Role of oblique convergence in the active deformation of the Himalayas and southern Tibet plateau

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ABSTRACT

Noting similarities with subduction along curved oceanic trenches and using a simple blend model, we show that radial vergence evident in earthquake slip vectors along the Himalayan deformation front, east-west extension on north-trending normal faults in the Himalayas and southern Tibet, and right lateral strike slip on the Karakorum-Jial Fault zone can all result from basalt shear caused by the Indian plate sliding obliquely beneath Tibet along a gently dipping, arcuate plate boundary. Within the framework of this mechanism, the normal faults in the Himalayas and southern Tibet are not proxies for the uplift history of Tibet. The distribution and style of the faults in the Himalayas and southeastern Tibet suggest that the basalt from the underthrusting Indian lithosphere extends northward beneath most of southern Tibet.

INTRODUCTION

Forecasts of many subduction zones undergo rapid arc-parallel extension, revealed by a systematic rotation of interplate earthquake slip vectors away from expected plate convergence direction (McCaffrey, 1994). In extreme cases, such as the Mariana, New Hebrides, and Sumatra, slip vectors are nearly radial (perpendicular to the trench) despite large lateral changes in convergence obliquity between the major plates. Pure thrusting during plate boundary earthquakes indicates that the trench-parallel force in the upper plate arising from oblique convergence is not balanced elastically but instead produces permanent deformation. For example, oblique convergence in Sumatra results in a trench-parallel strike slip fault 300 km from the trench and trench-parallel extension of the forearc above the dipping plate boundary (McCaffrey et al., 1997). In the Altiplano, trench-parallel motion is taken up by large, submarine faults. Models of the overlying crust that translate, separate, and rotate (Gripp et al., 1988). Such upper plate shear axes extension is caused by subduction beneath a curved margin (Abe Lalloussi and Ollier, 1993; McCaffrey, 1992).

The active tectonics of the Himalayas and the southern half of Tibet where they interact with the underthrusting Indian plate (Fig. 1) show a strong resemblance to subduction at curved oceanic trenches. Slip vectors of thrust earthquakes at the curved Himalayan deformation front as normal to it. Seismicity (McNally and Lynman, 1989) and active north-south-trending grabens (Armiyo et al., 1986) show that the Himalayas and southern Tibet extending in the east-west direction. A right-lateral, strike-slip shear zone across southern Tibet is roughly parallel to the deformation front (Armiyo et al., 1989). Similarities between the surface deformation in Tibet and in upper plates at subduction zones suggest that the deformation in both settings is caused by a common mechanism (McCaffrey, 1992). As we show with a block model, basalt shear arising from relative motion beneath an arcuate upper plate can reproduce the observed deformation in southern Tibet. We thus infer that some part of the Indian lithosphere thrusts beneath most of the southern half of Tibet, resulting in east-west extension in the Himalayas and southern Tibet (McCaffrey et al., 1996).

Figure 1. Major faults associated with oblique convergence between India and Tibet. Thrust faults are shown by black lines with bars, strike-slip faults by heavy black lines with opposing arrows, and extensional grabens by thicker gray lines. Slip vectors of thrust earthquakes (small, thin vectors) show direction of India moving beneath Himalayas. Large black vectors south of thrust front show convergence of India with northern Tibet using a rule that includes slip on Altyn Tagh fault, and gray vectors are from NUVEL-1 A India-Eurasia plate with angular velocity divided by three. Heavy arrows in southern Tibet show predicted velocities of southern Tibet relative to northern Tibet for full partitioning. Labeled normal faults are ThaweSsu (T), Kun Co (K), Pum Qu (PQ), Yading (Y)1, and QuLi (G). Strike-slip faults are Karakorum (KX), Gyaring Co (GC), Been Co (BC), and Jial (JL). Lashed lines show smoothed outline of deformation front, used in partitioning calculations, and its projection onto Karakorum-Jial Fault zone. Topographic contour interval is 1 km, and triangles show Cenozoic volcanoes (McNally et al., 1993).

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Because the shear stress on the backstop boundary cannot exceed \( \tau \), the direction the block moves over the base relative to \( \gamma \) cannot exceed \( \gamma \). When \( \gamma \) is small, slip vectors are nearly parallel to \( \gamma \), that is, perpendicular to the deformation front. Knowing \( \gamma \), the velocity at which the forearc block moves along the backstop is

\[
v = \nu \cdot \gamma - \cos \gamma \cdot \tan \psi
\]

when \( 2 \gamma \geq \psi \) and \( v = 0 \) when \( 2 \gamma < \psi \), where \( \psi \) is the velocity of the backstop relative to the surface beneath (Fig. 2D). Positive velocities in \( \psi \), that is, of-parallel stretching of a forearc, can result from along-strike variations in convergence rate, or of the strike of thrust or upper plate faults. Specific examples include: (1) The backstop is straight and \( \psi \) decreases along strike due to an increase in basal shear or a divergence of vertical shear along the backstop. (2) The pole of rotation is located such that \( \psi \) increases along strike, and (3) like most oceanic forearcs, the backstop is convex toward the subducting plate. We focus on the third case because the Himalayan front is convex toward India, but a nearly pole of rotation may also contribute to the along-strike variation in obliquity. Margin parallel stretching will occur at a rate of

\[
dv / dt = \nu \cdot \psi - \tau / \eta
\]

when \( 2 \gamma > \psi \) and \( dv / dt = 0 \) when \( 2 \gamma < \psi \), where \( \eta \) is the distance along strike, \( r \) is the radius of the arc, and \( \phi \) is the angle of equation (1) through which I predict that the backstop will be pushed, we see (1) blocks at the leading edge of the backstop (where \( \gamma = \psi \) moving with the backstop); (2) at obliquity \( \gamma \neq \psi \), blocks moving slowly relative to the backstop but separating rapidly; (3) at highest obliquity \( \gamma \gg \psi \), blocks moving faster relative to the backstop but having slow separation rates; and (4) the blocks' motion over the base forms an angle \( \psi \) with the normal to this backstop. Our block experiments (Fig. 2) reveal these features in quantitative agreement with theory. In particular, because \( \gamma \) is small, the blocks have nearly radial slip vectors (Fig. 2C).

For similar partitioning to occur in the Earth, the underplating plate interface must be able to generate a stress large enough to cause normal and strike-slip faults in the overriding plate to fail. The force needed to stretch the forearc adds to the numerator of the right side of equation 1, but if the numerator remains less than 1, then partitioning will still occur according to equations 2 and 3.

**APPLICATION TO INDIA-TIBET CONVERGENCE**

Figure 1 reveals patterns of deformation and slip vectors in the Himalaya and southern Tibet similar to the block model (Fig. 2). In this analogy, India forms the base of the model, northern Tibet forms the backstop, and the Himalaya and southern Tibet, between the deformation front and the
Karakorum-Indus fault zone, is the region we call the "favourable blocks". Within the Himalayas and southern Tibet, from 82°E to 92°E, 'obversion' is revealed by normal faults and eneaplines. West of 82°E, extension appears to be minor, yet transpression is relatively rapid (along the Karakorum fault). As in the block model, slip vectors are perpendicular to the deformation front all along the Himalaya. Hence, oblique thrusting of India beneath the Himalayas and southern Tibet can account for first-order tectonic features of the southern margin of the India-Tibet collision.

The average rates of shortening across vertical planes parallel to the deformation front and east-west extension in the Himalayas and southern Tibet can be estimated quantitatively from equations 2 and 3 by knowing the pole of rotation between India and northern Tibet, the orientation of the Himalayan thrust fault, and the angle \( \phi \) (Fig. 3). Slip vectors at the Himalayan front show that \( \phi \approx 0 \). We assume that the angle slip vector west of 88°E, which are largely parallel to the deformation front, take up all the shear. Because the slip rate on an individual fault depends on its orientation relative to the expected shear-parallel shear, we separately estimate slip rates for the fault strike-slip faults east of 88°E that are oblique to the maximum shear direction (Fig. 1).

The calculated motion between India and northern Tibet depends on the assumed slip rate along the Alaknanda fault. If there is no slip on the Alaknanda fault, a reasonable estimate of the \( \rho \) between India (I) and northern Tibet (NT) is the modern India- Eurasia plate (DeMets et al., 1994), but with angular velocity \( \Omega \) due to a factor of three (called the I-NT\( \rho \) value) for allow for convergence taken up within Asia. This pole predicts westward convergence along all the margin (Fig. 1), resulting in shearing rates that are much smaller than observed slip rates on the Karakorum-Indus fault zone (Fig. 3). It predicts a fairly uniform slip along major strike-slip extensional strain in the Himalayas and southern Tibet with a factor of two increase in southeastern Tibet (Fig. 3), where the largest normal faults are found.

A better match to the deformation can be obtained with a model that includes slip on the Alaknanda fault (Fig. 3). From a plate circuit of India, southern Tibet, the 72°N basin, and Eurasia, and assuming a slip rate of 25.3 \( \pm \) 3 mm/yr along the Alaknanda fault (Rita et al., 1989) and shortening rate of 17.2 mm/yr across the 72°N Shan (Ando et al., 1995), the pole of rotation between India and northern Tibet (\( \rho_{\text{NT-I}} \approx 12°/12°, 57°E, \) angular velocity \( \Omega \approx 0.077 \) per m.y.) predicts convergence perpendicular to the deformation front at 94°E and higher obliquity to the northwest (Fig. 1). The \( \rho_{\text{NT-I}} \approx 12°/12°, 57°E, \) angular velocity \( \Omega \approx 0.077 \) per m.y.) predicts convergence perpendicular to the deformation front at 94°E and higher obliquity to the northwest (Fig. 1). 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geological history. In our mechanism, margin-parallel extension can extend all the way to the deformation front, as recent Global Positioning System measurements confirm (Laronz et al., 1997). Hence, we argue that normal faults in both southern Tibet and the Himalayas have the same underlying cause. To the degree that the dikes reported by Yin et al. (1994) indicate westward extension, this mechanism was already operating by 15 to 18 Ma. Extension could be even older than 18 Ma because, like most subduction zones, this original deformation front was probably curved from the beginning of the collision. However, if extension in southern Tibet did accelerate at about 10 Ma or earlier, then a possible explanation is that the Aylu Tagh fault was initiated about that time.

Whereas explanations that restrict extension to high elevations predict that normal faulting should be at least as prevalent in northern Tibet as it is in southern Tibet, the grabens in southern Tibet appear to be largely truncated in the north by the Iliu fault zone (Ambroz et al., 1986, 1989). Our mechanism localizes the normal faulting in the Himalayas and southern Tibet above areas having basal shear from the underthrusting Indian lithosphere. On the basis of experiments with multiple rows of blocks, observations from subduction zones, and reasoning that upper plate shear strain concentrates near boundaries where basal traction is varying, we suggest that the Karakorum-Julai fault zone marks the northern termination of the strong basal shear beneath southern Tibet.

Our model does not require wholesale subduction of Indian lithosphere with crust intact. It is more likely that the Indian crust is detached from its mantle and incorporated into the thickened crust of Tibet (Nelson et al., 1996). In our view, some part of India’s mantle continues to slide under southern Tibet along a gently dipping plate. All of southern Tibet is underthrust by high-seismic velocity mantle, which is likely of India, whereas the northern Tibet mantle has low seismic velocity (Owen and Zandt, 1991). Small earthquakes as deep as 90 km are found only beneath southern Tibet, indicating an upper mantle that is probably cold and capable of maintaining shear stress (Chen and Kan, 1990).

The largest uncertainty in our partitioning model arises from the separation between India and northern Tibet, which determines the slip rates to be expected on the Karakorum-Julai fault zone. We favor a high slip rate on the Aylu Tagh fault, not only because it matches the distribution of normal faulting in the Himalayan and southern Tibet but also because the Karakorum-Julai fault zone, but also because late initiation of the Aylu Tagh fault offers a possible mechanism for triggering normal and strike-slip faulting in the history of the collision.

We have shown that the common process of partitioning oblique convergence in response to drag from the downwelling plate simultaneously produces radial slip vectors, along-strike translation, and extension parallel to the deformation front, all observed features of the Himalayan and southern Tibet. In addition to the agreement between our model and the limited data available for Tibet, support for our hypothesis comes also from its relevance to convergent margin tectonics in many other parts of the world.

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