

Surface uplift of the southeast margin of the Tibetan Plateau is interpreted to have progressed from the northwest, near the Tibetan border, to the southeast, in the Red River region of the central Yunnan Province, China. This interpretation is based on existing thermochronologic data and new mapping and sedimentologic and paleobotanic data demonstrating incision in the headwaters of the Red River in Pliocene time or later. Together with previously published data demonstrating surface uplift and a gradient in crustal thickness in the absence of upper crustal shortening, this is strong evidence for growth of the southeast margin of the Tibetan Plateau through lower crustal flow. Displacement along the Ailao Shan–Red River shear zone slowed or ceased in early Pliocene time, and the Xianshuihe–Xiaojiang fault system initiated, accommodating diffuse deformation and rotation around the Eastern Himalayan syntaxis. We suggest a kinematic link between the change in mode of deformation and the introduction of a weak crustal layer through lower crustal flow.

Keywords: Tibetan Plateau, lower crustal flow, continental extrusion, Red River fault, crustal deformation.

INTRODUCTION

The India-Eurasia continental collision is the most spectacular example of mountain building, plateau development, and continental-scale strike-slip faulting on Earth. Models for the evolution of the collision zone vary between two end members: those that emphasize the lateral extrusion of coherent crustal blocks, with strain localized along major shear zones, and those that emphasize crustal thickening and diffuse or continuous deformation. These models, while not mutually exclusive, represent fundamentally differing views of the nature of continental deformation and the long-term strength of the continental lithosphere.

The southeast margin of the Tibetan Plateau (Fig. 1) is particularly important for understanding the development of the collision zone in the context of these models because of the nearly 1000-km-long sinistral Oligocene–Miocene Ailao Shan shear zone (Fig. 1; Tapponnier et al., 1990; Leloup et al., 1995), and the active, dextral Red River fault along the northeast edge of the shear zone (Allen et al., 1984; Replumaz et al., 2001). Tapponnier et al. (1982) proposed that in the early stages of the collision, Indochina extruded to the southeast, bounded on the northeast by the Ailao Shan shear zone. Deformation reversed in Miocene–Pliocene time, when a second crustal block to the north began to extrude, bounded by the right-lateral Red River fault to the southwest. This extrusion model is in the first category of models.

The second category comprises models that emphasize continuous deformation (e.g., England and Houseman, 1988). Recent viscous models with a depth-dependent rheology have successfully reproduced the flat-topped, steep-sided morphology of the Tibetan Plateau as well as general strain patterns observed in geodetic data (Bird, 1991; Royden et al., 1997; Shen et al., 2001). These models assume the presence of weak lower crust, which flows in response to lateral pressure gradients

and is driven from beneath Tibet into adjacent regions (Clark and Royden, 2000). Where blocked by strong lithosphere (such as the Sichuan basin), flow is impeded, and a steep topographic margin develops. Between the Sichuan basin and the eastern Himalayan syntaxis, however, relatively unimpeded flow is hypothesized to have resulted in long-wavelength crustal thickening of the southeast margin of the Tibetan Plateau (Clark and Royden, 2000).

We suggest that the resolution of these models, at least for the southeast margin of the Tibetan Plateau, may be in the time intervals to which they are applied. We first summarize evidence for lower crustal flow, and then demonstrate the propagation of plateau uplift to the southeast by using river incision as a proxy for surface uplift. We compare new data for incision in the headwaters of the Red River to existing data farther northwest (Clark et al., 2005b). We conclude with a reexamination of the Cenozoic fault systems of the southeast margin in light of these new data and suggest that intrusion of lower crust into the region triggered a gradual replacement of extrusion tectonics with diffuse deformation and rotation around the Eastern Himalayan syntaxis, thus reconciling opposing models.

LOWER CRUSTAL FLOW

Along the southeast margin of the Tibetan Plateau, both crustal thickness and topographic elevation smoothly decrease from Tibet to the southeast Asian margin (Li and Mooney, 1998; Clark and Royden, 2000; Wang et al., 2003). Crustal thickening, however, appears to have occurred in the absence of significant upper crustal shortening. Cenozoic shortening adjacent to the Sichuan basin is inadequate to account for present crustal thickness; the thrust belts farther southwest are truncated by the relict landscape (Burchfiel et al., 1995). Most active faults on the southeast margin are strike slip, with minor transpression and transtension on fault stepovers, but no significant thickening (Tapponnier et al., 1990; Leloup et al., 1995; Wang and Burchfiel, 1997; Wang et al., 1998). There is no record of shortening along the Red River since mid-Miocene time (Schoenbohm et al., 2006). In contrast, many areas (including the Red River fault, the Dali Highland, and the Tengchong region) are currently undergoing extension (Allen et al., 1984; Leloup et al., 1993; Wang and Burchfiel, 1997; Wang et al., 1998; Schoenbohm et al., 2004).

If the gradient in crustal thickness is not created through shortening apparent at the surface, thickening may have occurred at depth through the introduction of lower crustal material from beneath Tibet (Royden et al., 1997; Shen et al., 2001). An important prediction of this model is Cenozoic surface uplift of the southeast margin. This is supported by the observation of a low-relief landscape perched above the deeply incised rivers of the southeastern plateau margin. The topographic envelope of this landscape is smooth across the active and inactive structures of the southeast margin. It is interpreted as a paleo-landscape that has been passively isostatically uplifted as a response to crustal thickening (Clark and Royden, 2000). Though the precise original morphology of this surface is unknown, Clark et al. (2004) argued for a minimum 2000 m surface uplift along the Yangtze River, and Schoenbohm et al. (2004) calculated ~1400 m uplift along the

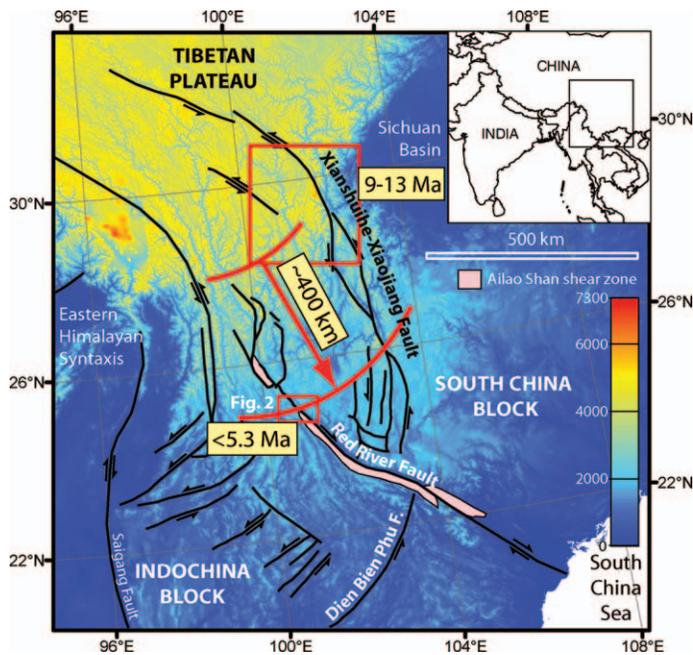


Figure 1. Topography from GTOPO30 data set (<http://edcdaac.usgs.gov/dataproducts.html>) and active faults of southeast margin of Tibetan Plateau (location shown in inset). Red boxes—regions of late Cenozoic river incision discussed in text. Red arrow—distance between sites along strike of margin. Lower crustal flow is assumed to be perpendicular to topographic gradient. Arcs used to project study areas are therefore approximated as parallel to smoothed topography.

Red River, meaning that the original surface was of relatively low elevation, and has been uplifted to its current position. Every major river of the southeast margin has incised this surface (Clark et al., 2004; Schoenbohm et al., 2004).

SOUTHEAST PROPAGATION OF SURFACE UPLIFT SIGNAL

Another important, testable prediction of the lower crustal flow model is the progressive penetration of lower crustal material, and therefore a southeastward propagation of surface uplift, perpendicular to the gradient in topographic and crustal thickness. The primary contribution of this study is to demonstrate that this has occurred, using river incision as a proxy. We make the implicit assumption that uplift drives incision. Incision is a regional phenomenon, and therefore is not likely the result of local drainage reorganization driven by displacement on strike-slip faults. Climate change is also an unlikely cause, as the Asian monsoon may have initiated significantly earlier than river incision in this region (ca. 16 Ma; Clift et al., 2002). Furthermore, if incision is triggered by monsoon intensification, a uniform age is expected regionally. We demonstrate here that this is not the case. There is likely a lag time between the beginning of surface uplift and the onset of incision, which may be 1–2 m.y. (Clark et al., 2005b). However, the lag time should be comparable in different locations, allowing us to use river incision as a proxy for uplift.

Clark et al. (2005b) determined the timing of river incision in a region adjacent to the Sichuan basin, situated on the transition from the Tibetan Plateau to the gently ramping southeast margin. Incision there along the Yangtze River and major tributaries is 3.5–4.5 km, enough to exhume rocks in which low-temperature thermochronometers have been partially or completely reset. Modeling of (U-Th)/He and apatite fission track cooling ages indicates that incision began between 9 and 13 Ma in this region (Fig. 1; Clark et al., 2005b). This is consistent with (U-Th)/He and $^{40}\text{Ar}/^{39}\text{Ar}$ data that demonstrate uplift

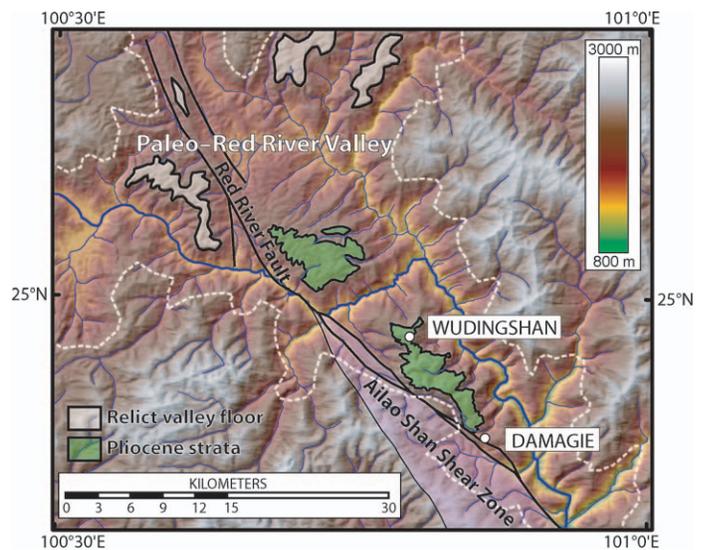


Figure 2. Generalized map of headwaters of Red River with SRTM data (<ftp://edcgs9.cr.usgs.gov/pub/data/srtm/>). Green indicates Pliocene rocks deposited on former valley floor of paleo-Red River Valley, and gray indicates remnants of valley floor with no covering strata. White dashed lines outline possible former walls of paleo-Red River valley. Red River has incised ~800 m into this surface since Pliocene time. See Figure 1 for location.

of the plateau adjacent to the Sichuan basin in late Miocene time (5–12; Kirby et al., 2002).

We show that river incision in the Red River region is Pliocene or younger. In the headwaters of the Red River (Fig. 2), ~200 m of Pliocene strata (GSA Data Repository Fig. DR1¹) are deposited on a subhorizontal surface with its base at ~2000 m, ~800 m above the modern river. Low-relief regions are found at a similar elevation upstream, and Chinese maps indicate equivalent deposits downstream in the Ailao Shan shear zone (Bureau of Geology and Mineral Resources of Yunnan Province, 1990). There are no similar deposits beyond this zone along the Red River. The Pliocene age of these rocks is well defined by plant fossils [*Quercus pannosa* (H.-M.); *Ulmus cf. miopumila* (Hu et Chaney); *Ulmus hedini* (Chaney); Bureau of Geology and Mineral Resources of Yunnan Province, 1990]. The strata comprise sandstones and conglomerate, with finer-grained fossil-bearing intervals. Conglomeratic horizons contain a variety of lithologies, including material derived from the Ailao Shan shear zone and from both Indochina and south China sedimentary strata. In many places these rocks are well cemented, probably related to a high limestone clast component, but in other places lithification is poor. In general, conglomerate clasts are well rounded and relatively small (<10 cm diameter), but rare interbeds of more angular clasts are present. Tan sandstones, siltstones, and mudstones are common, as are organic-rich, fossil-bearing layers. Channel structures are also observed. The contact between the Pliocene and Triassic strata is depositional. Deformation (open folds and minor shearing) is probably related to recent activity along the Red River fault, but may also result from downslope sliding as these units are undermined by downcutting of the Red River. Deformation of these strata along the Red River fault is consistent with the model presented here.

In our interpretation (Fig. 2), these Pliocene fluvial sediments were deposited by the paleo-Red River at a time when the river was flowing in a broad valley slightly lower in elevation than the flanking

¹GSA Data Repository item 2006179, Figure DR1, a detailed map, field photos, and descriptions, is available online at www.geosociety.org/pubs/ft2006.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

landscape. The floor of this valley is defined by the basal contact of the Pliocene units, and by nearby low-relief patches at similar elevation. The Red River has subsequently incised the landscape and its former valley, stranding these strata above the modern river, cutting them off from any possible supply source. This is not a local phenomenon, as the Red River has incised along its entire length in China, with the amount of incision decreasing smoothly and consistently upstream to this point (Schoenbohm et al., 2004). Oblique-normal displacement along the Red River fault has resulted in elevation of the footwall (Schoenbohm et al., 2004), but both these strata and the majority of incision occur in the hanging wall. The elevation of these strata above the modern riverbed therefore results from incision, not vertical displacement on the fault.

Because this unit is Pliocene in age, river incision must have begun in Pliocene time or later, or since ca. 5.3 Ma. This is supported by offshore clastic sediment accumulations in the Yinghai Basin and Gulf of Tonkin at the mouth of the Red River that indicate sharply increased sediment flux since 4 Ma (Clift, 2006). These data together imply that plateau growth began in the mid-Miocene near Tibet, propagated southeastward, and reached the Red River region no earlier than Pliocene time (Fig. 1). We cannot assess whether propagation rate has been steady from our data. However, the average rate is 50–200 mm/yr, comparable to that predicted independently (80 mm/yr; Clark et al., 2005a) through geodynamic modeling of topographic anomalies associated with flow of material around the Sichuan basin. This average rate, however, is less important than the interpretation of a propagation of surface uplift. Given that crustal thickening is an unsatisfactory answer, it would be difficult to explain this phenomenon by any means other than flow of lower crustal material to the southeast.

REGIONAL UPPER CRUSTAL DEFORMATION

If lower crust has propagated into the southeast margin it should have had an observable effect on structural deformation. We see evidence for this in the late Miocene to early Pliocene. Prior to that time, the southeast margin was dominated by displacement localized along major strike-slip shear zones, most of which reactivated older structures (Leloup et al., 1995; Wang and Burchfiel, 1997). The magnitude of displacement along the Ailao Shan shear zone (~700 km; Leloup et al., 1995) is consistent with involvement of the entire crust and potentially lithosphere in lateral extrusion. Right-lateral displacement along the Red River fault appears to be less significant, but Schoenbohm et al. (2006) demonstrated at least 15 km of displacement prior to river incision. Thus the early dextral displacement history along the Red River fault may also be consistent with the classic extrusion model.

However, there has been a dramatic shift in the mode of deformation since Pliocene time. Geomorphic data record an additional displacement of ~25 km along the Red River fault since river incision began, yielding a minimum Pliocene–Quaternary slip rate of ~5 mm/yr (Replumaz et al., 2001; Schoenbohm et al., 2006). Slip rates at present appear to be lower: Weldon et al. (1994) calculated 1–4 mm/yr from a trenching study, Rangin et al. (1995) suggested minimal or no post-Pliocene displacement based on offshore seismic data from the extension of the Red River fault into the Gulf of Tonkin, and geodetic data indicate negligible dextral slip of 2 ± 2 mm/yr (Shen et al., 2005).

Active crustal deformation on the southeast margin instead appears to be dominated by the Xianshuihe-Xiaojiang fault system (Fig. 1), which accommodates rotation around the eastern Himalayan syntaxis possibly driven by excess gravitational potential energy in Tibet and trench rollback in Burma (Wang et al., 1998). Deformation is broadly distributed, particularly along the southern strands of the Xiaojiang fault, and deflects the Red River fault. Many of these faults cut across older structural features. Displacement in Yunnan is consistently ~60 km (Wang et al., 1998). To the southwest, rotation may be ac-

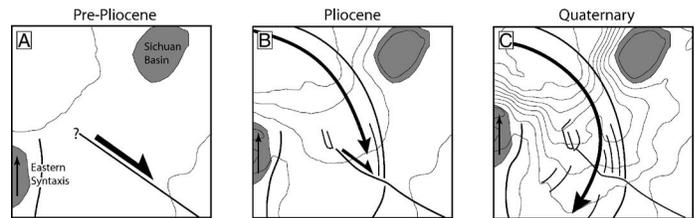


Figure 3. Proposed tectonic evolution of southeastern margin. Red River fault decreases in importance as margin grows. Detachment zone may develop in middle to lower crust, and Xianshuihe-Xiaojiang fault system accommodates rotation around eastern Himalayan syntaxis. Syntaxis moves north at ~35 mm/yr. Contours plotted at 500 m interval, calculated from smoothed topography (GTOPO30) for Quaternary, inferred for Pliocene and earlier. Compare to topography in Figure 1.

commodated along the Mengxing, Nam Ma, and Wanding faults, with 24 km, 12 km, and 9.5 km displacement, respectively (Lacassin et al., 1998), and 9.75 km displacement on the Dien Bien Phu fault (Fig. 1; Zuchiewicz et al., 2004). The fault system is thought to have become active by at least 2–4 Ma, the age of oldest sediments in fault-related pull-apart basins (Wang et al., 1998). An early Pliocene initiation ca. 4 Ma yields a slip rate of 15 mm/yr. Shen et al. (2003) estimated a similar slip rate of 13–15 mm/yr from paleoseismic data and optically stimulated luminescence dating of offset geomorphic features. Global positioning system data are consistent with rotation around the eastern Himalayan syntaxis but suggest slightly lower slip rates (~10–11 mm/yr; Chen et al., 2000; Shen et al., 2005). An interpreted ca. 12 Ma syntectonic granite along the Xianshuihe portion of the fault system in Sichuan may support an earlier initiation (Roger et al., 1995), but this is inconsistent with other data summarized here. The Xianshuihe portion of the fault may have formed first, with the system propagating and younging to the south.

Both slip rate and absolute displacement are at least two times higher along the Xianshuihe-Xiaojiang fault system than on the Red River fault since early Pliocene time. Though this may partly result from northward progress of the Eastern Himalayan syntaxis (Wang et al., 1998), the style of deformation underwent a dramatic change as well, from largely concentrated along a few discrete tectonic features, to broad distribution across the margin, and deformation and rotation of individual crustal blocks within the larger rotating system and formation of new faults, which is unexplained by current models.

MODEL FOR TECTONIC DEVELOPMENT OF THE SE TIBETAN MARGIN

Although timing can only be broadly constrained, evidence shows an overlap in the initiation of the southern Xianshuihe-Xiaojiang fault system and surface uplift in the Red River region. This coincidence suggests a kinematic link between plateau growth and the initiation of the new fault system. Lower crustal flow provides a linking mechanism: the development of a detachment zone in the weak middle to lower crust could be a trigger for the initiation of the Xianshuihe-Xiaojiang fault system, freeing the upper crust to respond to the gravitational potential of thick crust in Tibet and trench rollback in Burma.

We suggest a model for the development of the southeast margin of the plateau (Fig. 3), in which early deformation is dominated by lateral extrusion of Indochina along the Ailao Shan shear zone, and possibly later extrusion of the South China block along the reactivated Red River fault. However, ca. 9–13 Ma near Tibet (Clark et al., 2005b), lower crustal material began to flow into the southeast margin region, inflating crustal thickness and causing passive surface uplift and subsequent river incision (Clark and Royden, 2000). As material continued to propagate to the southeast in Pliocene time, weak lower crust underlying the region allowed the initiation of the Xianshuihe-Xiaojiang

fault system. Meanwhile, the Red River fault decreased in significance. Transport directions in the upper and lower crust may be strongly decoupled, with rotation around the Eastern Himalayan syntaxis in the upper crust and southeast-directed flow in the middle to lower crust. In the Red River region, transport directions may be nearly orthogonal.

From this study, and from the studies cited herein, the picture emerges of a dynamically deforming region, evolving with time as the rheological properties of the crust changed as a result of the intrusion of weak lower crust. Continental deformation cannot be treated as the lateral translation of rigid blocks, or as a continuum, but instead may dramatically evolve as the orogen develops.

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