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Applying geodesy and modeling to test the role of climate controlled erosion in shaping Himalayan morphology and evolution

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Abstract: The Himalaya-Tibet system is the archetype of continent-continent collision, but the role of climate in modulating orogenesis is a relatively new paradigm that has not been well tested with field-based deformation measurements. Phenomenal monsoon precipitation (>3 m/year) falls along the Himalayan front, and the resulting erosion is thought by some to promote out-of-sequence thrusting or even channel flow within the High Himalaya, leading to the observed, profoundly steep morphology. Others attribute High Himalayan morphology to a more traditional paradigm of a steeper underlying décollement ramp. The two paradigms predict different patterns of current deformation, but both at rates readily measurable with global positioning system (GPS). In this paper we review the current impasse which researchers from both sides of the debate have reached using methods of structural mapping, morphological analysis, spirit-leveling, seismicity, thermochronometry, cosmogenically-determined erosions rates, and thermokinetic modeling and propose that the addition of continuous geodetic measurements of surface deformation combined with elastic half-space modeling could help resolve the issue. To this end we deployed a network of 6 permanent GPS stations in the Nepal Himalaya in summer 2008 and have plans to expand to it to 16 stations. Preliminary model results demonstrate that within a couple years differences between the two paradigms should be discernable.

INTRODUCTION

The Himalaya-Tibet system is perhaps the best example on earth today of a continent-continent collisional orogen and thus has received great attention over the years. Fundamental questions nonetheless remain about its structural architecture and evolution - particularly the role of climate and erosion in modulating active faulting within the orogen. Through study of the Himalaya we gain insights into collisional tectonics in general and this high-population, earthquake-prone area in particular.

Ample evidence suggests the southern edge of the orogenic wedge is bounded by the active Main Frontal Thrust (MFT; Fig. 1) on which great earthquakes ($M_w > 8$) are known to occur (e.g., Bilham *et al.* 2001; Feldl & Bilham 2006; Lavé *et al.* 2005). This is in accord with the critically tapered wedge theory which states that as collisional belts develop, younger faults initiate progressively towards the foreland and older faults becoming inactive (Dahlen 1990; Davis *et al.* 1983; DeCelles & Mitra 1995). Only if mass is removed from within the wedge (for example, by localized erosion), would one expect to see active thrust faults within the wedge. Presently, there is substantial disagreement as to whether active faults exist within the orogenic wedge ("out-of-sequence" faults). Should such faults be present (e.g., reactivated Main Central Thrust) it would provide strong evidence that erosion rates are not uniform and that orogenic develop can be affected by climate-modulated erosion. Absence of out-of-sequence faults suggests that Himalayan structures are defined solely by tectonics and that climate and erosion are passive responders.

By measuring the rate of ongoing strain accumulation across the orogeny, we can identify the active structures and thus identify the dominant collisional mechanisms and earthquake hazards. The overarching goal of this research is to test the extent to which climate and erosion, versus just tectonics, control the evolution of the Himalayan collision; but other research questions will be addressed simultaneously (but are not further discussed in this paper: e.g., Himalayan strike-slip fault activity and active structures in the Kathmandu basin). We are pursuing a two-pronged approach of measuring deformation across the Nepal Himalaya with GPS and modeling theoretical motion expected for different tectonic scenarios.

The deformation data is being acquired by our recently established network of 6 permanent GPS stations in the Nepal Himalaya that will and expanding it to 16 stations (Fig. 2) pending funding (TRIBHUGNET = TRIBHUvan Geodetic NETwork; tribuj = triangle in Nepali). The project is being jointly run by Central Washington University, USA and Tribhuvan University, Nepal (http://www.panga.cwu.edu/panga/maps.php; check TRIBHUGNET box in upper left). Additional deformational data will come from another recently

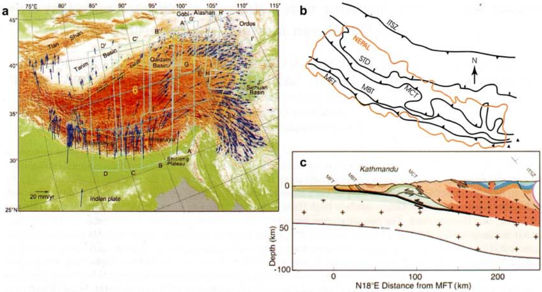

Fig.1. **a)** Himalaya-Tibet ground motion from GPS (Zhang *et al.* 2004). **b)** Schematic map of major tectonic Structures (modified from An & Harrison 2000). **c)** Geologic section across central Nepal at latitude 0 Kathmandu (Avouac 2003).

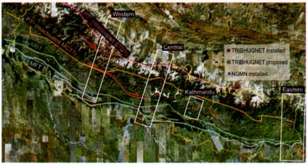

Fig.2. Satellite image of Nepal with overlay of known/proposed active structures and installed/proposed permanent GPS stations. White rectangles indicate TRIBHUGNET transects. MFT = Main Frontal Thrust. MBT = Main Boundary Thrust. Pt1 = Physiographic Transition 1. Pt2 = Physiographic Transition 2. MFT and MBT after Hodges (2000) and other sources, PT1,2 after Hodges *et al* (2001), strike-slip faults after Nakata *et al.* (1984, 1990) and Yagi *et al.* (2000). Base image from Google Earth.

installed permanent GPS network, the Nepal Geodetic Monitoring Network (NGMN) which is run jointly by the Caltech Tectonics Observatory, the Département d'Analyse et Surveillance de l'Environnement, France, and the Department of Mines and Geology, Nepal (http://web.gps.caltech.edu/facilities/gps_facilities.html). In contrast to NGMN, which gives broad coverage of Nepal, our network targets key regions with dense transects specifically designed to differentiate between climate-driven or purely tectonic modulation of faulting. Synthetic surface deformation patterns will be generated in an elastic half space back-slip model.

TECTONIC SETTING

The ongoing Indian-collision (e.g., An & Harrison 2000) is accompanied by significant crustal thickening, lateral escape, and the uplift of the highest topography on Earth-the Himalaya and Tibet (Fig. 1). The most recent geodetic measurements across the orogen show that the total convergence between stable India and Asia across the central Himalayan arc is 35-40 mm/yr (Apel in preparation; Bettinelli *et al.* 2006). Approximately half, 19 ± 2.5 mm/yr (Bettinelli *et al.* 2006; Lavé & Avouac 2000), is accommodated as shortening in the central Himalaya. The remainder is accommodated as shortening across Tibet and central Asia and eastward extrusion of Tibetan crust through a mixture of strike-slip and extension (e.g., Zhang *et al.* 2004).

At a broad scale, most workers agree about the relations between the Himalayan orogen and Tibetan plateau. The original boundary between the two continents is the Indus-Tsangpo Suture Zone (Fig. 1) which is now located in southern Tibet. The rocks which compose the Himalaya were originally sediments on the northern edge of the Indian continent and have been incrementally accreted onto the leading edge of Asia as the Indian continent was underthrust (e.g., Brunel 1986; Gansser 1964; Le Fort 1986). The major structures and rock formations from north to south are: 1) Tibetan Sedimentary Sequence (TSS) bounded on the south by the

South Tibetan Detachment (STD), a normal-sense down-to-the-north fault; 2) Greater Himalayan Sequence (GHS) high-grade metamorphic rocks bounded by the Main Central Thrust (MCT); 3) Lesser Himalayan Sequence (LHS) medium-grade metasediments and the Main Boundary Thrust (MBT); and 4) Siwalik hills of folded foreland sediments with the Main Frontal Thrust (MFT) marking the southern edge of significant deformation (Fig. 1). Locally faults have other names or multiple splays, but the overall structure is consistent across the main arc between the syntaxes. All the thrusts are believed to root to the same décollement (e.g., Schelling & Arita 1991), usually called the Main Himalayan Thrust (MHT) or Himalayan Sole Thrust (HST). The thrusts initiated from north to south as the prograding orogenic wedge overthrust India.

Significant movement occurred on the MCT and STD during the early Miocene (e.g., Hodges *et al.* 1996) in what has been proposed to be erosion-induced channel flow (Beaumont *et al.* 2001)(Fig. 3). Under the channel flow model, the rocks between the MCT and STD (the Greater Himalayan Sequence) originated in the mid-to-lower crust and were extruded more rapidly than the rocks to the north or south due to unloading from focused denudation on the edge of the plateau. Although most researchers agree that the MCT and STD experienced significant movement during the early Miocene, the concept of channel flow, and whether these structures have experienced more recent or even Quaternary motion is a point of considerable controversy. The measurement and modeling of current deformation across the orogenic wedge to test the hypothesis of modern channel flow is one of the major goals of our ongoing research.

THE DEBATE: DOES CLIMATE MODULATE OROGENIC EVOLUTION?

The case FOR climate-driven orogenic evolution

Since the possible interplay between tectonics and climate was first proposed (Molnar & England 1990), researchers around the world have investigated whether climatic gradients can lead to spatial variations in erosion and thus ultimately affect the mass distribution and structural development of mountain ranges. Because the Himalaya have a dramatic climatic gradient (Fig. 3)(e.g., Bookhagen & Burbank 2006), high erosional flux (e.g., Galy & France-Lanord 2001), and rapid tectonic convergence (e.g., Zhang *et al.* 2004), they have attracted considerable research in this regard. Every summer the Indian monsoon sweeps tremendous amounts of water from the Bay of Bengal and drops it on the Himalayan front. In Nepal peak monsoon rainfall is >3 m/yr on the southern margins of the Lesser and Greater Himalaya, but drops off dramatically to the north (Bookhagen & Burbank 2006; Burbank *et al.* 2003).

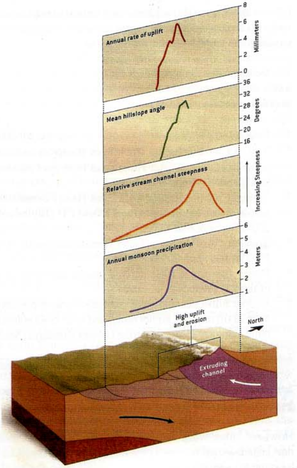

Fig.3. Geographic coincidence of proposed channel flow and precipitation maximum, channel steepness, hillslope angle, and uplift rate (Hodges 2006).

The Greater Himalayan peak in rainfall is coincident with the highest rates of vertical uplift (Jackson & Bilham 1994) and hillslope steepness (Wobus *et al.* 2006) and lies just to the south of the maximum topographic relief (Bookhagen & Burbank 2006). Therefore it has been proposed that strain in this region is enhanced by erosional removal of material and active faults are present (Hodges 2006; Hodges *et al.* 2004). Although this area lies in the middle of the orogenic wedge, if sufficient excess material is eroded, out-of-sequence faults could be activated to maintain the critical taper (e.g., Davis *et al.* 1983; Mukul *et al.* 2007). Or alternatively, channel flow could be continuing and motion would be expected along modern versions of the MCT and STD. Hodges *et al* (2001) proposed that the locations of "physiographic transitions" PT^2 and PT^1 define the margins of active channel flow and thus can be thought of as reactivated MCT and STD, respectively (Fig. 2). The former case (out-of-sequence thrust faults within the wedge) suggests involvement of upper crustal rocks in climate-modulated orogenesis; whereas channel flow would involve mid-to-lower crustal rocks.

Geologic observations which could support the proposal of recent or modern active faulting within the orogenic wedge and/or deformation associated with precipitation maxima include:

- Quaternary thrust faulting near PT[2] (Hodges *et al.* 2004)
- Younger apatite fission track ages (faster denudation) coincident with Greater Himalayan front max monsoon precipitation (Grujic *et al.* 2006)
- Younger apatite fission track ages (faster denudation) across the region between the PT[2] and PT[1] (Blythe *et al.* 2007; Burbank *et al.* 2003)
- Younger ^{40}Ar/^{39}Ar ages (faster denudation) north of the PT[2] (Wobus *et al.* 2003)
- Faster cosmogenic 10Be-derived erosion rates to the north of the PT[2] (Wobus *et al.* 2005)
- Steeper hillslopes and river channels, lack of preserved alluvial fill terraces, higher relief, and river knickpoints all point to higher uplift rates in the Greater Himalaya (Seeber & Gornitz 1983; Wobus *et al.* 2006)
- Pliocene monazite ages from directly below MCT zone (Catlos *et al.* 2001)

The case AGAINST climate-driven orogenic evolution

However, other work compellingly argues for a tectonics dominated system in which climate is a passive responder to topography and does not drive faulting within the orogen (reviewed in Avouac 2003). Geodetic rates of shortening across the Himalaya match geologically-inferred shortening across the MFT, strongly suggesting that this southern-most structure accommodates all the offset. The central Himalaya have a well established modern shortening rate of 19 ± 2.5 mm/yr (Bettinelli *et al.* 2006). Analysis of alluvial terraces folded by movement on the MFT in Nepal show Holocene shortening rates of 21 ± 1.5 mm/yr (Lavé & Avouac 2000) and 19 ± 6 mm/yr (Mugnier *et al.* 2004). Out-of-sequence thrusts, it is argued, would have no additional shortening to accommodate if modern geodetic rates are representative of Holocene rates.

Higher rates of denudation and other indications of faster rock uplift (steepness, knickpoints, etc.) across the Greater Himalaya can be explained by a steeper décollement ramp below this region (e.g., Cattin & Avouac 2000; Molnar 1987); therefore no need exists to invoke out-of-sequence thrusting or channel flow (Fig.1c). Faster rock uplift is simply due to a greater component of vertical motion for each increment of horizontal shortening. Detailed structural geology studies across the Lesser Himalaya in western, central, and eastern Nepal suggest that this region has experienced southward propagating thrusts and duplex formation that does not support significant reactivation of the MCT or channel flow (Robinson *et al.* 2006; Robinson *et al.* 2003) (Fig. 1c). Bollinger *et al.* (2006) thermal and kinematic model of orogenic wedge development through underplating and duplex formation produces the inverse geothermal gradient and discontinuous peak metamorphic temperatures observed by Catlos *et al. (2001; 2002; 2004; 2007)* also without MCT reactivation.

The rebuttal

Proponents of climatic modulation of orogenic strain (Wobus *et al.* 2006) counter with another model that suggests Bollinger *et al.* (2006) model represents a special case and a reactivated MCT is a simpler explanation. It can also be pointed out that the entire argument for geologic convergence rates matching geodetic rates (19 ± 2.5 mm/yr) rests on one geologic study with small error bars (21 ± 1.5 mm/yr; Lavé & Avouac 2000) and one with larger errors (19 ± 6 mm/yr; Mugnier *et al.* 2004); whereas other work suggests a mismatch between the rates on the order of 2-6 mm/yr (Kumar *et al.* 2001; Thakur 2008). In addition, if full channel flow is occurring and motion is being accommodated along both the PT[2] (MCT) and PT[1] (STD), than the full apparent convergence across the Himalaya could be occurring at the MFT without negating intra-orogen active faulting.

METHODS

GPS network design

This debate can be resolved with continuous GPS measurements along dense (≥5 station) N-S transects that spans the MFT and the orogenic wedge around the MCT to show, precisely, where and how convergence is accommodated. The current TRIBHUGNET transect of 5 stations is located in central Nepal with one additional station in Kathmandu (Fig. 1). The NGMN has a number of transects with 3-4 stations each. Future TRIBHUGNET expansion will add 1-2 stations to the existing Central transect, densify 2 of the NGMN transects (Kathmandu and Western Nepal), and establish a new transect in far eastern Nepal. The higher density of stations will permit all major Himalayan structures (MFT, MBT, MCT-PT2, STD-PT1) to be straddled in multiple locations along strike and place several additional stations in the region of the proposed décollement ramp inflection points. This will allow strain accumulation to be measured for each structure separately and, in particular, help resolve the underlying cause of deformation occurring along the Himalayan front (i.e. is it due to strain accumulating on a reactivated MCT-PT2 or simply a steeper crustal ramp). The permanent GPS stations of TRIBHUGNET and NGMN offer significant improvement in data quality and volume over the primarily or entirely campaign GPS data of previous studies (e.g., Bettinelli *et al.* 2006; Bilham *et al.* 1997). Through collaboration with Indian colleagues the opportunity exists to extend the analysis across the entire Himalayan Arc by including transects in eastern India (8 permanent stations already installed; Jade *et al.* 2007) and western India (10 permanent stations currently being installed; Arora Personal communication October 2008).

The central Nepal transect was established first because of the extensive research done in this region on structural analysis and climate-tectonic studies (Burbank *et al.* 2003; Catlos *et al.* 2001; Coleman 1998; Coleman & Hodges 1998; Hodges *et al.* 2001; Hodges *et al.* 1996; Hodges *et al.* 2004; Robinson *et al.* 2001; Searle & Godin 2003; Wobus *et al.* 2005; Wobus *et al.* 2003; Wobus *et al.* 2006). The other major TRIBHUGNET transect will be along the eastern border of Nepal. Jade *et al.* (2007) work in the Arunachal Himalaya of eastern India suggests that shortening in that region is accommodated across both the Lesser and Greater Himalaya; whereas campaign GPS from central and western Nepal (e.g., Bilham *et al.* 1997; Jouanne *et al.* 2004) suggests the shortening is mainly across the Greater Himalaya. Placing a transect in far eastern Nepal, where little GPS work has been done, will allow for along-strike comparisons in deformational style. The additional TRIBHUGNET stations in western Nepal and the Kathmandu area will define deformation patterns across: 1) the proposed steeper décollement ramp/PT^2 transition and 2) the main Nepali population center, respectively.

GPS data analysis

GPS data from the combined networks of existing and proposed TRIBHUGNET stations (6+10), the relevant NGMN stations (~12), and International GPS Service (IGS) stations from throughout Asia and the Indian subcontinent (~20) is being processed with GIPSY (Zumberge *et al.* 1997). Both NGMN and IGS data are publicly available. Figure 4a shows a subset of Asian IGS GPS receivers that are being used to define a "Stable Asia" reference frame, akin to the Stable North American (SNARF)" frame used for western North American GPS stations. The vectors as shown in figure 4a, c, d are in the ITRF2005 reference frame (Altamimi *et al.* 2002). We are experimenting with the Stable Asian reference frame to account for intra-station deformation. If more Indian GPS stations become publically shared (which they are not currently) we will also experiment with a "Stable India" reference frame. Because the channel-flow and related hypotheses in this proposal are constrained by the long-term, secular GPS velocity rates, seasonal signals that stem from sources such as mis-modeled tropospheric and ionospheric delays, reference frame errors, and hydrologic signals are being estimated and removed by established methods (Szeliga *et al.* 2008). In this approach, the resultant time series of GPS positions within the Stable Asia reference frame will be 'cleaned' by decomposition into a set of basis functions that include the linear velocity (wanted), annual and semiannual sinusoids, and a summation of step functions introduced at times of known earthquakes, aperiodic tectonic transients (should any be found), or GPS instrumentation upgrades. This approach yields the full covariances of all estimated parameters and allows a robust determination of long-term velocities at the precision of 1, 2, and 4 mm/year in north, east, and vertical velocities, respectively, within 2 years of operation.

Modeling deformation patterns

Modeling the resultant GPS time series allows for discrimination between the competing tectonic scenarios that address how 2 cm/yr of convergence is accommodated across the Himalayan orogeny. We specify the major fault surfaces in the main Himalaya fault sequence by linearly interpolating between depth contours drawn from geologic maps. These surfaces are then divided into variable sized subfaults whose typical dimensions are approximately 25 km along strike and 15 km down dip. Figure 4b shows a three-dimensional representation of these surfaces, as viewed from the northwest. The MFT-MHT (grey), MBT (blue), and MCT/PT^2 (red) all dip towards the northeast and connect at depth (e.g., Schelling & Arita 1991). The STD/PT^1 is yellow.

In order to accurately represent the GPS time series, we model the deformation during interseismic periods. Savage (1983) has shown that interseismic strain accumulation along reverse sense faults can be approximated by normal sense slip along the surface in an elastic half-space. This method is known as the back slip method. The surface velocities modeled for each tectonic scenario will be compared with the actual velocities determined from the GPS time series. The best match between modeled and observed surface velocities will determine which faults are the ones most likely to be accumulating the interseismic strain and thus which tectonic scenario is most compatible with observations. In the preliminary model presented here, we have modeled two scenarios. In the first scenario, all of the convergence is accommodated on the MFT. In the second scenario 75% of the convergence is accommodated on the MFT and 25% on the MCT.

PRELIMINARY MODELING RESULTS

Figure 4e shows the expected signals at 41 existing (red symbols) and proposed (blue symbols) Nepal GPS sites, for two end-member tectonic scenarios. The first (blue vectors) assumes that 100% of the 2 cm/yr shortening across the Himalaya is accommodated along the Main Frontal Thrust at an azimuth of N20E (as opposed to ITRF2005 in figure 4a, c, & d) and represents the "passive climate" hypothesis in which no out-of-sequence faulting is present. Red vectors, by contrast, show the expected signal if 75% of the total convergence is accommodated along the Main Frontal Thrust region, while another 25% is accommodated across the Main Central Thrust in a fashion in keeping with climate modulated erosional initiation of out-of-sequence thrusting. Fig. 4f shows the difference these two predicted scenarios, which approaches 0.5 cm/yr throughout most of Nepal. Due to this large signal, and because of the precision and timeliness with which long-term secular velocities can now be extracted from GPS time series, it will be possible to begin differentiating between alternate hypotheses by the middle of the second year.

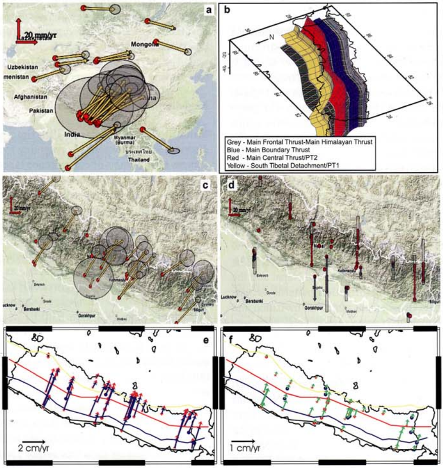

Fig. 4. a) Asian GPS station relevent to this project. Available IGS stations are being used to construct a 'stable Asia' reference frame suitable for tectonic modeling of GPS transects across the Himalayan orogeny. Vectors shown in the ITRG2005 reference frame; those with large covariances are new in 2008. **b)** Digital representation of the major faults of the greater Himalayan convergence zone, being used to model the predicted GPS deformation time series. **c)** Horizontal and **d)** Vertical time series in ITRF2005 of available GPS data from Nepal. These include 6 stations deployed from 1995-1998 by Roger Bilham (available from UNAVCO), 6 existing TRIBHUGNET stations, and ~10 NGMN stations. The horizontal vectors point more easterly due to the ITRF2005 reference frame than they will in a stable Asia reference frame, which will be developed as part of the proposed research. Preliminary vertical motion shows elastic subsidence in the 'forearc' and uplift in the higher regions to the north at rates reaching 2 cm/yr- unmistakable signs of elastic strain accumulation that portends great seismogenic potential. **e)** Predicted GPS velocities in a stable Asia reference frame for 100% of convergence accommodated by the Main Frontal Thrust (blue vectors) versus 25% of total strain accommodated along the Main Central Thrust (possible climate-driven erosion hypothesis). **f)** Shows the difference in deformation rate between these two mechanisms nears 0.5 cm/year - a signal readily measured with GPS within ~2 years. Red circles indicate existing TRIBHUGNET stations, red stars existing NGMN stations, red diamonds Roger Bilham's mid-90's stations, blue circles indicate proposed stations

It should be noted that although figure 4c is shown in the ITR2005 reference frame whereas figures 4e and 4f were computed within a Stable Asia reference frame, the coarse pattern of measured convergence in figure 4c is very broad towards the north. This preliminary analysis suggests that convergence may take place across more of the Himalaya than the MFT. Further modeling will iron out the roles of the various structures, as well as their along-strike variation.

CONCLUSIONS AND NEXT STEPS

The difference between the geodetic signatures corresponding to the two end-member tectonic scenarios (erosion-modulated MCT/PT2 motion versus all convergence across the MFT) approaches 0.5 cm/year. If this degree of out-of-sequence thrusting is indeed occurring, it will be well within the scope of the existing and proposed GPS networks to detect with a few years of permanent GPS data.

Our on-going modeling efforts are exploring a much broader range of potential tectonic scenarios than the two presented above. These include: 1) lower percentages (than 25%) of total movement accommodated across the MCT/PT^2 to determine the detection limit of the GPS network to out-of-sequence strain accumulation; 2) channel flow models in which strain is accumulating along both the MCT/PT^2 and STD/PT^1 as Great Himalayan Sequence rocks extrude more rapidly than the rocks to the north and south and the entire 2 cm/yr Himalayan convergence is still accommodated across the MFT. The method presented in this paper of combining back-slip modeling with geodetic measurement of ground surface deformation holds the exciting potential to finally determine whether or not climate is modulating erosion sufficiently to induce out-of-sequence thrusting and/or channel flow or whether climate is purely a passive responder to tectonic movement in the Himalaya.

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