Convergence rate across the Nepal Himalaya and interseismic coupling on the Main Himalayan Thrust, implications for seismic hazard

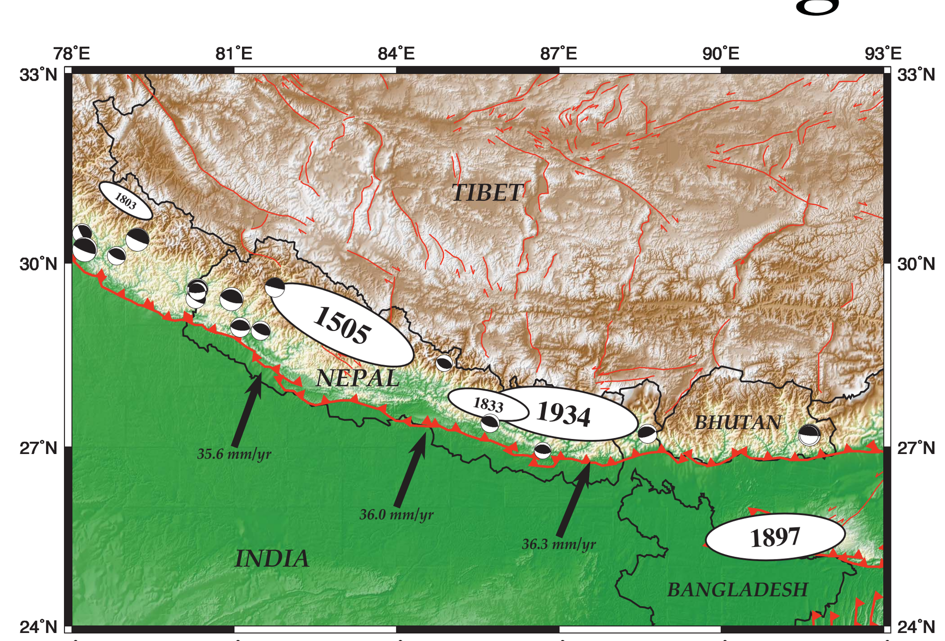
Thomas Ader,[1,2] Jean-Philippe Avouac,[1] Jing Liu,[3] Hélène Lyon-Caen,[2] Laurent Bollinger,[4] John Galetzka,[1] Jeff Genrich,[1] Marion Thomas,[1] Kristel Chanard,[1] Soma Nath Sapkota,[5] Sudhir Rajaure,[5] Ding Lin,[3] and Mireille Flouzat[4]

Abstract

We document geodetic strain across the Nepal Himalaya using GPS times series from 30 stations in Nepal and southern Tibet, in addition to previously published campaign GPS points and leveling data and determine the pattern of interseismic coupling on the Main Himalayan Thrust fault (MHT). The noise on the daily GPS positions is modeled as a combination of white and colored noise, in order to infer secular velocities at the stations with consistent uncertainties. We then locate the pole of rotation of the Indian plate in the ITRF 2005 reference frame at longitude = -1.34°±3:31°, latitude = 51.4° ±0.3° with an angular velocity of Ω = 0.5029°±0.0072°/Myr. The pattern of coupling on the MHT is computed on a fault dipping 10° to the north and whose strike roughly follows the arcuate shape of the Himalaya. The model indicates that the MHT is locked from the surface to a distance of approximately 100 km along dip, corresponding to a depth of 15 to 20 km. In map view, the transition zone between the locked portion of the MHT and the portion which is creeping at the long term slip rate seems to be at the most a few tens of kilometers wide and coincides with the belt of midcrustal microseismicity underneath the Himalaya. According to a previous study based on thermokinematic modeling of thermochronological and thermobarometric data, this transition seems to happen in a zone where the temperature reaches 350°C. The convergence of the Indian plate underneath the Tibetan plateau proceeds at a rate of 17.8±0.5 mm/yr in central and eastern Nepal and 20.5±1.0 mm/yr in western Nepal. The moment deficit due to locking of the MHT in the interseismic period accrues at a rate of 6.6±0.4x10^{19} Nm/yr on the MHT underneath Nepal. For comparison, the moment released by the seismicity over the past 500 years, including 14 M_W>7 earthquakes with moment magnitudes up to 8.5, amounts to only 0.9x10^{19} Nm/yr, indicating a large deficit of seismic slip over that period. We discuss the magnitude and return period of M>8 earthquakes required to balance the long term slip budget on the MHT.

[1] *Department of Geological and Planetary Sciences, California institute of Technology, Pasadena, CA 91125, USA.*
[2] *Ecole Normale Superieure, 24 rue Lhomond, 75004 Paris, France.*
[3] *Institute of Tibetan Plateau Research, Beijing, People Republic of China.*
[4] *Commissariat à l'énergie Atomique, Bruyères-le-Châtel, 91297 Arpajon Cedex, France.*
[5] *National Seismological Centre, Department of Mines and Geology, Lainchaur, Kathmandu, Nepal.*

Seismotectonic setting

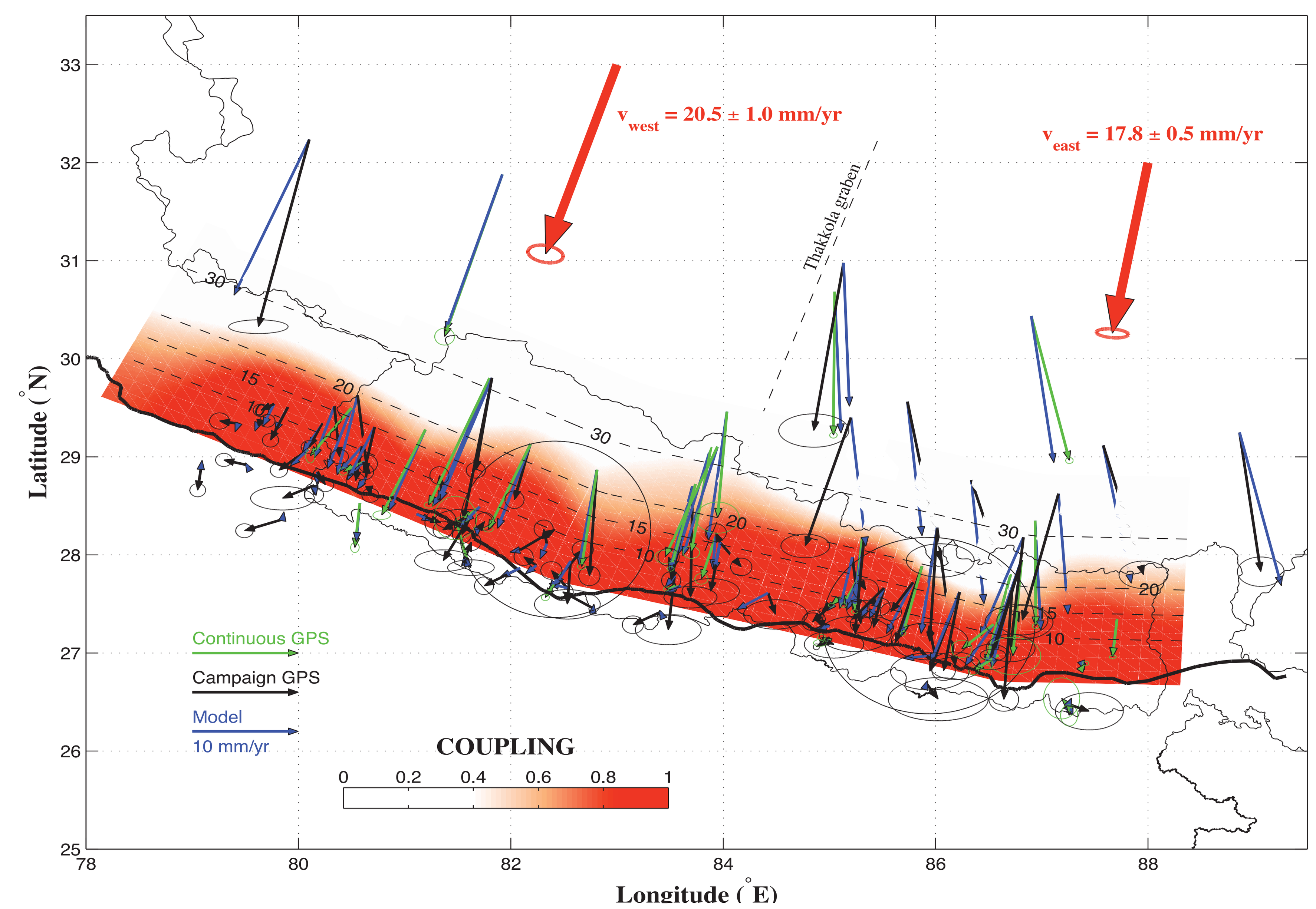


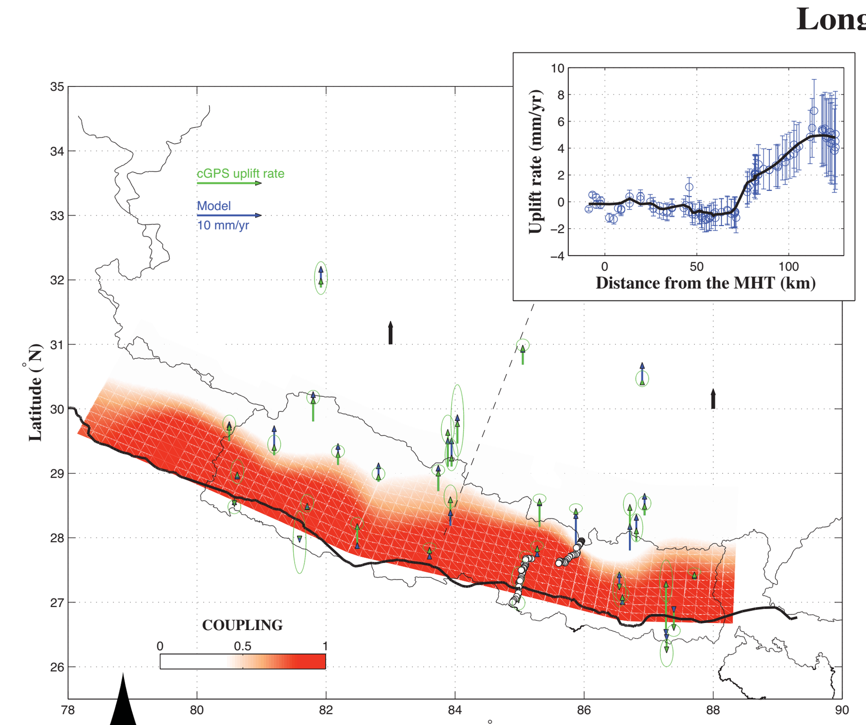
Seismotectonic setting of the Himalaya. Arrows show Indian plate motion relative to Eurasia computed using the rotation poles of Eurasian plate in ITRF 2005 from Altamimi [2009], and Indian plate in ITRF 2005 from this study. Focal mechanisms show thrust events (rake = 90°±45°) from the CMT catalog between 1976 and 2011. White ellipses show locations of historical earthquakes according to Ambraseys and Douglas [2004]. Ellipses sizes are scaled with the earthquakes magnitudes, and might not represent reliably the area ruptured during these earthquakes. Active faults (in red) map from Styron et al. [2011].

Left figure: Mapview of the midcrustal microseismicity from 1996 to 2010 superposed to the map of the shear stress accumulation rate on the MHT, deduced from the coupling pattern. The thick red line represents the 3500m elevation contour line above which the
seismicity seems to drop, and the 2 thin pink lines are the 3000m and 2500m elevation contour lines.

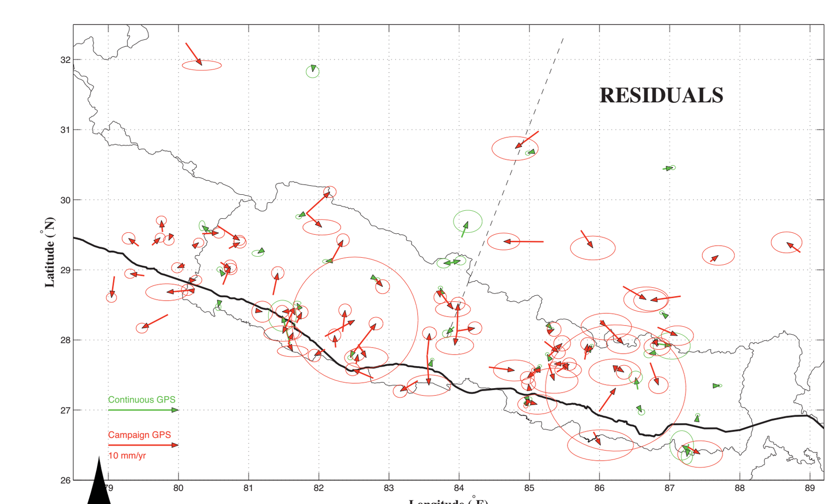
Right figure: Comparison of the coupling, temperature and seismicity rate along the dip direction. The red line with error bars corresponds to the coupling underneath the leveling line, where the resolution is the best. The shaded pink curve in the background is a stack of the coupling on the whole fault, the dark pink shaded area representing the 1-σ scatter of coupling, and the light pink shaded area showing the whole scatter of coupling with respect to the distance to the MFT. The blue histogram shows the seismicity rate, normalized to a maximum value of 1. The green curve shows the temperature variation along a MHT dipping 10°, determined by Herman et al. [2010], corresponding to the duplex formation model. The thin dashed green line indicates the critical temperature of 350°C, above which frictional sliding is generally thought to be dominantly rate-strengthening, promoting
stable sliding, according to lab experiments on quartzo-feldspathic rocks [Blanpied et al., 1995; Marone, 1998].

Interseismic coupling on the MHT



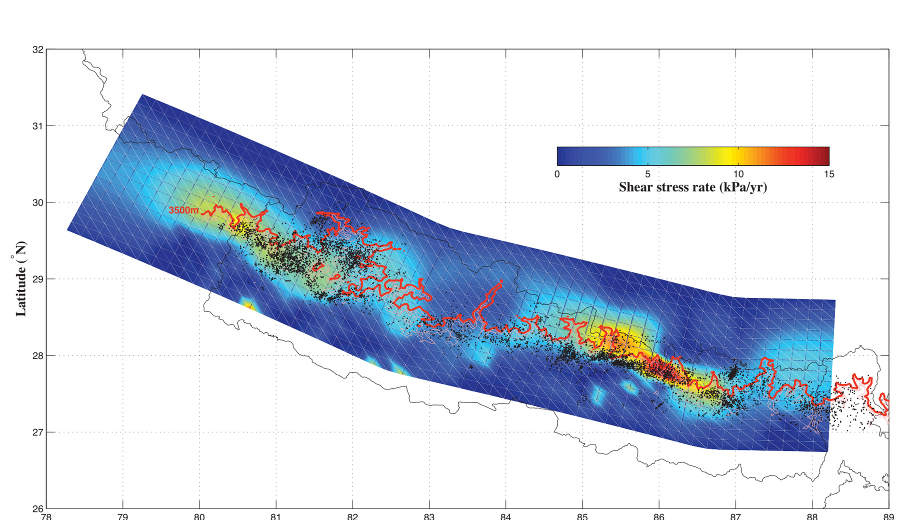


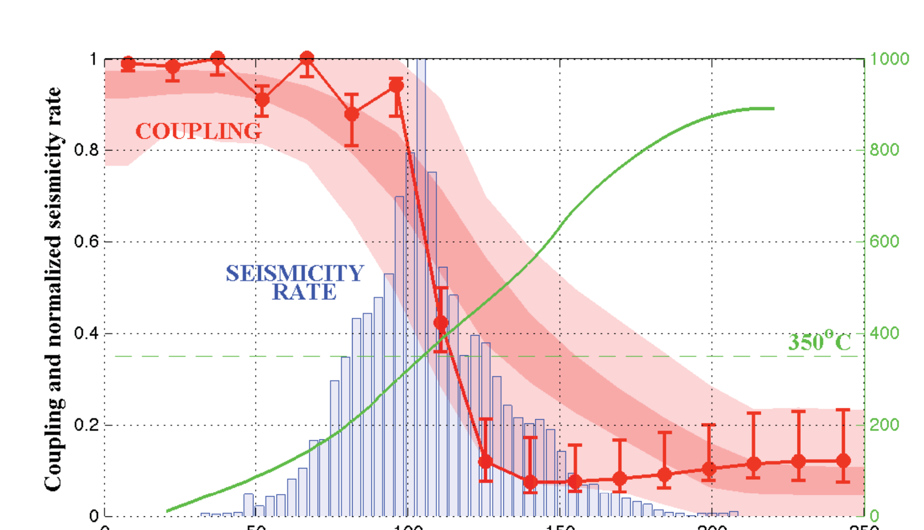
Fit to the continuous GPS vertical velocities (map) and to the spirit leveling data (inset). White dots show location of the leveling line. The inset shows the fit to leveling data.

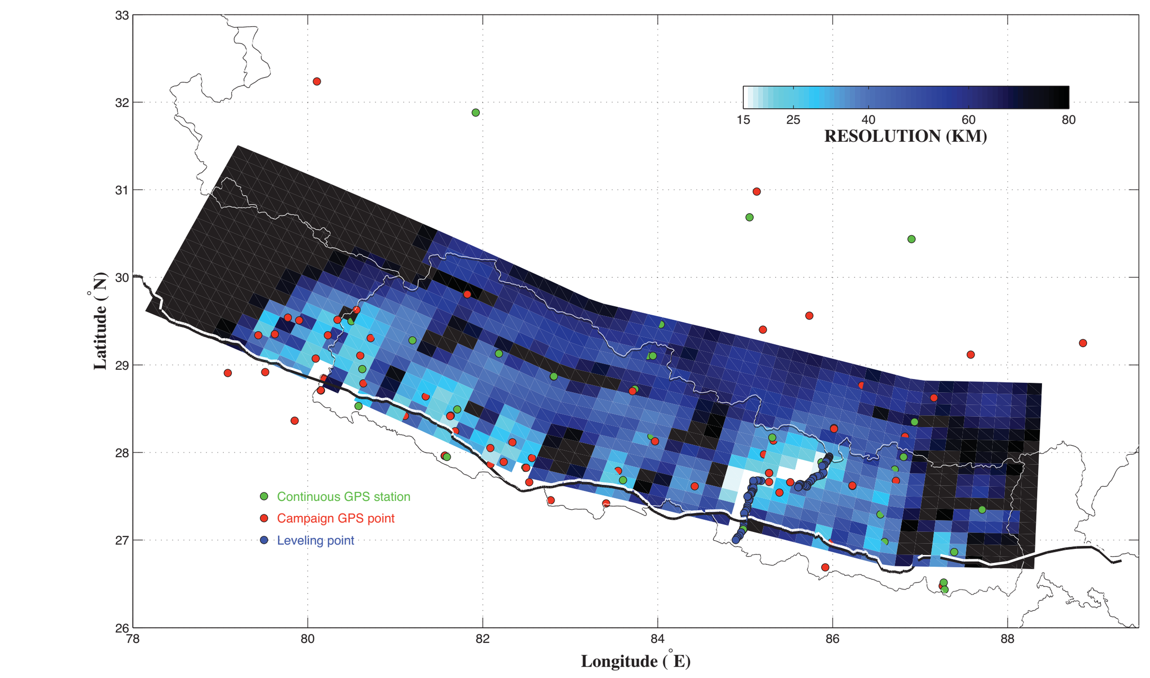


Residuals of the fit to the geodetic data. The GPS residuals with corresponding 1-σ error bars are plotted as red arrows for the campaign measurements and as green arrows for continuous GPS. The dashed line represents the position of the Thakkola graben. The residuals show no systematic misfit, indicating that no significant signal has been left out by the model.

UPPER PLOT: Comparison between observed and predicted horizontal velocities. Interseismic coupling is shown as shades of red on the fault. The GPS data with corresponding error bars are plotted respectively as green and red arrows for the continuous and campaign GPS measurements. Blue arrows show predicted velocities according to the plotted pattern of interseismic coupling. Dashed line indicates position of the Thakkola graben, on each side of which the secular velocity can be different. Red arrows represent the long term convergence rate across the Himalaya on each side of the graben. Black dashed lines represent contour lines of fault depth (in km). Grey masked patches are the patches with bad resolution.

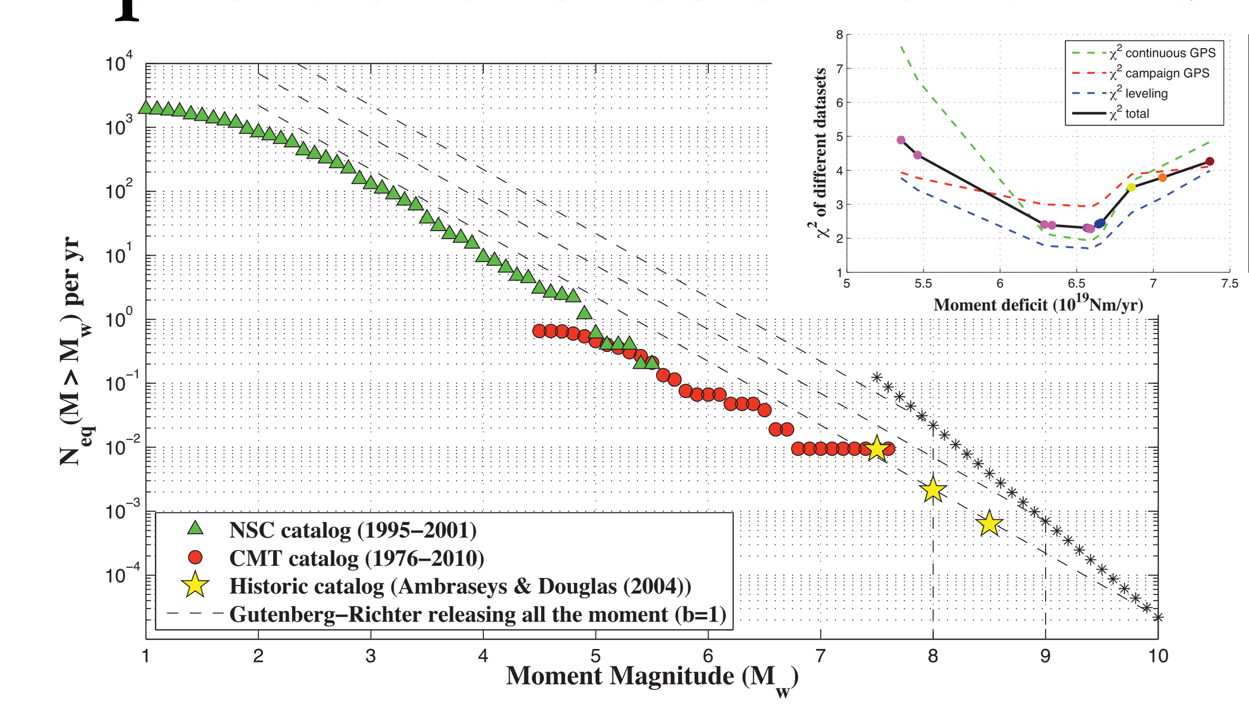






Resolution on each of the patches of the fault, given in km. This resolution size measures the distance over which the slip on a patch is affected by the slip on its neighboring patches. Locations of the data points used to compute the resolution are indicated in the figure and legend.

Implications for seismic hazard



Inset: Impact of the weights applied to the Laplacian. The plots shows the value of the reduced χ^2 of the fit as well as the moment deficit accumulation rate for each inversion. The best fitting model has a moment deficit rate of 6.6±0.4x10^{19} Nm/yr.
Lower plot: Gutenberg-Richter plot of the seismicity in Nepal, using the different catalogs available: The NSC catalog (1995-2001), the CMT catalog (1976-2010) and an historic catalog compiled using the catalog from Ambraseys and Douglas [2004]. We used the last 500 years of the historic catalog for M_W > 8 and M_W > 8.5 earthquakes, and the last 200 years for M_W > 7.5 earthquakes. The dotted lines are the distribution that the seismicity should follow if 100% of the moment deficit was released seismically following a Gutenberg-Richter distribution with b = 1, up to a given maximum magnitude of 8, 9 and 10. The asterisk line shows, for a given maximum possible magnitude for Himalayan earthquakes, the return period of such earthquakes.

Conclusion

The MHT appears to be nearly fully locked from the surface to beneath the front of the high Himalaya, over a width of about 100km. Interseismic coupling decreases abruptly, within a transition zone probably narrower than 30km. This transition occurs a depth of about 15-20 km, where the temperature on the MHT is estimated to reach 350°C. This might reflect that stable aseismic sliding is promoted where the temperature exceeds 350°C as inferred from laboratory experiments and observations in other continental contexts. This favors the scenario of a primary control by temperature of the locked-creeping transition. The microseismicity on the MHT seems to cluster where the shear stress accumulation is the greatest, and drops under topography greater than 3500m of elevation, i.e. where the principal Coulomb stresses become vertical. The apparent segmentation of the microseismicity then comes off as a result of the competition between the relative positions of the 3500m contour line and of the locked-creeping transition, where the stress rate is the greatest. The lack of any apparent lateral variation of coupling is an interesting result, since it differs from observations at subduction zones, whose patterns of coupling exhibit noticeable segmentations. This might point to a fundamental difference between intracontinental and subduction megathrust. In any case, the rate of accumulation of moment deficit on the MHT within Nepal is large, and comparison with the historical seismicity suggests that infrequent (with return period larger than 1000yr) events with magnitude larger than the M_W8 value assigned to the largest known earthquakes of 1934 and 1505 should be taken into consideration, as inference based on paleoseismological investigations have also suggested. However, one should keep in mind that those seismic hazard assessment rely on a few hypothesis (no significant release of moment by afterslip or slow slip events) that could alter our conclusions if proven inexact.