GEOPHYSICAL RESEARCH LETTERS, VOL. 23, NO. 22, PAGES 3107-3110, NOVEMBER 1, 1996

Global positioning system measurements of Indian plate motion and convergence across the Lesser Himalaya

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Abstract. We use Global Positioning System (GPS) measurements acquired from 1991 to 1995 to constrain the motion of sites in Bangalore, in southern India, and Kathmandu, Nepal, relative to a global GPS network. These measurements permit estimates of the northward motion of the Indian plate and convergence between the southern Himalaya and the Indian subcontinent. The velocities of Bangalore and Kathmandu in the ITRF92 reference frame agrees with that predicted by the NNR-NUVEL1A plate motion model for Indian plate motion, and differ from that predicted for the Australian plate, confirming the independent motion of the Indian and Australian plate fragments. No significant motion was detected between Bangalore and Kathmandu during the three years from 1991-1994, even though Kathmandu is located in the hanging wall of the active Himalayan thrust system. The Himalayan thrust system is thought to accommodate 18 ± 7 mm/yr of convergence and has been the source of several historic M ~ 8 earthquakes. The absence of motion of Kathmandu relative to the Indian plate can be explained if the thrust system is presently locked south of the Greater Himalaya. Our preferred model has no steady slip on the detachment south of the Greater Himalaya, and steady slip at a rate greater than 6 mm/yr (1/3 of the long-term convergence rate) can be ruled out at 95% confidence level.

Introduction

Space geodesy can measure global tectonic motions directly, with a precision approaching that of models averaged over the last few million years (the NUVEL1 and NUVEL1A plate motion models of DeMets et al. [1990] and DeMets et al. [1994a]). Space geodetic measurements of global plate motions have shown excellent agreement with the geologic estimates for those plates which have been adequately sampled by geodetic data, and relative motions of sites within the stable plate interiors are small [Gordon and Stein, 1992; Smith et al., 1990; Larson and Freymueller, 1995; Argus and Heflin, 1995].

The instantaneous motion of the Indian plate is poorly constrained due to a paucity of data. New data have recently improved knowledge of the location of the (diffuse) India-Australia plate boundary, and the relative motion between the plates [DeMets et al., 1994b]. These data show India rotating clockwise relative to the Australian plate about a pole located within the plate boundary zone just east of the Chagos-Laccadive Ridge. Excepting a partial remeasurement of the 1913 Indo-Russian survey link in Pakistan [Mason, 1914; Chen et. al., 1984], and 1991-1992 GPS measurements in Nepal [Jackson and Bilham, 1994a], which both suggest convergence rates less than 2 ± 2 cm/year, there are no prior geodetic measurements on the Indian plate or across the Himalaya.

GPS measurements spanning four years have been used to determine the relative velocities of sites in Bangalore in southern India, and Kathmandu in Nepal, providing the first direct measurement of Indian plate motion and convergence across the Lesser Himalaya. Figure 1 shows our estimated velocities for the two sites in the ITRF92 reference frame together with the NNR-NUVEL1A model (henceforth NNR-A) predictions [Argus and Gordon, 1991; DeMets et al., 1994a].

Data Analysis and Results

Initial GPS measurements were first undertaken near Kathmandu, Nepal and Bangalore, southern India, during the GIG '91 campaign of January-February 1991 [Melbourne et al., 1993]. The two sites belong to different regional GPS networks [Jackson and Bilham, 1994a; Paul et al., 1995], and their simultaneous measurement in 1991 was a fortuitous benefit of the GIG '91 global densification effort. Kathmandu (Nagarkot Geodetic Observatory) was reoccupied in October 1992 and April 1994. Bangalore was reoccupied in April and July 1994, and has been in continuous operation since September 1994. We include Bangalore in weekly solutions from September 1994 until March 1995. The 1991 Ban-

Paper number 96GL02518.
0094-8534/96/96GL-02518$05.00

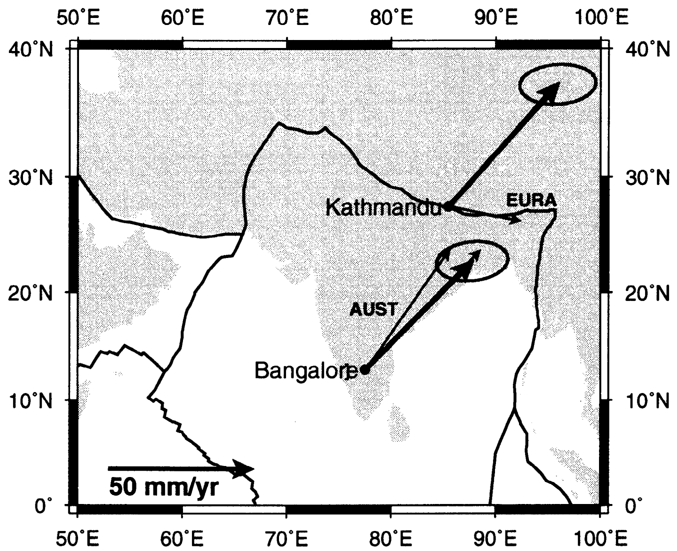

Figure 1. Measured site velocities between 1991 and 1995 and their 95% confidence ellipses in the ITRF-92 reference frame. The GPS results are compared to the NNR-NUVEL-1A (NNR-A) [DeMets et al., 1994a; Argus and Gordon, 1991] plate-motion model (thin arrows without ellipses). For Bangalore, the predictions for the Indian and Australian plates are shown; the Indian plate result is very close to the observed velocity. For Kathmandu, the predictions for the Indian and Eurasian plates are shown; the Indian plate prediction is obscured by the data vector. Filled circles show M > 5 earthquake locations from 1980-1990.

galore site was located approximately 6 km from the present site on the campus of the Indian Institute of Science. A survey between the two Bangalore observation sites was completed in July 1994.

All data were analyzed using the GIPSY/OASIS II software. For each day of data we analyzed a globally distributed set of sites from the IGS network, and included data from Bangalore and Kathmandu when available. We estimated corrections to the GPS orbits in the ITRF92 reference frame. Our standard analysis procedures are described in more detail in Larson and Freymueller [1995]. In addition to analyzing all days when data were taken at Kathmandu and Bangalore, we include one solution per week for the global network spanning the time period from February 1992 until March 1995. We have estimated velocities for Bangalore, Kathmandu, and 15 other sites on the Australian, Pacific, Antarctic, African and South American plates (Table 1, Figure 2) based on the solutions described above. Results for the sites in common agree with the earlier published results of Larson and Freymueller [1995], which was based on a smaller data set.

We find the velocities of both Bangalore and Kathmandu in the ITRF92 reference frame to be consistent with NNR-A model predictions for the Indian plate, and not the Australian plate. The NNR-A Australian plate model prediction for Bangalore differs from the observed velocity by 9.8 mm/yr, while the Indian plate model prediction differs by only 3.6 mm/yr (Table 1, Figure 1). The NNR-A Australian plate model prediction lies on the boundary of the 95% confidence region of the observed velocity. The velocity of Kathmandu differs from that predicted for the Indian plate by only 1 mm/yr, but by 24 mm/yr (about 5σ) from that predicted for the Australian plate. Our results for sites on the Australian plate also agree with the NNR-A predictions: the weighted rms difference between our results for 4 sites on the Australian plate and the NNR-A predictions is 4.3 mm/yr. Similar agreement with NNR-A is obtained for 2 sites on the African plate and 2 sites on the stable South American plate. Based on this result we are confident that we can compare our results directly to the NNR-A model, and reject the hypothesis that Bangalore and Kathmandu move at Australian plate velocity at a high confidence level.

Our results show no significant motion between Kathmandu and Bangalore between 1991 and 1994. Kathmandu is not moving significantly relative to the Indian plate, even though it lies on the hanging wall of the Himalayan thrust system. During the period 1991-1995, and probably during the interseismic period in general, the convergence rate between Kathmandu and the Indian plate is smaller than a few mm/yr. The uncertainty in our velocity estimate for Kathmandu is about 5 mm/yr.

Discussion

To explain the GPS observations and historical leveling data [Jackson and Bilham, 1994b], we employ a simple model with the shallow portion of a fault locked during the interseismic period, while the deeper portion of the fault undergoes steady slip at the long-term slip rate as the rock at depth cannot sustain high shear stresses (e.g., Savage, 1983). The shallow portion of the fault then slips only during earthquakes. We compute displacements from a dislocation model in an elastic half space [Okada, 1987]. Figure 2 shows the data and our preferred model projected onto a profile striking N10°E, normal to the strike of the range. The fault geometry is constrained based on geologic and seismologic observations [Baranowski et al., 1984; Ni and Barazangi, 1984; Zhao et al., 1993; Jackson and Bilham, 1994b; Pandey et al. 1995]. We assume a shallowly dipping detachment, with a steeper ramp beneath the Greater Himalaya.

Figure 2 also shows uplift rates along the model profile from leveling data of the Nepalese Topographic Survey [Jackson and Bilham, 1994b], and the velocity of Kathmandu relative to the Indian plate and its 1 sigma uncertainty (-1 ± 5 mm/yr, negative ve-

Table 1. Site velocities determined in this study

Site	*Plate*	*Lat*	*Long*	*East*	*North*
Bangalore	INDI	12.95	77.51	38. ± 5 (40)	38. ± 3 (41)
Kathmandu	INDI	27.53	85.52	38. ± 5 (37)	42. ± 3 (42)
McMurdo	ANTA	-77.77	166.67	11. ± 3 (7)	-13. ± 2 (-12)
Yaragadee	AUST	-28.89	115.35	35. ± 2 (39)	59. ± 1 (59)
Canberra	AUST	-35.22	148.98	20. ± 1 (18)	54. ± 1 (54)
Hobart	AUST	-42.61	147.44	19. ± 4 (13)	51. ± 2 (54)
Townsville	AUST	-19.14	146.81	35. ± 4 (30)	57. ± 2 (55)
Kokee	PCFC	21.99	200.34	-61. ± 2 (-58)	36. ± 1 (32)
Pamatai	PCFC	-17.46	210.43	-85. ± 5 (-63)	32. ± 2 (32)
Fortaleza	SOAM	-3.85	321.57	-12. ± 4 (-6)	10. ± 2 (12)
Kourou	SOAM	5.22	307.19	-7. ± 3 (-6)	9. ± 1 (11)
Mas Palomas	AFRC	27.61	344.37	14. ± 3 (17)	15. ± 1 (17)
Hartebeesthoek	AFRC	-25.74	27.71	16. ± 3 (21)	16. ± 2 (20)
Wellington	AUST	-41.09	174.78	-13. ± 2 (-1)	34. ± 1 (37)
Santiago	SOAM	-32.98	289.33	10. ± 3 (-1)	13. ± 2 (9)

Site velocities are given in mm/yr. NNR-NUVEL1A model predictions are given in parenthesis for each velocity component. East and North refer to the local east and north directions at each site. The weighted rms difference (vector magnitude) between our results and NNR-A for four sites on the stable Australian plate is 4.3 mm/yr, and similar differences are found for other plates. Results for Bangalore and Kathmandu are consistent with both sites moving at stable Indian plate velocity.

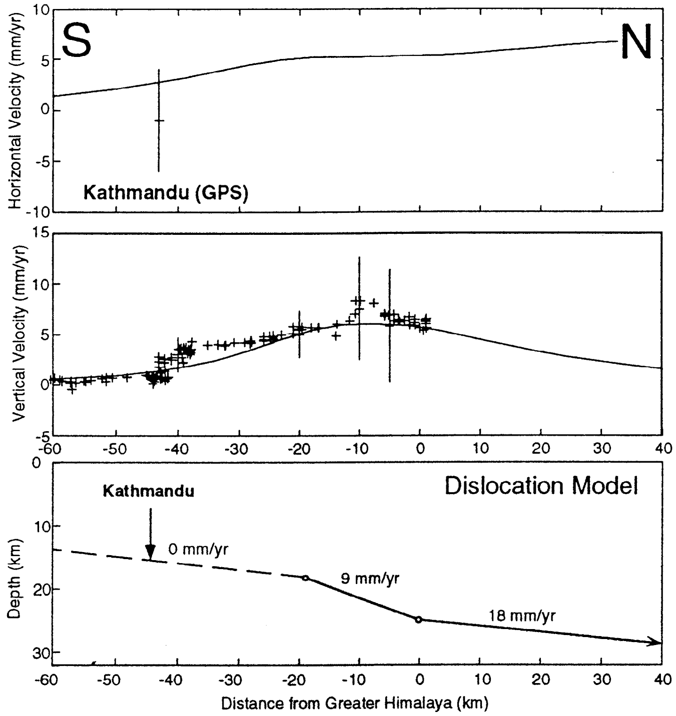

Figure 2. Vertical and horizontal (N-S) displacement rates computed from an elastic dislocation model [Okada, 1987] of interseismic deformation across the Himalaya range front. Zero on the horizontal axis refers to the location of the Greater Himalaya. Steady slip north of the Greater Himalaya at the rate of the long-term convergence rate (18 mm/yr) and a locked detachment below central and southern Nepal is compatible with leveling [Jackson and Bilham, 1994b] and GPS results. Error bars are shown for representative leveling points.

locity indicates divergence). In our preferred model, the main Himalayan thrust system is locked south of the Greater Himalaya. Slip at depth below Tibet occurs at 18 mm/yr, based on the estimated long term convergence rate of 18 ± 7 mm/yr [Molnar, 1990]. The GPS data are not sensitive to the amount of slip occurring on the steeper ramp, although 9-18 mm/yr slip is required to fit the uplift observed in the leveling data [Jackson and Bilham, 1994b]. Slip on the shallow detachment would produce southward motion of Kathmandu relative to the Indian plate, contrary to observation. In our preferred model, a slip deficit equal to the total long-term convergence rate is accumulating on the detachment.

How much slip can there be on the detachment? This is a critical issue because any steady slip on the detachment reduces the rate at which a (seismogenic) slip deficit accumulates. Based on modeling of the leveling observations, Jackson and Bilham [1994b] suggested that 5 mm/yr of aseismic slip occurs on the detachment south of the Greater Himalaya. Given their model fault geometry, this slip was required to explain localized uplift in southern Nepal (a broad, gentle area of uplift from the Mahabharat Range to just south of the Siwaliks). If we were to adopt this 5 mm/yr slip rate on the detachment, it would predict about 8 mm/yr of convergence relative to India at Kathmandu rather than 3 mm/yr as in our preferred model. Slip on the detachment at a rate of 5 mm/yr is not consistent with our data for Kathmandu at the 68% confidence level (1σ), although we cannot rule out that much slip at the 95% confidence level. Slip on the detachment greater than 6 mm/yr (1/3 of the long-term convergence rate) would predict a velocity of Kathmandu relative to the Indian plate which would be outside of the 95% confidence region.

No locked zone, and no slip deficit, would be required by the data if the long-term convergence rate across the Himalaya were very low (< 8 mm/yr). If we assume that the entire detachment slips steadily at the long-term convergence rate, a long-term rate greater than 8 mm/yr would predict motion of Kathmandu which exceeds the 95% confidence limit of the observations. Such a low long-term convergence rate across the Himalaya is very unlikely. Previous studies estimate the long-term convergence rate to be 10-25 mm/yr across the Himalaya [Molnar and Deng, 1984; Lyon-Caen and Molnar, 1985], with a best estimate of 18 mm/yr [Molnar, 1987; Molnar, 1990] based on several lines of evidence: seismic moment release rate for major thrust events this century along the Himalayan arc [Molnar and Deng, 1984], changes in the age of basal sediments in the Ganga basin over the last 10-20 Ma [Lyon-Caen and Molnar, 1985], and inversion of uplift rate profiles [Molnar, 1987]. Our preferred model is compatible with a slip rate up to 25 mm/yr. To better constrain the slip rate we will need additional data from northern Nepal and southern Tibet.

Conclusions

We find the velocities of Bangalore (India) and Kathmandu (Nepal) to be consistent with the hypothesis that the Indian plate moves independently of the Australian plate. Our results agree with NNR-NUVEL1A model predictions for the Indian plate (to within one sigma) for both components at both sites, confirming for the first time through geodetic measurements the amplitude and direction of the India-Eurasia convergence vector which must be partitioned on active structures between India and the stable Eurasia interior [Molnar and Tapponnier, 1975].

The absence of significant motion of Kathmandu relative to the Indian plate confirms earlier studies of leveling data which suggest that the Himalayan thrust system is locked south of the Greater Himalaya, and undergoes very little or no slip between earthquakes. We cannot rule out a small amount of slip on the detachment. Unless the assumed long-term convergence rate across the Himalaya are grossly in error, the detachment must be locked or slipping at less than 6 mm/yr south of the Greater Himalaya at the longitude of Kathmandu. The downdip width of the locked zone probably extends at least from the Greater Himalaya to the Himalayan frontal thrusts, a distance exceeding 100 km.

Great earthquakes have ruptured approximately 50% of the Himalayan front in the past 100 years although the precise limits of rupture are poorly known [Seeber and Armbruster, 1981; Molnar, 1990]. It is plausible that most or all of the locked zone near Kathmandu could rupture in a single great earthquake. Significant earthquakes occurred in 1833 and 1934 close to or beneath Kathmandu [Bilham, 1995] and although the rupture boundaries of these events are not known, at least the 1934 event probably ruptured from the greater Himalaya to at least the northern edge of the Ganga Plain. Our results confirm conclusions derived from leveling data that the rupture zone is presently locked, and that minor deformation beneath and south of the Lesser Himalaya is insufficient to release more than 1/3 of the convergence rate, and possibly much less [Bilham et al. 1995]. Future great earthquakes thus appear inevitable.

Acknowledgements. We thank Ashtech Inc. for the loan of a receiver to the project in 1991 during the GIG '91 campaign, and M. Jackson and the Survey of Nepal for establishing the Nagarkot monument and operating the receiver there. We thank Prof. Reigber (GeoForschungsZentrum) for undertaking the initial measurements in Bangalore, and Dr. K. S. Yanik, Head of C-MMACS, for his enthusiastic and continued support of GPS and tectonic research activities in Bangalore. The measurement of the Nagarkot and Bangalore sites were funded by NSF grants EAR 87-21163, 93-06190, and 95-06677. Work on this project by JF and publication costs were funded by NSF grant EAR 95-21922. Reviews by J. P. Avouac and two anonymous reviewers helped improve this paper.

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(Received: October 23, 1995; revised: March 5, 1996; accepted May 12, 1996.)