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An analysis of GPS-derived velocities in the Bengal basin and the neighbouring active deformation zones

Mallika Mullick* and Dhruba Mukhopadhyay

Raman Centre for Applied and Interdisciplinary Sciences,
16A, Jheel Road, Kolkata 700 075, India

The Bengal basin, the largest fluvio-deltaic sedimentary system in the world, located in an area covering Bangladesh and three eastern states of India (West Bengal, Assam and Bihar) has been formed by sediments brought by the Ganga, Brahmaputra and Meghna rivers. This complex foreland basin originally emerged on a trailing margin of the Indian continental crust and was later complicated by convergence with Eurasia to the north and oblique convergence with Burma to the east. Apart from these tectonic events, another major source of crustal deformation in the vicinity of the Bengal basin was the formation of the Ninety East Ridge (NER) in the Indian Ocean. The Bengal basin, which is in the near vicinity of these three active boundaries, needs to be studied thoroughly for assessing seismic hazard in this region. A brief discussion of the tectonics of the neighbouring active zones is given here. The GPS-derived velocities of stations located in these zones and that at Kolkata, located in the Bengal basin show that the Kolkata–Coco Island baseline crossing the NER shortens at 18.5 ± 1.3 mm/yr, whereas the baseline between Kolkata and Aizawl, Mizoram shortens at 10.5 ± 1.5 mm/yr. The Kolkata–Siliguri baseline shortens at 8.1 ± 1.5 mm/yr and the Kolkata–Baradighi baseline shortens at 5.2 ± 1.4 mm/yr. The difference in shortening rates of these two stations located in the North Bengal foothill Himalayan zone relative to Kolkata is due to the presence of a highly active transverse zone lying between them.

Keywords: Baseline shortening, crustal deformation, GPS-derived velocity, seismic hazard.

ACCORDING to Mukhopadhyay and Krishna[1], the Ninety East Ridge (NER), which extends from 30°S northward into the Bay of Bengal, is buried beneath the Bengal Fan sediments. According to Curray *et al*.[2], NER is an aseismic ridge representing a hotspot trace. But according to Weins *et al*.[3], NER is a broad seismic zone considerably more active than the interior of any other oceanic plate. Seismic and gravity data and a study of earthquake focal mechanism suggest that NER is probably at the initial stages of subduction under the Andaman arc coupled with partial left lateral strike–slip motion along the ridge on its northern segment[4]. Wiens *et al*.[5] have proposed a diffused plate boundary (DPB), a zone of concentrated seismicity,

*For correspondence. (e-mail: mallika_xav@yahoo.co.in)

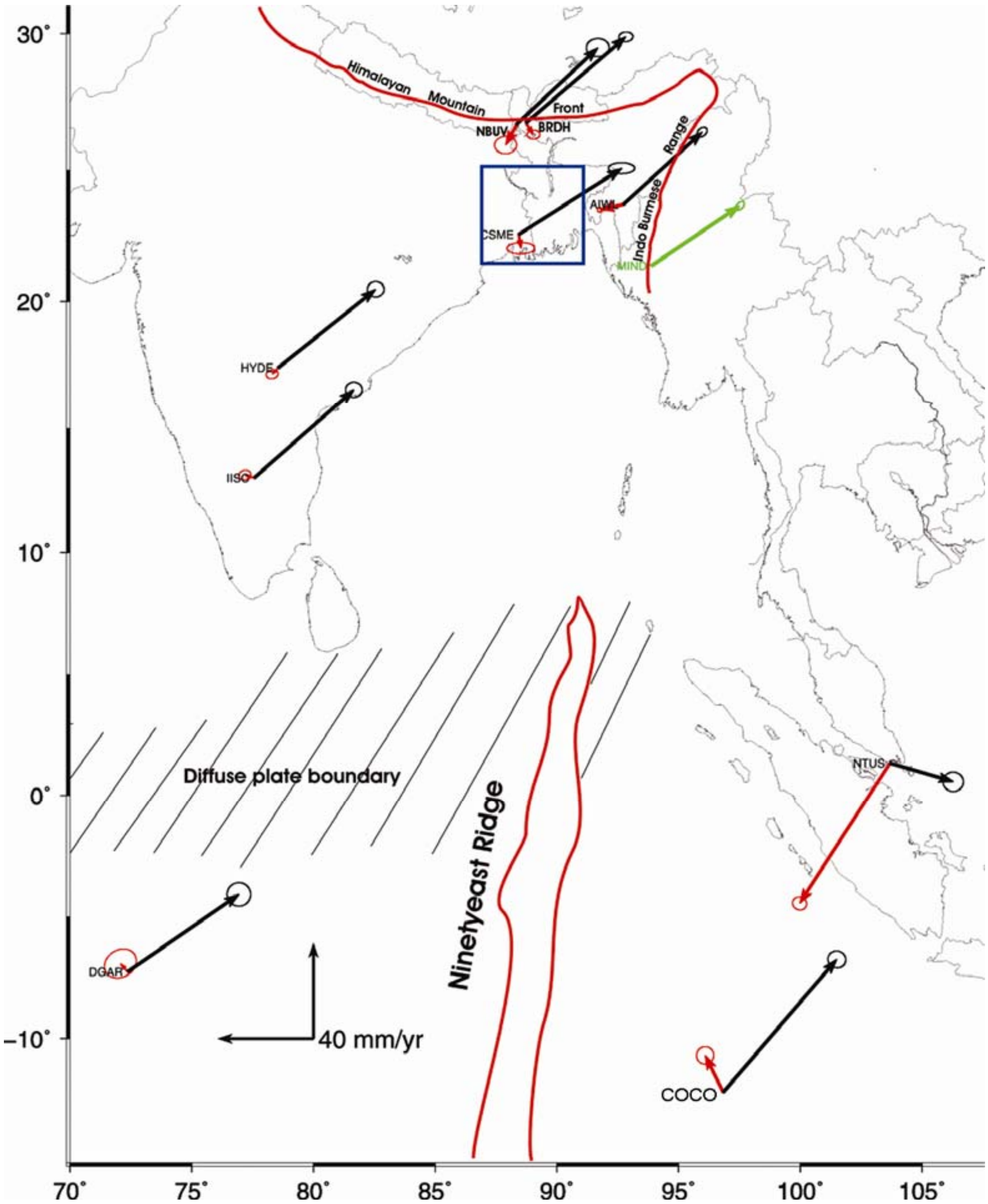

Figure 1. Outline map showing GPS-derived velocities of stations around the Indian Ocean in ITRF05 reference frame (black) and in India fixed reference frame (red). Velocity of station MIND is in ITRF05 reference frame. The Bengal basin is roughly shown in the blue box and the neighbouring active zones are marked in red; the shaded region marks the diffuse plate boundary proposed by Wiens *et al*.[5].

in the Indian Ocean at about 0° latitude running E–W normal to NER, separating the India–Arabia combined plate and the Australian plate.

The India–Eurasia collision resulted in a complicated kinematics of underthrusting of the Indian plate below Eurasia and subsequent rising of the Himalayas[6] (Figure 1), and the process is continuing till today. Nakata[7] reported the presence of a few active faults in the Quaternary Piedmont zone in the Eastern Himalayan foothills of North Bengal. From GPS-derived velocities, we[8] have confirmed the existence of an active transverse structure along the Gish river valley in the same region, referred to as the Gish transverse zone by Mukul and Matin[9], oriented at a high angle to the trend of the Himalayan belt.

The Indian plate has been subducting eastward below the Burma microplate since Cretaceous, leading to the emergence of the Indo-Burmese ranges (Figure 1). This active subduction zone has generated giant tsunamigenic earthquakes in the past. Cummins[10] suggests that the seismogenic zone extends beneath the Bengal Fan. From deep penetration seismic reflection surveys conducted by Maurin and Rangin[11], it has been found that between lat. 18°N and 19°N, the northern tip of NER collides with the Indo-Burmese arc.

Table 1. Location of GPS stations and their velocities in ITRF05 reference frame and relative to India-fixed reference frame

Station code	Station	Longitude (°E)	Latitude (°N)	Velocity in ITRF05 frame (mm/yr)				Velocity relative to India fixed reference frame (mm/yr)			
				V_E	V_N	σ_E	σ_N	V_E	V_N	σ_E	σ_N
Stations of our network discussed in this communication											
BRDH	Baradighi	88.73	26.75	41.6	35.9	1.4	0.8	–3.0	–4.7	1.0	0.7
NBUV	N.B. University	88.35	26.71	33.8	31.9	1.6	1.5	–4.6	–8.6	1.9	1.6
CSME	Kolkata	88.43	22.59	43.0	27.5	1.9	0.8	–5.8	–8.5	2.0	0.8
Stations from Jade *et al.*[12] and Vigny *et al.*[13]											
AIWL	Aizawl	92.73	23.72	32.9	30.2	0.8	0.8	–9.1	–11.9	0.8	0.7
MIND	Myanmar	93.89	21.38	36.9	25.0	0.7	0.7	Not available			
Few IGS stations near Bengal basin included in our analysis											
IISC	Bangalore	77.57	13.02	41.5	36.7	1.3	0.7	1.3	–0.7	1.5	0.9
HYDE	Hyderabad	78.55	17.42	40.7	32.7	1.4	1.2	–1.9	–4.2	1.4	1.3
COCO	Coco Island	96.83	–12.19	47.4	55.5	1.5	1.4	–6.02	12.9	1.5	1.4
NTUS	Singapore	103.68	1.35	26.4	–7.7	1.6	1.6	–25.6	–51.3	1.6	1.5
DGAR	Diego Garcia	72.37	–7.27	46.4	32.3	1.5	1.5	–8.9	–1.7	1.9	1.9

Within the Bengal basin itself, there are records of earthquakes in 1885, 1918, 1923 and 1930. In the recent past, shallow depth earthquakes occurred in this part, one of magnitude 4.0 on 13 December 2005, at 22.31°N, 87.64°E, and another of magnitude 4.9 on 6 February 2008, at 23.47°N, 87.12°E. These earthquakes indicate neo-tectonic activity along some underlying seismogenic source in the western part of the Bengal basin.

In the present communication, a study has been made of the baseline shortening rates between GPS stations located at the above-mentioned active deformation zones and at Kolkata, using GPS-derived velocities. Lack of other GPS stations inside the basin itself prohibits us from deriving any conclusion about the deformation within the basin across the fault systems present there, but the velocities of these stations relative to that of Kolkata give an idea about the movement of the entire basin relative to the surrounding active zones.

The GPS stations whose velocities have been discussed here belong to three categories: (i) Stations of our own network in North Bengal and one in Kolkata; (ii) International GNSS Service (IGS) stations located in the eastern part of Asia, and (iii) station AIWL in Mizoram reported by Jade *et al.*[12] and station MIND in Myanmar reported by Vigny *et al.*[13]. GPS data have been collected from stations in North Bengal in campaign mode using Trimble 5700 GPS receiver and Zephyr geodetic antenna set during the period of December 2005–April 2009 in four campaigns at an interval of 12–14 months. At each station the instrument was installed continuously for 5–6 days and kept well-guarded to avoid any local disturbance. The GPS station CSME was run permanently from January 2006 to December 2008 within the premises of the Centre for Study of Man and Environment at Kolkata. The data have been processed using GAMIT/GLOBK suite of software[14,15]. Data from stations of our network, along with those from IGS stations with codes IISC, POL2, KIT3, KUNM, HYDE, ULAB, URUM, PIMO, GUAO, NTUS, and data about IGS orbits and orbital initial conditions for all satellites are given as input to GAMIT. The primary output of GAMIT is passed onto GLOBK, a Kalman filter[15], where the local solution is combined with global solutions from IGS stations to estimate station positions, velocities, orbital and earth-rotation parameters in a well-defined reference frame. In GLOBK, the reference frame is defined using generalized (internal) constraints, minimizing the adjustments of coordinates and velocities with respect to a selected set of stations, while estimating translation and rotation parameters. All the station velocities in ITRF05 and India fixed reference frame are shown in Table 1 and plotted in Figure 1.

The present-day left-lateral strike–slip movement on NER is indicated by the fact that the east components of the velocities of the two IGS stations, COCO and DGAR, on either side of NER estimated in ITRF05 reference frame hardly vary, whereas their north components vary by ~23 mm/yr. The baseline connecting COCO and station CSME located in Kolkata is shortening at a rate of 18.5 ± 1.3 mm/yr. But this baseline crosses the DPB discussed earlier. Hence what part of 18.5 mm/yr is consumed in subduction across DPB and what part in the strike–slip movement along NER cannot be confirmed from these results. Though the CSME–COCO baseline is huge, such active motion would pose seismic hazard on the Bengal coast if the ridge extends northward under the Bengal Fan.

The velocities of stations CSME in ITRF05 reference frame and in India fixed reference frame are 51.0 ± 2.5 and 4.7 ± 1.9 mm/yr respectively. These estimates indicate that there is very small convergence between Kolkata and the stable part of the Indian shield. Our GPS network of eight stations in North Bengal has identified the Gish transverse zone (GTZ) along the Gish river to be an active oblique-slip extensional fault[8]. The station velocities in North Bengal have also established that greater part of the convergence across the Himalayas in this area is taking place in the frontal zone rather than in the Higher Himalayas[8]. Here we discuss only the southernmost stations in this network nearest to the Bengal basin, NBUV (Siliguri) and BRDH (Baradighi), located to the west and east of GTZ respectively. These baselines which are about 550 km in length show different shortening rates relative to CSME. CSME–NBUV baseline shortens at a rate of 8.1 ± 1.5 mm/yr, whereas CSME–BRDH baseline shortens at 5.2 ± 1.4 mm/yr. The difference in shortening is indicative of sinistral sense of motion on GTZ. E–W extension across this fault has already been established on the basis of GPS data[8]. The currently active GTZ and the fast rate of convergence between frontal and Higher Himalayas might trigger earthquakes capable of sending tremors to the Bengal basin.

The eastern border of the Bengal basin in Bangladesh is demarcated by the Indo-Burmese arc, and the north-eastern border of the Bengal basin is marked by the Shillong massif. The faults present in the Shillong massif have caused damaging earthquakes in the Bengal basin in Bangladesh. As reported by Sahu *et al*.[16], the Indian plate moves at about 36 mm/yr along 13°N relative to the Burmese plate, and the motion across the Indo-Burmese arc is mainly strike–slip, probably with a small component of subduction. The GPS station AIWL in Aizawl shows a velocity of 44.7 ± 0.8 mm/yr in ITRF05 reference frame, obtained by translation and rotation of the ITRF00 frame[12]. The velocity of GPS station MIND in Myanmar is 44.6 ± 0.7 mm/yr in ITRF05 reference frame derived from the ITRF00 frame[13]. The velocity estimates of the two stations located on either side of Indo-Burmese arc (Figure 1) do not show any major E–W subduction. The AIWL–CSME baseline which spans the Bengal basin in the E–W direction has a shortening rate of 10.5 ± 1.5 mm/yr. The rate is not alarming but can cause intraplate earthquakes of small magnitude in the basin.

From the discussion of GPS-derived velocities made above, the Bengal basin does seem to be threatened by activity along NER and across DPB taken together. Activity along GTZ in North Bengal has high possibility of causing major earthquakes in that area, whose vibrations may be felt in the Bengal basin. The preliminary GPS data underscore the necessity of setting up GPS stations in the Bengal basin for monitoring the faults in the basin and also to estimate the shortening rates of different parts of the basin relative to the neighbouring active zones.

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