Active structures of the Himalayan-Tibetan orogen and their relationships to earthquake distribution, contemporary strain field, and Cenozoic volcanism

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ABSTRACT

We have compiled the distribution of active faults and folds in the Himalayan-Tibetan orogen and its immediate surrounding regions into a web-based digital map. The main product of this study is a compilation of active structures that came from those documented in the literature and from our own interpretations based on satellite images and digital topographic data. Our digital tectonic map allows a comparison between the distribution and kinematics of active faults with the distribution and focal mechanisms of earthquakes. The active tectonic map is also compared with the contemporary velocity field, obtained by global positioning system studies, that allows a better assessment of partitioning of decadal strain-rate fields across individual active structures that may have taken tens of thousands of years to a million years to develop. The active tectonic map provides a basis to evaluate whether the syncollisional late Cenozoic volcanism in Tibet was spatially related to the distribution and development of the active faults in the same area. These comparisons lead to the following findings: (1) Tibetan earthquakes >M5 correlate well with mappable surface faults; (2) the short-term strain-rate field correlates well with the known kinematics of the active faults and their geologic slip rates; and (3) Tibetan Neogene–Quaternary volcanism is controlled by major strike-slip faults along the plateau margins but has no clear relationship with active faults in the plateau interior. Although not explored in this study, our digital tectonic map and the distribution of Cenozoic volcanism in Tibet can also be used to correlate surface geology with geophysical properties such as seismic velocity variations and shear wave-splitting data across the Himalaya and Tibet.

INTRODUCTION

The Cenozoic tectonic evolution of the Himalayan-Tibetan orogen and its surrounding regions is expressed by the development of complex fault systems, folds, and widespread volcanism. How these structures have accommodated India-Asia convergence has important implications for understanding strain partitioning (England and Houseman, 1986; Peltzer and Tapponnier, 1988). The spatial and temporal relationships between the Cenozoic structures and late Cenozoic volcanism can also provide clues about the role of thermal conditions and mantle dynamics in the uplift history of the orogen (Molnar et al., 1993). The comparison between Quaternary fault kinematics and slip rates from global positioning system (GPS) velocity fields allows us to understand the mechanical behavior of the continental lithosphere as a function of time (e.g., England, 1993; Thatcher, 2007). In this paper, we present a digitally based active tectonic map that allows rapid spatial correlation of geologic observations against geophysical data (e.g., seismic tomographic data, shear-wave anisotropy data, gravity data). The map is also useful in guiding rapid determination of structures responsible for major earthquakes in the Himalayan-Tibetan plateau (e.g., Burchfiel et al., 2008). We outline the active tectonic setting of the Himalayan-Tibetan orogen and present our compiled active tectonic map (HimaTibetMap-1.0). The tectonic map is superposed against GPS velocity fields, earthquake distributions, and Cenozoic volcanism. The main findings of this study include the following: (1) Tibetan earthquakes with magnitudes >5 correlate well with surface faults; (2) the decadal strain-rate fields correlate well with the kinematics and rates of active faults; and (3) Tibetan Neogene–Quaternary volcanism is controlled by major strike-slip faults along the plateau margins but has no relationship with active faults in the plateau interior. Our compiled active structures are far from being complete; however, we wish to use this web-based map as a starting point for the community's feedback and updates.

ACTIVE TECTONICS OF THE HIMALAYAN-TIBETAN OROGEN

The Himalayan-Tibetan orogen comprises vast and complex systems of interacting faults, some of which have lengths of >1500–2000 km (e.g., the Himalayan Main Frontal thrust zone and the Altyn-Tagh fault) (Fig. 1). The Himalayan-Tibetan orogen has been the focus of many studies in the past four decades (Dewey and Burke, 1973; Allegre et al., 1984; Dewey et al., 1988; LeFort, 1996; Hodges, 2000; Royden et al., 2008; Tapponnier et al., 2001; Yin, 2006; Yin and Harrison, 2000); its development may have either been achieved by the interaction of a few large rigid blocks (e.g., Meade, 2007; Tapponnier and Molnar, 1977; Thatcher, 2007), or as a flowing continuum (e.g., England 1993; Houseman and England, 1996). Because of its immense size, most studies on the active structures of the orogen have focused only on a small part of the collisional system, leaving their regional correlation somewhat ambiguous. Although strain compatibility has been used to

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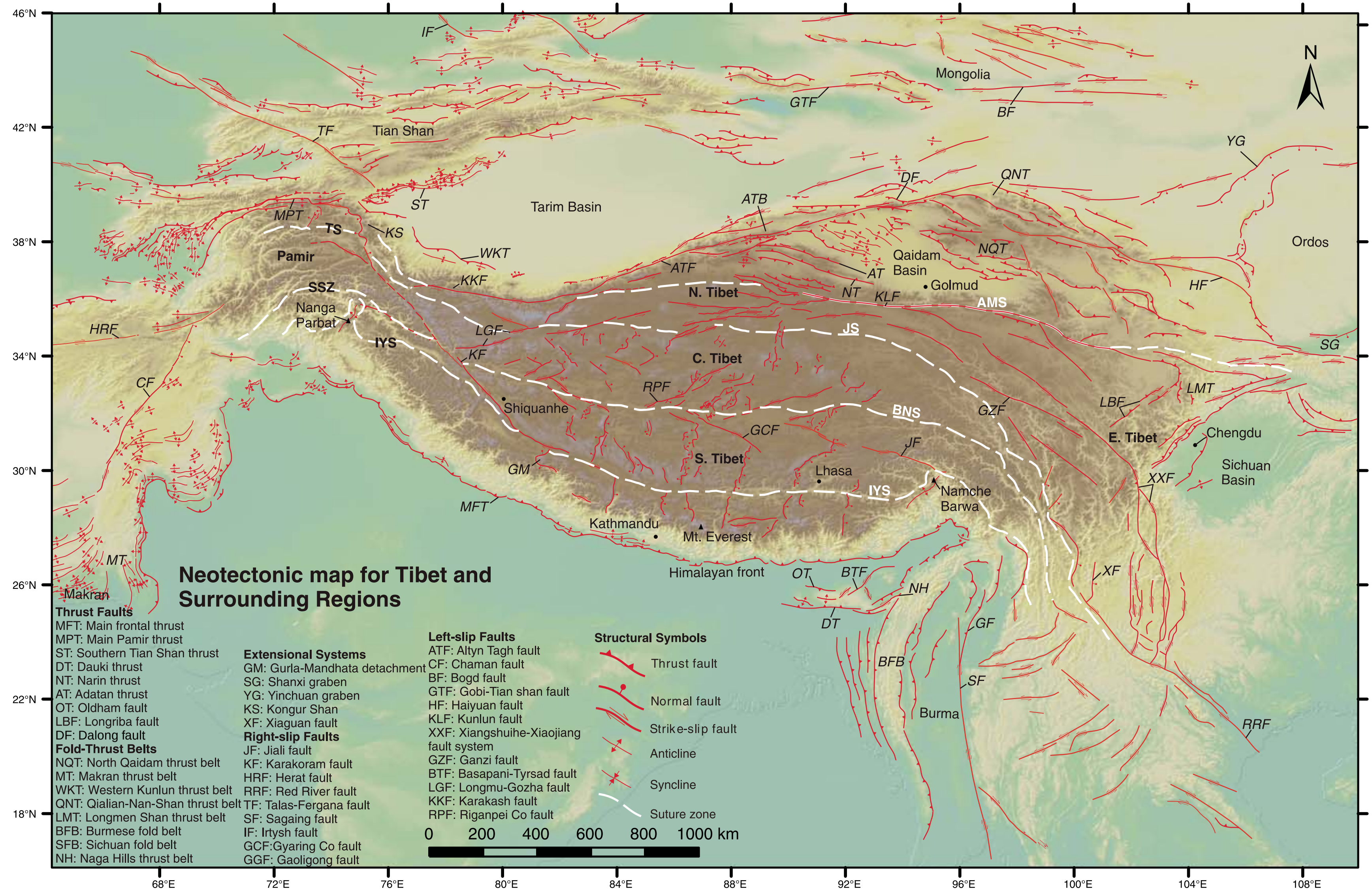

Figure 1. A color-shaded relief map with active to recently active faults related to the Indo-Asian collision zone and surrounding regions. The main sources of information are listed here (i.e., Armijo et al., 1986, 1989; Arrowsmith and Strecker, 1999; Avouac and Peltzer, 1993; Avouac et al., 1993; Burchfiel et al., 1991, 1995, 1999; Cowgill et al., 2000, 2004b; Darby and Ritts, 2002; Darby et al., 2005; Jackson, 1992; Jackson et al., 1995; Jackson and McKenzie, 1984; Kapp and Guynn, 2004; Kirby et al., 2000; Lave and Avouac, 2000; Meriaux et al., 2004, 2005; Murphy et al., 2000; Peltzer et al., 1989; Robinson et al., 2004; Tapponnier and Molnar, 1979; Tapponnier et al., 1981b, 2001; Taylor and Peltzer, 2006; Taylor et al., 2003; ten Brink and Taylor, 2002; Thatcher, 2007; Thompson et al., 2002; Wang and Burchfiel, 2000; Wang et al., 1998; Xu et al., 2008; Yeats and Lillie, 1991; Yin et al., 2008a; Yin and Harrison, 2000), and are augmented by our own kinematic interpretations. Thrust faults have barbs on the upper plate, normal faults have bar and ball on the hanging wall, arrows indicate direction of horizontal motion for strike-slip faults. Dashed white lines are Mesozoic suture zones: IYS—Indus Yalu suture zone; BNS—Bangong Nujiang suture zone; JS—Jinsha suture zone; SSZ—Shyok suture zone; TS—Tanymas suture zone; AMS—Anyimaqen-Kunlun-Muztagh suture zone.

provide a coherent picture of fault kinematics and velocity fields across the India-Asia and Arabia-Asia collision zones (e.g., Liu and Bird, 2008), the lack of detailed and coherent geologic data leaves this assumption untested.

Our understanding of how continental lithosphere responds to collisional orogenesis has developed in part from geophysical studies in the past two decades across the Himalaya-Tibetan orogen (Klemperer, 2006). The results have led to the following first-order observations. (1) Seismic attenuation and velocity inversions seen in southern and central Tibet may result from partial melting in the middle to lower crust of the plateau (Brown et al., 1996; Makovsky and Klemperer, 1999; Nelson et al., 1996; for an alternative explanation see Yin, 2000). (2) Earthquake focal mechanisms indicate that upper crustal faulting is currently active throughout the orogen, and in Tibet is restricted to the upper ~10 km of crust, with exceptions along a few north-trending rifts in southern Tibet, where earthquakes may have occurred within the lower crust or upper mantle lithosphere (Chen and Yang, 2004; Langin et al., 2003; Liang et al., 2008; Maggi et al., 2000a; Molnar and Lyon-Caen, 1989; Zhao and Helmberger, 1991). (3) Indian lithosphere has been imaged as far north as central Tibet near the Bangong-Nujiang suture zone (Huang et al., 2000; Kind et al., 2002; Owens and Zandt, 1997; Tilmann et al., 2003). Farther north, receiver functions indicate a dramatic decrease in upper mantle Pn velocities with an associated increase in seismic attenuation, suggesting that north of central Tibet, the plateau is underlain by hot and possibly weak material with low viscosity, that is arguably capable of flow (Klemperer, 2006). (4) Shear wave splitting fast axis orientations are generally east trending, and splitting magnitudes show a systematic parabolic distribution with values increasing from south to north; maximum split times are ~150 km to the north of the Bangong-Nujiang suture zone and decrease farther to the north (Fig. 2B) (Huang et al., 2000; Kind et al., 2002; Owens and Zandt, 1997; Tilmann et al., 2003) (see Fig. 1 of Klemperer, 2006, for locations of major geophysical transects in Tibet).

The active structures shown in Figure 1 are mainly based on those documented in the literature (see Fig. 1 caption). For regions that were not covered by previous studies, we rely on interpretations of satellite images and digital topographic data, including ASTER, LANDSAT, SPOT, CORONA, web-based Google Earth images, and 90 m digital elevation models from the Shuttle Radar Topography Mission (SRTM). We digitally mapped individual structures using ESRI Arcmap software and compiled a digital database. We assigned each structure an identification number that is linked to an attribute table that provides information on its kinematics. Our mapping was limited by the resolution of the satellite images; in some cases only LANDSAT imagery was available and minimum detectable map view offsets or truncations of ~30 m were needed to identify a Quaternary fault. We realize that a significant number of active structures related to the India-Asia collision have likely escaped our detection, or insufficient information was available to make a compelling case for active deformation. Therefore, we adopt a conservative approach and identify only the first-order active structures that have a strong morphological expression.

Our neotectonic interpretations are based on the following geomorphic criteria: (1) the texture of incised geomorphic surfaces, (2) proximity to known active structures with well-documented fault kinematics, (3) juxtaposition of tonal variations observed in satellite imagery, (4) mountain front sinuosity, (5) triangular facets, (6) linearity of topographic features such as fault scarps, (7) beheaded and deflected streams, rivers, and drainages, (8) locations of earthquake epicenters and focal mechanisms (Fig. 2A), and (9) proximity to highly localized GPS velocity gradients with a linear trend (Fig. 2B). In regions of steep and rugged terrain, Quaternary deposits are often rare or completely absent. Thus, the likelihood of preserving deformed landforms is low. In this case, we only map active structures if we observe obvious bedrock escarpments and if Quaternary sediments are cut along strike of that bedrock escarpment.

In addition to using the above geomorphic indices for undocumented structures, we can infer their kinematics by first-order comparisons with adjacent active structures with known kinematics. For example, the kinematics of the ~N70°E striking Altyn-Tagh fault is well documented as an active left-slip structure that accommodates a significant portion of India-Asia convergence (Fig. 1). If a linear topographic scarp is identified within close proximity to the left-slip Altyn-Tagh fault and strikes N40°E, then a left-slip Reidel shear interpretation might be a viable kinematic explanation. Further support of the kinematic inference could come from geomorphic observations (e.g., deflected streams and drainages, as shown in Fig. 3). Similarly, a more sinuous topographically high feature with a general N40°E strike in the same tectonic setting could be consistent with a fault-related fold, or if bounded by a sinuous scarp, a thrust fault generated in a zone of left-slip simple shear. While we realize that other viable kinematic interpretations are possible (especially along-strike of individual structures), we believe our approach identifies the simplest kinematic interpretation based on the geometry of adjacent structures. We applied this approach in a systematic fashion to each tectonic domain of the India-Asia collision zone by (1) building upon the first-order regional structures compiled from the literature, (2) identifying adjacent geomorphic landforms, and (3) developing a self-consistent geometric and kinematic model. In the following sections we present examples of active structures shown in Figure 1.

ACTIVE STRUCTURES IN THE HIMALAYA

The east-west extent of the 2000-km-long Himalayan orogenic belt is defined by the Nanga Parbat syntaxis in the west and the Namche Barwa syntaxis in the east (Fig. 1) (Yin, 2006). Both syntaxes display the world's largest relief; exhumation rates are as high as 5–10 mm/a (Finnegan et al., 2008; Stewart et al., 2008; Zeitler, 1985; Zeitler et al., 2001). Juxtaposed crystalline basement over Quaternary sediments is observed locally along Nanga Parbat thrust faults, attesting to its recent activity (Shroder, 1989). West of the Nanga Parbat syntaxis, northward motion of India with respect to Afghanistan and Iran is accommodated mainly by the left-slip Chaman fault (Fig. 1) (Tapponnier et al., 1981a). Merging with the Chaman fault to the northeast is the east-striking Herat fault, which is a right-slip structure (Fig. 1). The degree of Quaternary activity along the Herat fault is debated; it has been suggested to be an inactive structure because locally post-Miocene deposits show no clear offsets (Tapponnier et al., 1981a). However, the Herat fault is also mapped as an active structure based on the following evidence. (1) It is well expressed in the landscape as a linear topographic feature. (2) Quaternary sediments appear to be truncated based on satellite interpretations. (3) It has undergone recent earthquakes in its vicinity (Wheeler and Rukstales, 2007). From the above arguments, we identify the Herat fault as an active to recently active structure, with the caveat that future neotectonic studies are necessary to accurately assess its slip history and slip rate. Similarly, at the eastern end of the Himalayas, the Namche Barwa syntaxis is bounded by active faults on its west and east sides, indicating that it is also an active structure (Ding et al., 2001). East of the Namche Barwa syntaxis, the northward motion of India is accommodated along the Indo-Burmese fold belt and the right-slip Sagaing and Red River fault systems (Armijo et al., 1989; Ding et al., 2001; Leloup et al., 1995; Wang et al., 1998).

Along the central segment of the Himalayas, active thrusting and folding occurs along

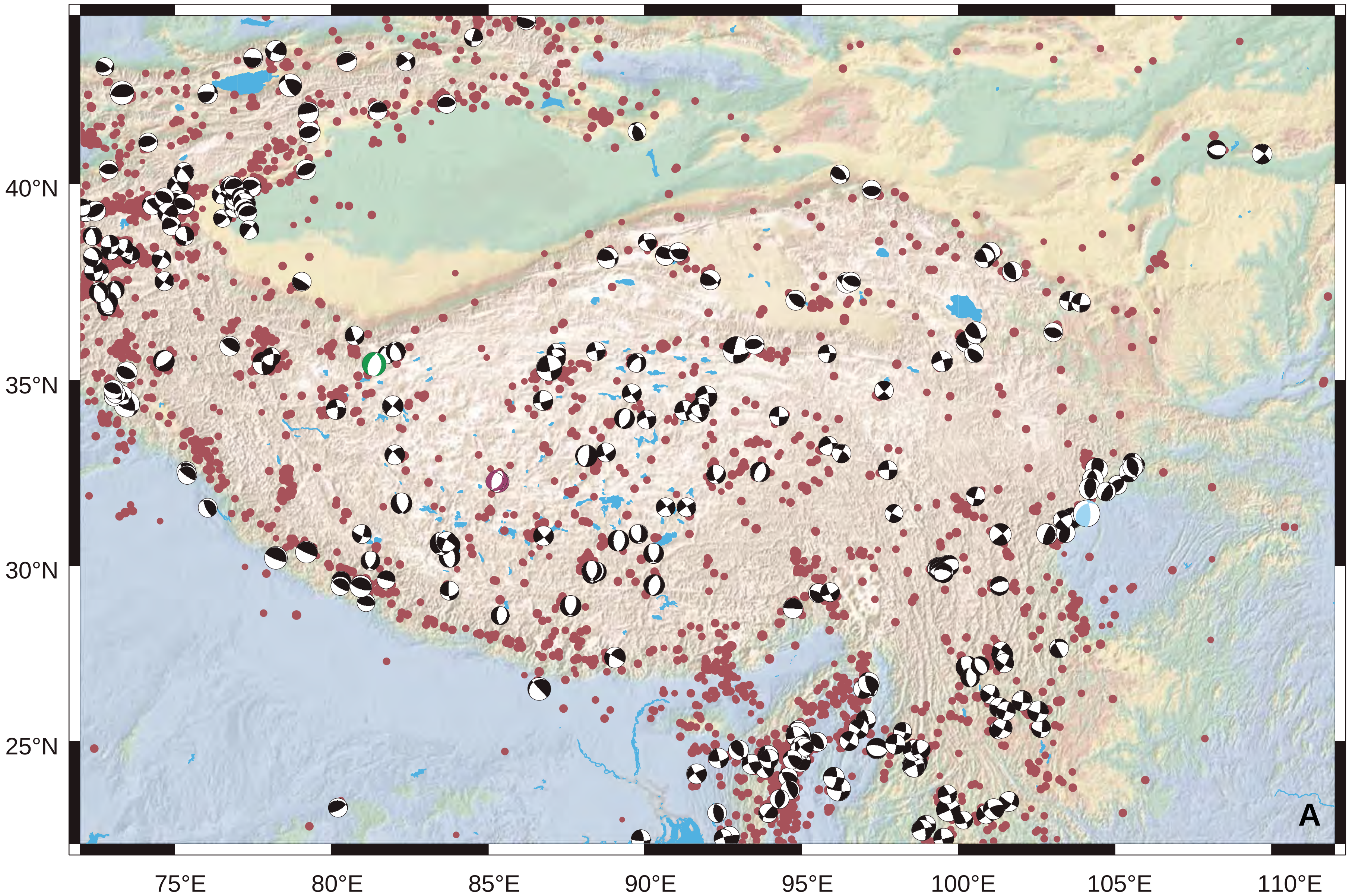

Figure 2 (*continued on next pages*). (A) Color-shaded relief map overlain with Harvard centroid moment tensor (CMT) earthquake focal mechanisms from 1 January 1977 to 1 January 2009 and background seismicity from Engdahl and Villasenor (2002) with events >M5.5 for both data sets. Green, purple, and light-blue earthquake focal mechanisms are locations of 2008 western Kunlun, Nima, and Wenchuan events, respectively. See text for a detailed discussion.

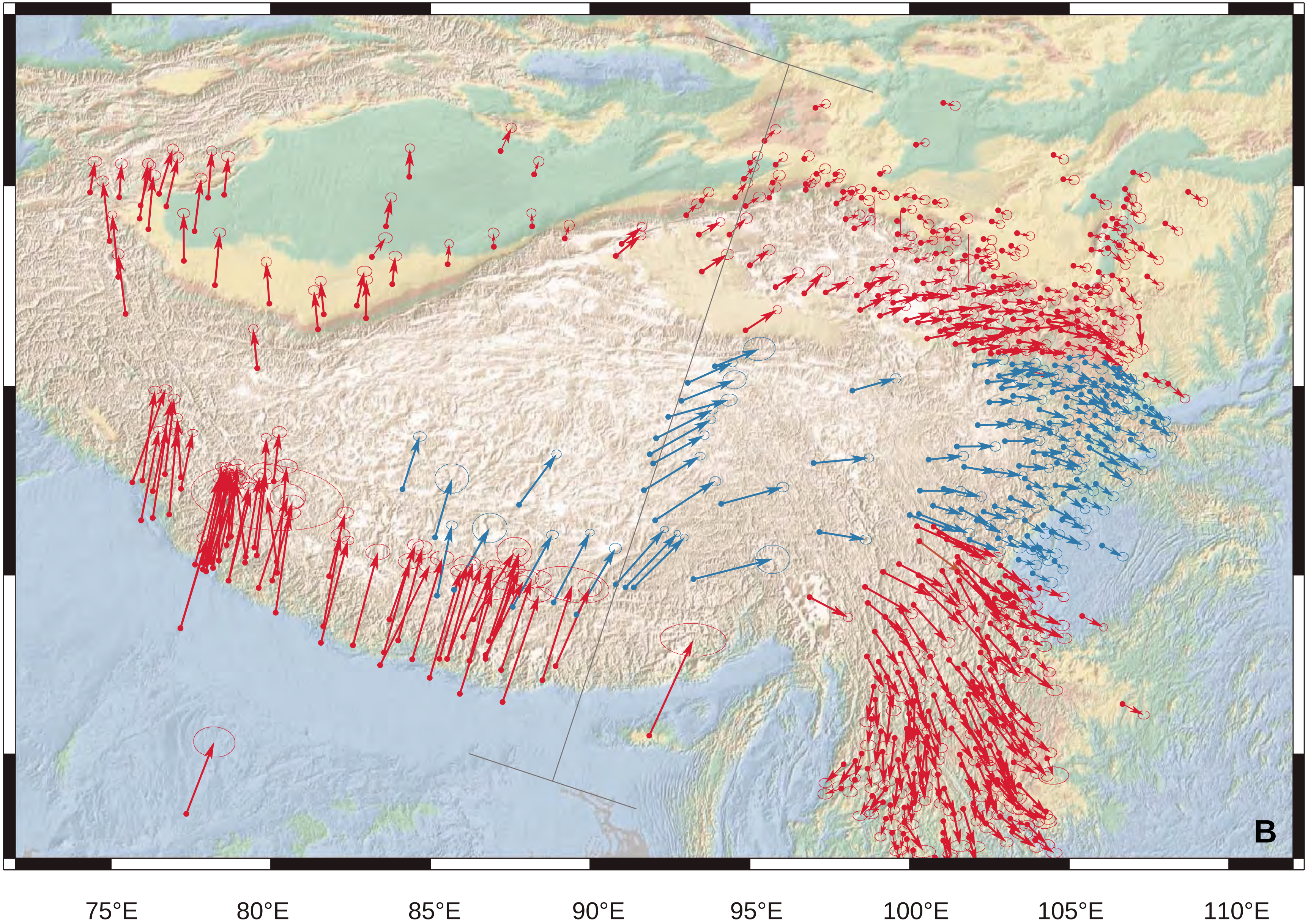

Figure 2 (*continued*). (B) Color-shaded relief map of the Indo-Asian collision zone with global positioning system (GPS) velocities (arrows) from the Zhang et al. (2004) compilation. Blue arrows indicate data used in Figure 4A and line indicates data used in Figure 4B.

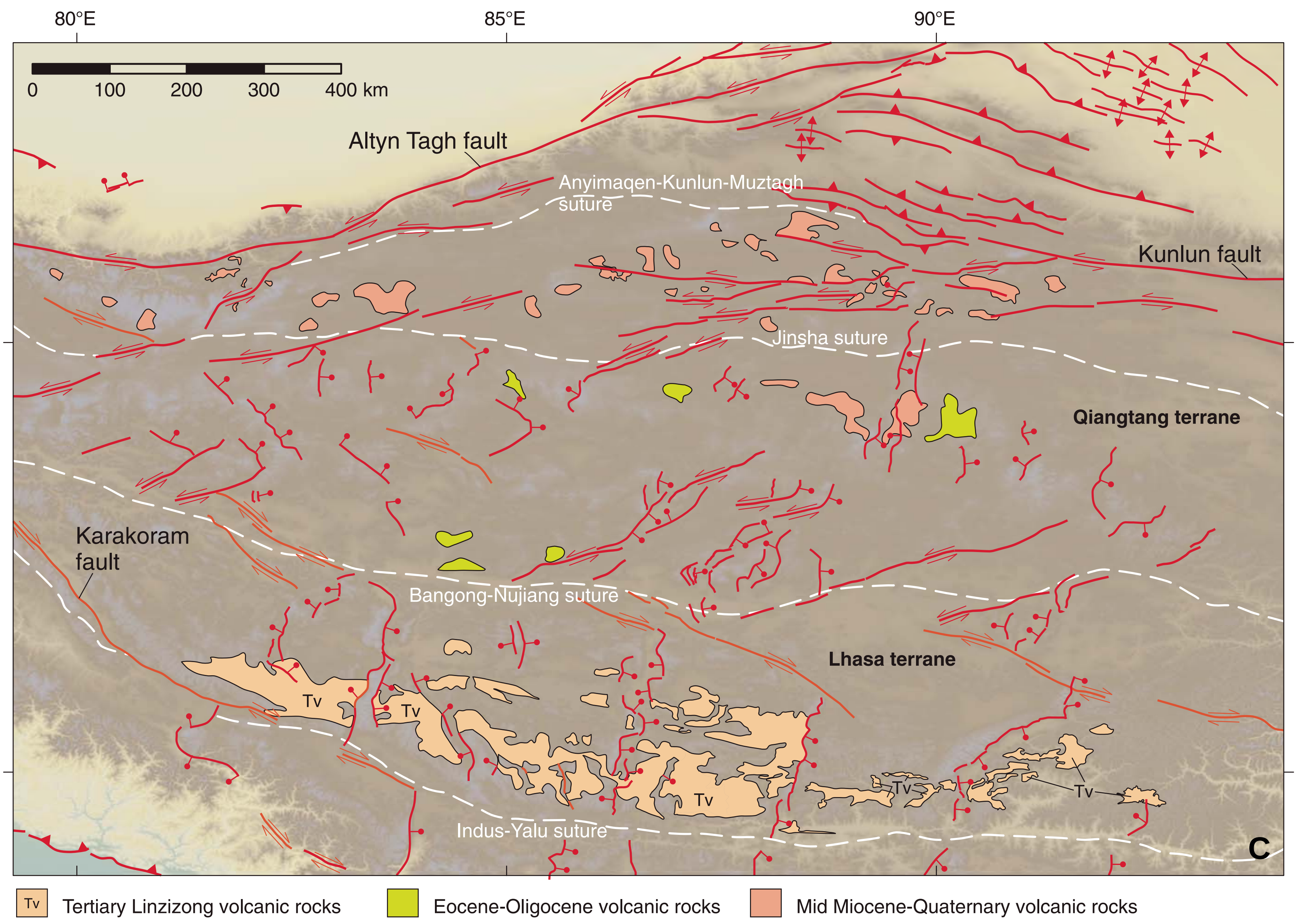

Figure 2 (*continued*). (C) Distribution of late Cenozoic volcanism in Tibet compiled from Pan et al. (2004), Ding et al. (2003), and Chung et al. (2005). Pink units are middle Miocene volcanic rocks, green units are Eocene–Oligocene volcanic rocks, and tan units are Paleogene Linzizong volcanic rocks. See Figure 1 for location.

the mountain front (Fig. 2A). Locally, the active Main Frontal thrust places the Miocene–Pliocene Siwalik Group over Quaternary sediments (Lave et al., 2005). In addition, it is not uncommon for blind structures to fold the overlying Quaternary sediments (Lave and Avouac, 2000; Lave and Avouac, 2001; Nakata, 1989). Using the technique of balanced cross sections and Quaternary dating methods, Lave and Avouac (2000) determined that the Main Frontal thrust is moving at 21 ± 5 mm/a and ultimately feeds slip into the Main Himalayan thrust at depth. The Main Himalayan thrust is believed to be the dominant structure accommodating north-south convergence, although this view has been challenged (Wobus et al., 2005). Geodetic rates of horizontal shortening across the Himalaya determined using GPS are generally similar, with values of 18 ± 2 mm/a and 15 ± 5mm/a (Bendick and Bilham, 2001; Jouanne et al., 1999, 2004; Larson et al., 1999), assuming a locked fault ~100 km wide in the downdip direction from the surface trace of the Main Frontal thrust that in map view extends ~80 km north of the Main Frontal thrust. The constancy of shortening rates over geologic and geodetic time periods led Avouac (2003) to conclude that Himalayan orogenesis is currently in a steady-state mode over a time scale of millions of years. However, he cautioned that over a seismic cycle, deformation is not in a steady state and is likely expressed as large earthquakes or transient aseismic creep. Spatially, seismic gaps along the Himalayan arc can be as long as 800 km (Avouac, 2007). It has been argued that strike-slip faulting is more active in the High Himalaya than previously recognized (Murphy and Copeland, 2005; Li and Yin, 2008; Meyer et al., 2006; Velasco et al., 2007).

ACTIVE STRUCTURES IN THE TIBETAN PLATEAU

Southern Tibet

The boundaries of southern Tibet are defined by the Indus-Yalu suture zone in the south and the Bangong-Nujiang suture zone in the north (Fig. 1). Active structures along the western boundary of southern Tibet are dominated by the Karakoram fault, which is believed to have initiated between 18 and 11 Ma ago (Murphy et al., 2000; Searle et al., 1998). To explain the along-strike age variation, the Karakoram fault is believed to have initiated along its central segment ca. 18 Ma ago (Searle et al., 1998), followed by southward propagation (Murphy et al., 2000). The continuation, evolution, and possible inactivity of the northern Karakoram fault is currently under debate (Robinson and Cowgill, 2007). The geologic slip rate for the central Karakoram fault is not well constrained because it may be as low as 1–3 mm/a (Brown et al., 2002) or as high as 10 mm/a (Chevalier et al., 2005); both slip rates were determined from cosmogenic dating of offset geomorphic landforms, but at different locations. If a high geologic slip rate on the Karakoram fault is correct, it is much higher than geodetically determined rates using interferometric synthetic aperture radar (InSAR) (Wright et al., 2004), and may imply that the Karakoram fault undergoes transient pulses of increased velocity followed by lower slip rates that may be modulated by near-surface brittle faults communicating with ductile downdip extensions in the middle to lower crust (Chevalier et al., 2005).

A salient topographic feature of southern Tibet is the north-trending rift systems cutting across the otherwise low relief surface of the plateau. Since their initial discovery more than three decades ago (Molnar and Tapponnier, 1978), studies on the north-trending rifts in southern Tibet have led to questions spanning a multitude of disciplines. These include (1) probing the geophysical properties of the crust and lithosphere (Cogan et al., 1998); (2) the geochemical composition of the crust in the Nyainqentanglha region (Kapp et al., 2005a); (3) the kinematic significance in relation to extrusion tectonics (Armijo et al., 1986); (4) the low-temperature thermal history that could provide information for the onset of extension and, by implication, the attainment of high topography and onset of the Asian monsoon (Harrison et al., 1995; Maheo et al., 2007); (5) the mechanics of continental collisions (Kapp and Guynn, 2004; Yin, 2000); (6) the mechanics of low-angle normal faulting (Kapp et al., 2008); and (7) the elevation history of the Tibetan plateau (Garzione et al., 2003; Garzione et al., 2000). The formation of the Tibetan rifts has been argued to involve only the upper crust, based on an analysis of rift flank topography (Masek et al., 1994) and geophysical observations (Cogan et al., 1998; Nelson et al., 1996), but the rift spacing (Yin, 2000) and intermediate-depth earthquakes (Zhu and Helmberger, 1996) are consistent with involvement of the lower crust or mantle lithosphere. A case can also be made that the development of the Tibetan rifts and strike-slip faulting in central Tibet are intimately associated (e.g., the right-slip Gyaring Co fault in Fig. 1) (Armijo et al., 1986; Taylor and Peltzer, 2006; Taylor et al., 2003).

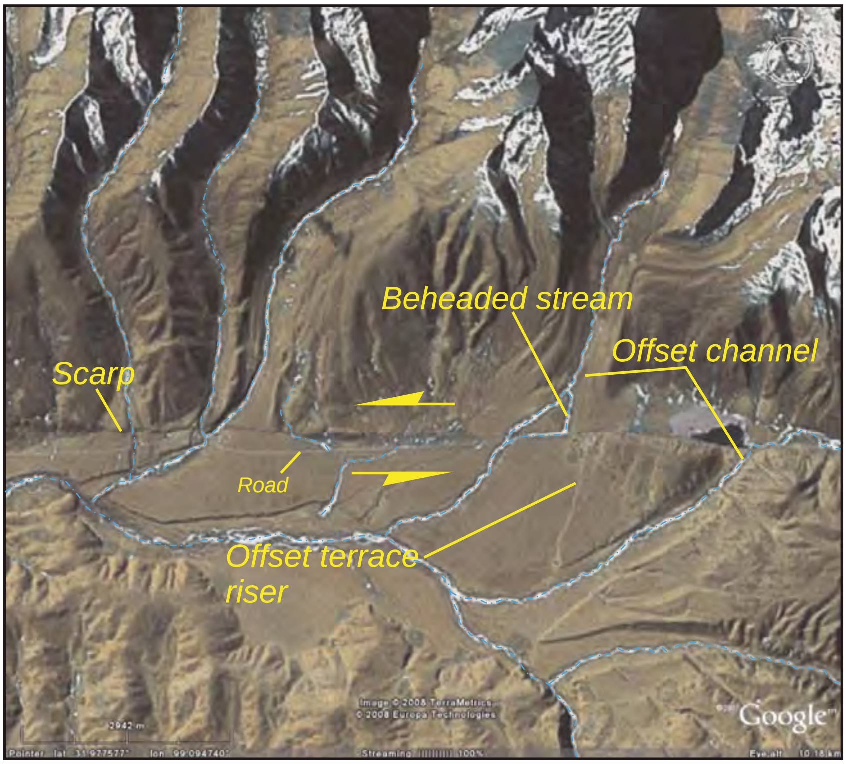

Figure 3. Southwest-looking view of the Ganzi fault system showing left-slip shear as defined by offset landforms with offset of ~2300 m of the large fluvial channel. An additional left-slip offset is smaller, ~500 m. Data are from Google Earth and DigitalGlobe. Look position is taken from ~31.98°N, 99.26°E.

Central Tibet

The north-south extent of central Tibet is defined by the Jinsha suture zone in the north and the Bangong-Nujiang suture zone in the south (Fig. 1). The Bangong-Nujiang suture is reactivated by the Karakoram-Jiali fault zone, which is a system of en echelon northwest-striking right-slip faults bounding the southern margin of central Tibet. The fault system was recently expanded to include sets of left-slip faults to the north that are conjugate to the right-slip faults to the south. Taylor et al. (2003) referred to the whole fault system as the central Tibet conjugate strike-slip zone, because faults to the north are dominantly northeast-striking left-slip faults that merge with the Karakoram-Jiali fault zone (Taylor et al., 2003). Individual right-slip or left-slip faults are kinematically linked to north-striking normal faults to the south or north, respectively (Fig. 1). The central Tibet conjugate strike-slip zone is ~1200 km long in the east-west direction and ~300 km wide north-south. The eastern extent of the fault system is not well defined, but can be traced to at least the eastern termination of the Jiali fault zone, in the vicinity of the eastern Himalayan syntaxis (Fig. 1) (Armijo et al., 1989; Ding et al., 2001). The fault system has been suggested to assist in the eastward extrusion of the Qiangtang terrane relative to the Lhasa terrane (Armijo et al., 1986; Armijo et al., 1989). If true, this implies that individual right-slip faults should have ~65 km of slip, the minimum displacement estimated for the Karakoram fault in western Tibet (Murphy et al., 2000). However, Taylor et al. (2003) showed that individual strike-slip structures in central Tibet have <20 km of fault slip; this is not enough to accommodate the extrusion of regional crustal scale blocks. GPS velocities across the central Tibet strike-slip zone indicate that the fault system is active and accommodates ~15–20 mm/a of east-west extension and ~10 mm/a of north-south contraction (Gan et al., 2007; Wang et al., 2001b; Zhang et al., 2004). Individual strike-slip faults have been imaged using InSAR and relatively high fault slip rates have been determined for the right-slip Gyaring Co fault and the left-slip Riganpei Co fault system to the north (Fig. 1) (Taylor and Peltzer, 2006; Taylor et al., 2003) which is the location of a Ms 6.4 event that occurred on 9 January 2008 (discussed in more detail on p. 207).

Northern Tibet

Active structures in northern Tibet include the east-striking left-slip Kunlun fault system. The Kunlun fault system is ~1000 km long and is along or adjacent to the Anyimaqen-Kunlun-Muztagh suture zone (Fig. 1). The western Kunlun fault splays into several left-slip faults that are seismically active (Peltzer et al., 1999) and appear to be kinematically linked to north-striking active normal faults farther south (Fig. 1). The main segment of the Kunlun fault ruptured in the Mw 7.8 November 2001 Kokoxilli earthquake, which at the time was the largest ever instrumentally recorded continental strike-slip event (Klinger et al., 2005, 2006; Lasserre et al., 2005). Prior to the 2001 event, the fault slip rate was determined along the central segment of the Kunlun fault using the cosmogenic dating technique on several sets of offset terrace risers, yielding an estimated slip rate of 11.5 ± 2 mm/a (Van der Woerd et al., 1998, 2000, 2002). The slip rate decreases dramatically along the eastern segment of the fault to <2 mm/a (Kirby et al., 2007), and is suggested to accommodate either eastward propagation of the Kunlun fault, internal deformation of eastern Tibet, or significant off-fault strain accommodating vertical-axis rotation of the fault (Kirby et al., 2007).

The northeast-striking, ~1200-km-long Altyn-Tagh fault system defines the northern margin of the Tibetan plateau and bounds the southern margin of the rigid Tarim block to the north. The Altyn-Tagh fault is kinematically connected with several fault systems; in its extreme westernmost part, the Altyn-Tagh links with the left-slip Karakax fault system and the Western Kunlun thrust belt (Fig. 1). At its southwesternmost end, the Altyn-Tagh fault links with the left-stepping left-slip Longmu-Gozha Co fault system, close to the 20 March 2008 Mw 7.1 earthquake (discussed further on p. 207).

To the northeast the Altyn-Tagh fault links with the Qilian Shan-Nan Shan thrust belt, and in the extreme northeast part, the contraction-dominated Hexi corridor. The Altyn-Tagh fault has been mapped in more detail than any other strike-slip fault in Asia; the magnitude of fault slip of ~550 km is based on the offset of a Paleozoic magmatic belt (Cowgill et al., 2003; Peltzer and Tapponnier, 1988). The geologic slip rate for the Altyn-Tagh fault was estimated to be ~20 mm/a using cosmogenic dating of offset terrace risers (Meriaux et al., 2004, 2005). Using the same age data at the same site, but using the assumption of accrued fault slip prior to abandonment of the upper terrace surfaces, Cowgill (2007) provided an alternative interpretation with a revised geologic slip rate that is consistent with geodetic and paleoseismic studies yielding rates of ~10 mm/a (Cowgill, 2007; Wallace et al., 2004; Washburn et al., 2001, 2003; Zhang et al., 2004).

While the Altyn-Tagh fault is dominated by horizontal motion, locally the fault system accommodates significant contraction along fault segments that deviate from the regional east-northeast strike of the fault. Examples include the Akato Tagh double bend and the southwest-dipping Dalong fault (Fig. 1) (Cowgill et al., 2004a, 2004b; Gold et al., 2006). Additional studies of adjacent thrust faults merging with the Altyn-Tagh fault include the Tanghe Nan Shan (Van der Woerd et al., 2001) and the Hexi corridor in northeast Tibet (Hetzel et al., 2002, 2006; Meyer et al., 1998) that are believed to result from the northeastward growth of Tibet during the Indo-Asian collision (Tapponnier et al., 2001). However, the view of northeastward growth of the Tibetan plateau has been challenged based on the early Cenozoic initiation of thrusting in northeast Tibet, assumed to be linked to the initiation of the Altyn-Tagh fault system (Yin and Harrison, 2000; Yin et al., 2002).

Eastern Tibet

Active deformation of eastern Tibet is mainly expressed by the northeast-trending Longmen Shan thrust belt, the east-striking left-slip Haiyuan fault, the north-striking left-slip Ganzi-Xianshuihe-Xiaozhang fault system, and the north-striking right-slip Red River fault system. Collectively, the geometry and kinematics of the structures are suggested to accommodate eastward extrusion of Tibet and south China (Leloup et al., 1995; Tapponnier and Molnar, 1977), rotation of crustal material around the eastern syntaxis (Burchfiel et al., 1995), or internal deformation due to eastward lower crustal flow originating in central Tibet (Royden et al., 1997). GPS studies (described in more detail on p. 209) indicate significant left-slip motion along the Ganzi fault system and a significant eastward velocity gradient in the hinterland of the Longmen Shan thrust to the west (Gan et al., 2007; Zhang et al., 2004).

One of the largest fault systems in eastern Tibet is the Ganzi-Xianshuihe-Xiaozhang fault system (GZF-XXF in Fig. 1), which is a prominent eastward-convex arc-shaped system of left-slip faults. Collectively, these structures accommodate clockwise vertical-axis rotation of crustal material around the eastern Himalayan syntaxis (Royden et al., 1997; Wang and Burchfiel, 2000), or alternatively southeastward extrusion of the Indo-China block (Tapponnier and Molnar, 1977). Beginning in the northwest part of this fault system, the Ganzi fault strikes northwest and is more than 400 km long. The magnitude of left slip is ~100 km, based on the left separation of a granitic pluton (Wang and Burchfiel, 2000). The southern segment of the Ganzi fault splays into several segments, and slip eventually terminates into a series of folds at a restraining bend within Triassic Songpan-Ganze sediments (Fig. 1). The Ganzi fault exhibits numerous fault scarps, offset moraines, pressure ridges, and deflected streams and rivers (Wang and Burchfiel, 2000). Historical records indicate that 21 moderate to large earthquakes have occurred along the Ganzi-Xianshuihe left-slip fault system (Tang et al., 1995). Summation of earthquake moment tensors indicates a slip rate of 10 mm/a along the Xianshuihe segment of this left-slip system (Molnar and Deng, 1984). Along the Ganzi fault, clearly deformed landforms are offset ~200 m and 500 m, and a stream valley is offset ~2300 m (Fig. 3).

ACTIVE STRUCTURES IN THE TIAN SHAN

The Tian Shan is a generally east-northeast–trending elongate contractional mountain range located ~1300 km north of the Himalayan thrust front between the Tarim Basin to the south and the Kazakh platform and Junggar basin to the north (Fig. 1). Bounding the western region of the Tian Shan is the northwest-striking right-slip Talas-Fergana fault system (Burtman et al., 1996). The Tian Shan is ~2500 km long and, based on GPS studies (Molnar and Ghose, 2000), absorbs ~2 cm/a of north-south shortening. Earthquake focal mechanisms suggest active thrust and reverse faulting consistent with GPS velocity gradients (Molnar and Ghose, 2000). Thrust faults in the Tian Shan are typically reactivated Paleozoic basement-involved structures in the hinterlands that bound Cenozoic intermontane basins. Active to recently active folding and thrust faulting is widespread across the range (Burtman, 2000; Hendrix et al., 1994). Reactivation of the Paleozoic structures is considered to have initiated ca. 24 Ma ago, with deformation becoming more intense 15 and 11 Ma ago (Hendrix et al., 1994; Sobel et al., 2006; Yin et al., 1998). Holocene and late Pleistocene thrust faults are located within the basins, and deformed terraces and broad basin uplifts are consistent with broad, shallow, active thrust ramps that root into the steeper crustal-scale basement ramps under the mountain ranges (Avouac et al., 1993; Burchfiel et al., 1999; Thompson et al., 2002). Thompson et al. (2002), in a comprehensive study of the western Tian Shan, showed that active deformation is distributed throughout the range on at least eight thrust faults. The Quaternary slip rates on individual north- and south-directed thrust faults range between 0.1 and 2.9 mm/a based on ^{14}C dating of warped river terraces (Thompson et al., 2002). The regional kinematics are interpreted in terms of clockwise rotation of the rigid Tarim block driving crustal shortening, with a large magnitude and rate of shortening in the western Tian Shan that decreases eastward (Avouac et al., 1993).

RELATIONSHIP BETWEEN ACTIVE FAULTS AND EARTHQUAKES

Using the active fault map of Figure 1 we make inferences about the kinematics and depth extent of faulting by making a comparison with recent earthquake double couple solutions from the U.S. Geological Survey National Earthquake Information Center (NEIC) online search catalogue, augmented with relocated background seismicity (Engdahl and Villasenor, 2002). In Figure 2A we plot only events above magnitude M 5.5. Earthquake focal mechanisms along the leading edge of the Himalayan orogen indicate radial south-directed thrust faulting with events distributed throughout the entire crustal thickness of the Indian shield and the Himalayan wedge (Fig. 2A). North of the Indus suture, the deepest events occur in the south Tibetan interior at depths of ~80–90 km, and are generally considered suggestive of a strong mantle lithosphere (Molnar and Chen, 1983). Another view suggests that deep earthquakes in the Himalaya and Tibet are restricted to crustal depths, most likely in granulitic lower Indian crust underthrusting Tibet (Jackson, 2002; Maggi et al., 2000a, 2000b). However, whichever view is correct, most earthquakes throughout the Himalayan-Tibet orogen typically occur at shallow crustal levels, at 10–15 km depth. It is commonly considered that the absence of earthquakes in the middle to lower crust of Tibet reflects aseismic deformation at temperatures exceeding 350 °C in material that is arguably capable of flow (Molnar and Deng, 1984; Molnar and Lyon-Caen, 1989), although this interpretation remains controversial (Priestley et al., 2008).

Earthquake focal mechanisms of events occurring at elevations above 5 km in south and central Tibet consistently indicate normal faulting. Below this elevation, focal mechanisms are consistent with combined strike-slip and normal fault events (Fig. 2A) (Langin et al., 2003; Molnar and Deng, 1984; Molnar and Lyon-Caen, 1989). In more detail, the strike-slip mechanisms south of the Bangong-Nujiang suture are associated with northwest-striking right-slip faults, whereas those located north of the suture are associated with northeast-striking left-slip faults (Fig. 2A). Earthquake focal mechanisms located in the Qaidam basin, southwest Tarim, and Tibet's northeast boundaries are consistent with active thrusting or reverse-slip events (Fig. 2A). Along the Altyn-Tagh fault, the few events are not purely dip slip, but in more detail are consistent with components of compression and left-slip simple shear (Fig. 2A). At ~95°E in central Tibet, a transition occurs in which focal mechanisms are dominantly strike slip and, based on the mapped structures, are likely associated with east-facing convex left-slip faults accommodating clockwise vertical axis rotations associated with crustal material transported around the eastern Himalayan syntaxis.

Over the past decade Tibet has had the largest instrumentally recorded earthquakes in China, specifically the Kokoxilli event that occurred on the Kunlun fault in 2001 (Klinger et al., 2005; Lin et al., 2002), and more recently the three moderate to large events in 2008 that occurred in the western Kunlun Shan (Mw 7.1), Nima (Ms 6.4), and the devastating Wenchuan event (Mw 8.0) in the Longmen Shan thrust belt (Burchfiel et al., 2008). The Mw 7.1 western Kunlun event occurred on 20 March 2008 on a coordinated system of northeast-striking en echelon right-slip faults, and at stepovers occupied by north-striking normal faults collectively referred to as the Longmu-Gozha Co fault system (Avouac et al., 1996). Several faults are possible candidates for the event, but the most likely is a northeast-striking fault bounding the eastern margin of the Tianshuihe terrane (Cowgill et al., 2003) (Figs. 1 and 2A). Coseismic slip is estimated to have exceeded 120 cm over a distance of 100 km with the dominant slip patch concentrated in the upper 4–5 km (Shao and Chen, 2008). The event was dominantly dip slip with a minor left-slip component consistent with the active northeast-striking faults occurring in releasing stepovers along the Longmu-Gozha Co fault system (Shao and Chen, 2008) (Fig. 1).

In central Tibet, near Nima, a sequence of three earthquakes of Ms 6.4, 5.9, and 5.4 occurred on 9 January 2008 on the southwest segment of the Riganpei Co fault system along two northeast-striking normal fault segments (Taylor et. al., 2003) (Fig. 1). The Riganpei Co fault system strikes N70°E and has an estimated geodetic slip rate of ~6 mm/a (Taylor and Peltzer, 2006). Preliminary elastic half-space modeling of InSAR observations suggests that the coseismic slip for the Ms 6.4 main shock is ~1.7 m with a main slip patch extending between 6.7 and 8.4 km depth on a fault striking N25°–30°E and dipping 65° west (Sun et al., 2008). Preliminary observations indicate that the main shock likely loaded a parallel 70° west-dipping fault in the hanging wall located ~9 km to the west. The second event is modeled with ~0.85 m of slip at shallow depths between 2 and 4 km (Sun et al., 2008), but there is not yet an accurate location for the third event of the sequence.

In eastern Tibet, the Mw 8.0 Wenchuan earthquake is the deadliest event to occur in China since the 1976 Tangshan earthquake; there were more than 69,000 deaths, more than 374,000 injured, and more than 5 million left homeless. The Wenchuan earthquake ruptured for ~270 km along a west-dipping fault in the Longmen Shan thrust belt, and preliminary estimates suggest that the coseismic slip exceeded 9 m to a depth of 10–15 km (Chen, 2008). Slip in the vicinity of the epicenter is dominantly reverse and transitioned to dominantly right slip in the northeastern end of the rupture as the fault changes to a more eastern strike (Chen, 2008).

RELATIONSHIP BETWEEN ACTIVE FAULTS AND CONTEMPORARY STRAIN FIELD

Understanding how the lithospheric architecture of an orogenic belt relates to contemporary deformation in the upper crust has lately been a topic of debate driven by new views of surface deformation from geodetic and geophysical studies. Geodetic studies in the Himalayan-Tibetan orogen have been stimulated with the advent of space-borne geodetic radar systems that are able to image large areas with a high spatial resolution (Lasserre et al., 2005; Peltzer et al., 1999; Taylor and Peltzer, 2006; Wright et al., 2004). The cited studies argue for the importance of discrete faulting in accommodating India-Asia convergence. Campaign and continuous GPS data have also increased in spatial and temporal density, and new images of the regional velocity field across central Tibet indicate a linear north-south velocity gradient associated with a constant north-south contractional rate of ~10 mm/a (Wang et al., 2001b; Zhang et al., 2004). GPS studies also indicate ~20 mm/a of east-west extension between the western and eastern Himalayan syntaxes (Wang et al., 2001b; Zhang et al., 2004) (Fig. 4A). It is interesting that the N120°E component of the surface velocity field shows a parabolic pattern similar to that of the SKS splitting times mentioned earlier (Wang et al., 2001b; Zhang et al., 2004). That is, eastward velocities increase northward, obtaining maximum values at the Bangong-Nujiang suture that decrease to the north (Fig. 4B). In addition, eastward surface velocities increase to ~20 mm/a near the eastern syntaxis as the eastern region of the plateau is approached from the west, consistent with east-west extension. The eastward velocities decrease dramatically by 10–15 mm/a as the Sichuan basin is approached (Fig. 4A). Allmendinger et al. (2007) calculated the strain-rate distribution across Tibet using the GPS velocity field of Zhang et al. (2004). Although the study demonstrates many consistencies between the kinematics of active Tibetan faults and the simulated strain-rate field, the large spatial filter eliminated many detailed yet important characteristics of the active deformation field

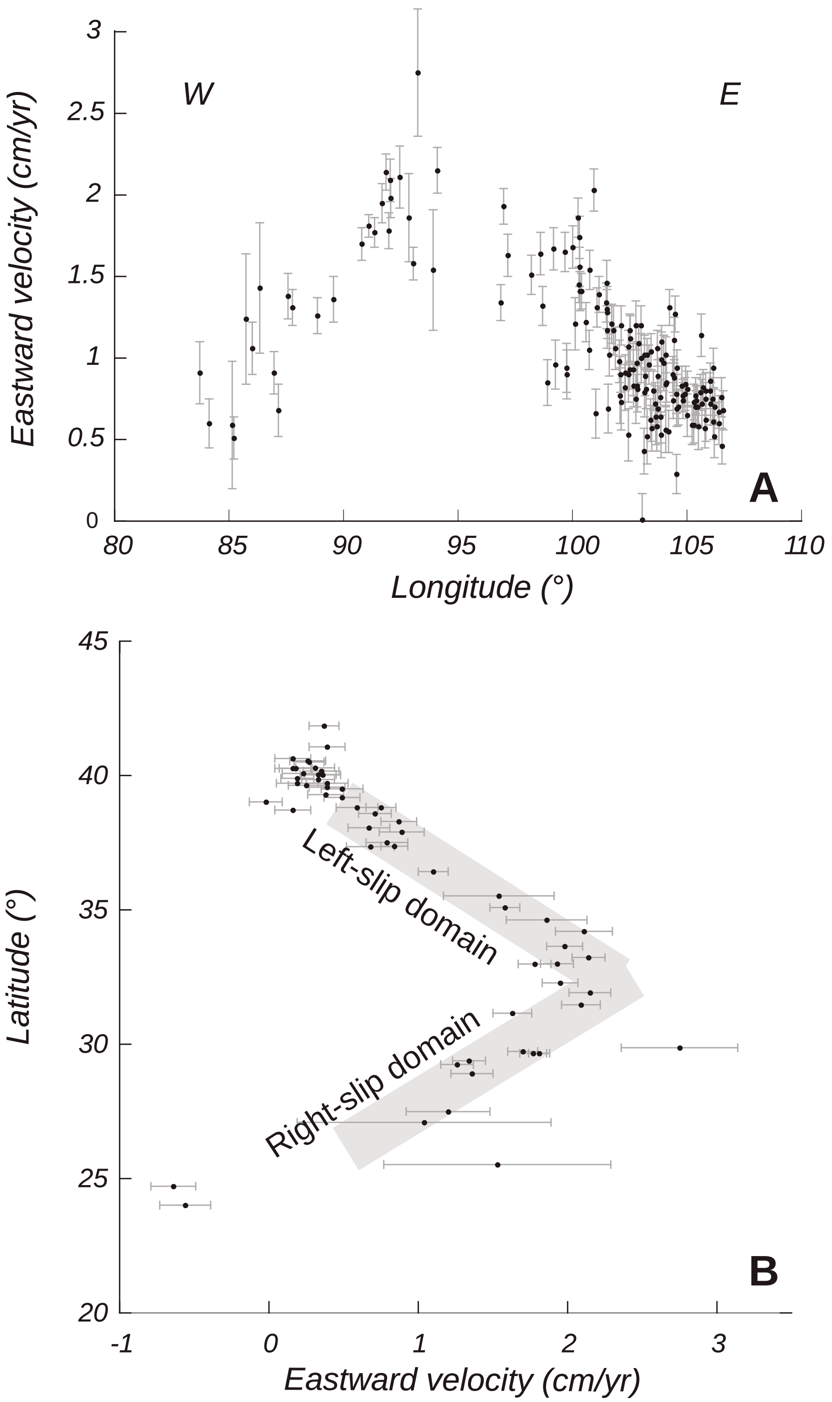

Figure 4. (A) East component of the global positioning system (GPS) velocity field from Zhang et al. (2004) as a function of longitude. Note the gradual increase in eastward velocity that attains maximum values near the eastern syntaxis that rapidly decrease to the east toward the Sichuan basin. Velocities are selected north of the eastern syntaxis so that vertical axis rotations are less significant. See text for a detailed discussion. (B) East component plotted as a function of latitude, with data from Zhang et al. (2004). Note that maximum eastward velocities occur in central Tibet (between 30–35°N) and are bounded by the contraction-dominated tectonic domain of the Himalayas to the south, and the left-slip simple shear domain along Tibet's northern boundary.

in central Tibet. For example, the presence of left-slip fault zones in the Qiangtang terrane as observed in the field (Taylor et al., 2003) and the related rotational fields as detected by GPS studies (Zhang et al., 2004) are not consistent with the interpreted strain rate and rotational fields presented in Allmendinger et al. (2007).

The GPS study of Zhang et al. (2004) across Tibet raises two important questions. (1) How does the surface velocity field change from central to eastern Tibet? (2) Are there active faults not yet identified corresponding to the velocity gradients detected by GPS studies? Gan et al. (2007) showed that significant gradients occur in the surface velocity field in eastern Tibet at the Xianshuihe fault system, and small but significant contractional strains occur near the Longmen Shan in the vicinity of the 2008 Wenchuan earthquake (Gan et al., 2007). While impressive vertical-axis rotation of the velocity field is observed in the vicinity of the eastern Himalayan syntaxis south of the Xianshuihe fault, the velocity field north of the Xianshuihe fault and adjacent to the Sichuan basin does not show significant vertical axis rotations (Fig. 2B). The magnitude of vertical axis rotations north of the Ganzi fault is ~0.1°/Ma (see Fig. 3a in Shen et al., 2005). We suggest that the observed gradient in the eastward component of the velocity field may be attributed to active crustal shortening. These observations are broadly consistent with Shen et al. (2005) and Gan et al. (2007), who identified velocity gradients in eastern Tibet, and suggest that faulting is actively occurring along unmapped shear zones located ~150 km northwest of the Longmen Shan (Shen et al., 2005). Xu et al. (2008) mapped the previously unidentified Logriba fault system that can potentially explain the observed high GPS velocity gradient in the hinterland of the Longmen Shan thrust belt in eastern Tibet.

RELATIONSHIP BETWEEN ACTIVE FAULTS AND CENOZOIC VOLCANISM

Cenozoic volcanism in the Tibetan plateau occurs locally along active to recently active fault systems, implying a genetic relation between magma ascent and faulting in the India-Asia collision zone. For example, late Pliocene to Quaternary basaltic volcanism along the southern end of the Altyn-Tagh fault occurred within a releasing bend or a pull-apart basin along strike-slip faults (Fig. 2C) (Cooper et al., 2002). Similarly, Jolivet et al. (2003) showed that a 15 Ma old volcanic field is located within a pull-apart basin at the western end of the left-slip Kunlun fault system (Fig. 2C). Although the above observations indicate that active faults control the location of late Cenozoic volcanism in Tibet, the exact role of faulting in magma ascent is not clear. The faults may either act as conduits for magma ascent or faulting may be initiated by thermal weakening from ascending magmatic bodies.

At a regional scale, Tibetan igneous activity shows systematic variations in space and time. Late Cretaceous to Cenozoic magmatism is considered to have begun in the Late Cretaceous with low-angle subduction of Tethyan oceanic lithosphere forming the Gangdese arc in southern Tibet (Chung et al., 2005; Ding et al., 2007; Kapp et al., 2005b). After magmatic quiescence between 70 and 60 Ma ago, subsequent rollback of the Tethyan slab or slab breakoff is considered to be responsible for the voluminous and widespread occurrence of the Linzizong volcanics in southern Tibet, considered to have terminated ca. 40 Ma ago (Fig. 2C) (Chung et al., 2005; Ding et al., 2007, 2003; Kapp et al., 2005b). During the later part of the Linzizong flare-up, the dominant locus of magmatism switched to the northern region of the Qiangtang terrane between 50 and 30 Ma ago (Chung et al., 2005), and has been suggested to result from southward subduction of the Songpan-Ganzi sedimentary complex along the Jinsha suture zone (Fig. 2C) (Ding et al., 2003; Kapp et al., 2005b; Roger et al., 2000; Spurlin et al., 2005; Tapponnier et al., 2001; Wang et al., 2001a). The most recent volcanism in the western Qiangtang and Songpan-Ganze regions is mid-Miocene (17 Ma ago) to Quaternary (<1 Ma ago) volcanic rocks (Fig. 2C) (Chung et al., 2005; Ding et al., 2007; Hacker et al., 2000). In the next section we discuss the relationship between active structures, their association with geodetic observations, and the Cenozoic magmatism discussed above.

DISCUSSION

Currently two end-member models advocating either continuum flow (e.g., England and Houseman, 1986) or discrete deformation (Tapponnier et al., 1982) in accommodating India-Asia convergence have been used to explain the nature of Cenozoic deformation across the Himalaya-Tibet orogen. Although microplate models can explain well the existing GPS data across Tibet (e.g., Meade, 2007; Thatcher, 2007), the assigned microplate boundaries are unsustainable under finite-strain deformation and thus require significant internal continuum deformation with each microplate (Cowgill, 2008). That is, the margins of small rigid block boundaries detected by the GPS observations are transient features that shift positions with time (Cowgill, 2008). The discrete model of Tapponnier et al. (2001) considers distributed crustal thickening of Tibet to be associated with discrete subduction of mantle lithosphere in a stepwise manner progressing northward. In contrast to the above models, some workers consider deformation of Tibetan upper crust to be decoupled from the lower crust and upper mantle due to flow within the middle crust (Royden, 1996; Clark and Royden, 2000; Shen et al., 2001).

Active faulting across the India-Asia collision zone is quite variable and complex, but nonetheless can provide a first-order understanding of continental deformation. From south to north, active faults change from south-directed thrusts across the Himalaya to coeval east-west extension and north-south contraction across kinematically linked conjugate strike-slip and normal fault systems in central Tibet (Figs. 1 and 2A). A left-slip simple shear domain occupies the plateau's northern boundary and a generally east-west contractional domain across its eastern boundary. The transitional regions between the central Tibet conjugate strike-slip zone and its boundaries to the south, north, and east are currently not clear. However, GPS results provide some insight into this issue where the known distribution of faults and their kinematics are considered together. GPS data in Figure 2B indicate that the eastward velocity gradient in the east direction along the southern and northern boundaries of the conjugate strike-slip zone are consistent with a domain of right-slip simple shear in the south and a domain of left-slip simple shear to the north, as pointed out by Zhang et al. (2004) (Fig. 4B). The eastward velocities increase to maximum values near the longitude of the eastern Himalayan syntaxis and then decrease toward the Longmen Shan and Sichuan basin (Fig. 4A). Significant vertical-axis rotation of the GPS velocity vectors around the eastern Himalayan syntaxis is consistent with the idea that crustal material is being transported around the syntaxis as it impinges northward into Eurasia (Fig. 2B) (Wang and Burchfiel, 2000). However, north of lattitude ~32°N there is little vertical-axis rotation of crustal material (Gan et al., 2007; Shen et al., 2005), suggesting that the decrease we observe in the eastward component of GPS velocities can be simply attributed to active upper crustal shortening. These observations show that at or near longitude 95°E, a significant component of east-directed extension originating from central Tibet is being accommodated by contractional structures along Tibet's eastern boundary.

Although the large strike-slip fault systems in Tibet such as the Altyn-Tagh, Karakoram, and Red River have accommodated a large fraction of India-Asia convergence (Avouac and Tapponnier, 1993), they are moving at rates comparable to those in the regional fault system, comprised of strike-slip and extensional faults within Tibet's interior (Zhang et al., 2004; Gan et al., 2007; Taylor and Peltzer, 2006; Washburn et al., 2003; Bendick et al., 2000). The pattern and style of faulting along Tibet's margins are broadly consistent with through-going and relatively continuous fault segments. In contrast, faults typifying Tibet's interior are generally en echelon, discontinuous, have <20 km of fault slip, and vary dramatically in strike and kinematics (Taylor et al., 2003). The highly complex and diffuse fault geometry of central Tibet compared to that of the large plateau bounding faults is simply explained by lower magnitudes of slip on individual structures that have been initiated more recently, probably in the middle Miocene, at or prior to 14 Ma ago (Blisniuk et al., 2001). The complex fault patterns in central Tibet may also result from the existence of an extensional component of the strain field, in comparison to the strain fields along Tibet's boundaries that are currently undergoing contractional and simple-shear deformation. The extensional strain in central Tibet may result from processes similar to those that occur in the Basin and Range, where continental extension over broad areas have variable spatial and temporal patterns, perhaps as a function of viscous dissipation in the lowermost crust and upper mantle (Bokelmann, 2002). However, we caution that strain is more strongly concentrated on the boundaries of the province, with more minor deformation in the interior regions (Bennett et al., 2003; Thatcher et al., 1999).

Kincaid and Silver (1996) suggested that viscous shear heating along an orogen-scale subhorizontal detachment horizon between the upper mantle and eastward-flowing asthenosphere may be responsible for the widespread volcanism in northern Tibet. Underthrusting Indian lithosphere may be colliding with Asian mantle lithosphere to the north, squeezing the intervening asthenosphere out of the way and forcing it toward the free boundary to the east, as suggested by several recent studies (DeCelles et al., 2002; Owens and Zandt, 1997) and implied by others (Huang et al., 2000).

Our new neotectonic map of the India-Asia collision has encouraged us to raise new questions about active continental deformation in Asia that we briefly summarize in the following. (1) What are the main structures accumulating elastic strain and are they late in their seismic cycle? (2) How is north-south convergence accommodated north of the Himalaya, into central Tibet, and then transferred to eastern Tibet? (3) Are there significant basal tractions in the lower crust or upper mantle, and if so, is this process causing significant loading on upper crustal structures? (4) What is the role of late Cenozoic volcanism and its relationship to active faulting? Clearly, more studies are needed to more accurately and completely portray active deformation in the Himalayan-Tibetan orogen. Acquisition of more campaign and continuous GPS occupations are required to quantify geodetic fault slip rates and post seismic transient strains related to the 2008 Tibetan earthquakes to infer crustal rheology. Additional field studies are needed to identify the geometry and kinematics of newly mapped faults described here, and their fault slip rates need to be quantified over different time scales. New mapping is needed in regions showing significant velocity gradients to identify sources for future large earthquakes. Finally, additional field studies of active to recently active faults and their relationship with late Cenozoic volcanic rocks are needed to understand magma accent mechanisms, which in turn may shed new light on deeper lithospheric processes related to the India-Asia collision.

SUMMARY AND CONCLUSIONS

The digital active tectonic map of Tibet and surrounding regions encompasses over 900 structures within the India-Asia collision zone and is available in shapefile format (for ArcGIS [geographic information system]), which is organized as follows. Individual structures are identified as faults or folds with their kinematics either inferred or published (thrust/reverse, normal, left slip, right slip, anticline, or syncline) and are delimited as vertices with geographic locations in decimal degrees. We also include in the database the geologic contacts of late Cenozoic volcanic rocks and suture zones. The files are included in Supplemental File 1[1]. In the near future, our working digital database, HimaTibetMap-1.0, will be updatable through external feedback provided by the scientific community through a web-based portal. Individual structures within the digital database are delineated based on their kinematics, which can be readily plotted in widely used open source software such as the generic mapping tools (GMT) of Wessel and Smith (1991).

Our digital tectonic map allows comparison between the distribution and kinematics of active faults with the distribution and focal mechanisms of earthquakes. The active tectonic map is also superimposed by the surface velocity field obtained by GPS studies. Using the same spatial template allows a better assessment of partitioning of the decadal strain-rate field across individual active structures that may have taken tens of thousands to a million years to develop. The active tectonic map provides a basis to evaluate whether the syncollisional late Cenozoic volcanism in Tibet was spatially related to the distribution and development of the active faults in the same area. The above comparisons have led to the following findings. (1) Tibetan earthquakes >M5 correlate well with mappable surface faults. (2) The short-term strain-rate fields correlate well with the known kinematics of the active faults and their geologic slip rates. (3) Tibetan Neogene–Quaternary volcanism is controlled by major strike-slip faults along the plateau margins, but has no clear relationship with active faults in the plateau interior. Although not explored in this study, our digital tectonic map and the distribution of Cenozoic volcanism in Tibet can also be used to correlate surface geology with geophysical properties such as seismic velocity distributions and shear wave-splitting data across the Himalaya and Tibet.

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[1]Supplemental File 1. This file contains an ArcGIS (geographic information system) shape file for active structures (normal, reverse, thrust, right-slip, and left-slip faults; anticlines and synclines) related to the India-Asia collision zone. The file can be unpacked using any standard decompression software (e.g., Winzip). The digitized structures are decorated using a standard set of symbols developed by Eric Cowgill at the University of California at Davis. A four-digit attribute code is used to classify fault contacts and fold axes using a standard set of map symbols provided in the file GPSec.style. Standard decompression software directions for downloading the Arc style file and implementing the mapping symbology in ArcGIS can be found beginning in section 2 of the manual provided by the University of California at Davis, W.M. Keck Center for Active Visualization in the Earth Sciences (KeckCAVES): http://keckcaves.geology.ucdavis.edu/software/RIMSG3/MANUALS/RIMS_Manual_v1b.pdf. If you are viewing the PDF of this paper or reading it offline, please visit http://dx.doi.org/10.1130/GES00217.S1 or the full-text article at http://geosphere.gsapubs.org to view the supplemental file.

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