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Notes

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Vineet K Gahalaut[1]*, Bhaskar Kundu[1], Sunil Singh Laishram[2], Joshi Catherine[1], Arun Kumar[2], M. Devchandra Singh[2], R.P. Tiwari[3], R.K. Chadha[1], S.K. Samanta[4], A. Ambikapathy[1], P. Mahesh[1], Amit Bansal[1], and M. Narsaiah[1]
[1]CSIR-National Geophysical Research Institute, Uppal Road, Hyderabad 500606, Andhra Pradesh, India
[2]Department of Earth Sciences, Manipur University, Canchipur, Imphal 795003, India
[3]Department of Geology, Mizoram University, Aizwal, Mizoram 796009, India
[4]Department of Geological Sciences, Jadavpur University, 188 Raja S.C. Mullik Road, Kolkata 700032, India

ABSTRACT

Plate motion, crustal deformation, and earthquake occurrence processes in the northwest Sunda Arc, which includes the Indo-Burmese wedge (IBW) in the forearc and the Sagaing fault in the backarc, are very poorly constrained. Plate reconstruction models and geological structures in the region suggest that subduction in the IBW occurred in the geological past, but whether it is still active and how the plate motion between the India and Sunda plates is partitioned between motion in the IBW and Sagaing fault is largely unknown. Recent GPS measurements of crustal deformation and available long-term rates of motion across the Sagaing fault suggest that ~20 ± 3 mm/yr of the relative plate motion of ~36 mm/yr between the India and Sunda plates is accommodated at the Sagaing fault through dextral strike-slip motion. We report results from a dense GPS network in the IBW that has operated since 2004. Our analysis of these measurements and the seismicity of the IBW suggest that the steeply dipping Churachandpur-Mao fault in the IBW accommodates the remaining motion of ~18 ± 2 mm/yr between the India and Sunda plates through dextral strike-slip motion, and this motion occurs predominantly through velocity strengthening frictional behavior, i.e., aseismic slip. The aseismic motion on this plate boundary fault significantly lowers the seismic hazard due to major and great interplate earthquakes along this plate boundary.

INTRODUCTION

The plate boundary region between the India and Sunda plates in the northwestern Sunda Arc consists of the Indo-Burmese wedge (IBW), the Myanmar Central Basin, and the Sagaing fault (Fig. 1). The region flanks the Bay of Bengal sediments on the Indian plate to the west, and the stable Shan plateau of the Sunda plate to the east. The relative plate motion is partitioned between the IBW and the Sagaing fault and is poorly resolved (Le Dain et al., 1984; Guzman-Speziale and Ni, 1996; Vigny et al., 2003; Gahalaut and Gahalaut, 2007). Tomographic images (Li et al., 2008; Pesicek et al., 2010), a gravity anomaly (Verma et al., 1976), the occurrence of ophiolitic rock sequences (Sengupta et al., 1990), arc magmatism and metamorphism (Bender, 1983; Maurin and Rangin, 2009), and plate reconstruction models (Hall, 2002) suggest that the subduction of the Indian plate probably occurred in the IBW until ca. 50 Ma, when the entire arc was predominantly southeast-northwest trending (Guzman and Speziale, 1996; Kundu and Gahalaut, 2012). Although there is evidence of the presence of the subducted Indian slab under the IBW (Li et al., 2008; Steckler et al., 2008; Pesicek et al., 2010), whether the subduction is still active is debated (Guzman-Speziale and Ni, 1996; Satyabala, 2003; Rao and Kalpna, 2005). Great and major earthquakes occur on the north-south–oriented, vertical dextral strike-slip Sagaing fault (Fig. DR1 in the GSA Data Repository[1]) to accommodate the relative motion of ~20 mm/yr through stick-slip motion (Guzman-Speziale and Ni, 1996; Vigny et al., 2003; Nielsen et al., 2004; Maurin et al., 2010). The earthquake occurrence processes in the IBW are complex. Earthquakes in the IBW are confined at shallow to intermediate depth, and are more pronounced at depths >70 km, where they appear to define the Wadati-Benioff zone. Under the thick outer and inner IBW, the level of seismicity is generally low and the earthquakes define a very gentle eastward-dipping trend surface at a depth of ~30–40 km (Fig. 1; Fig. DR1). However, the focal mechanisms of these earthquakes (Figs. DR1 and DR2) suggest that they do not occur at the contact surface between the wedge and the India plate, but within the India plate, because none of the nodal planes of these earthquakes coincide with the inferred gentle dip of the contact surface and that of the seismicity trend surface (Kundu and Gahalaut, 2012) (Fig. DR1). The orientation of the approximately northeast-southwest–trending nodal planes of the focal mechanisms of these earthquakes is consistent with the oldest geologic fabric of the Indian plate. The motion on these planes during earthquakes, and the derived stress state, is consistent with the relative motion between the India and Sunda plates. All these earthquakes are of intraplate (or intraslab) type (Kundu and Gahalaut, 2012) and therefore probably do not accommodate the relative India-Sunda plate motion. It is not known how the remaining relative motion between the India and Sunda plates is accommodated in the IBW, or the seismic hazard implications. We address these issues using GPS measurements in the IBW.

GPS MEASUREMENTS IN THE IBW

GPS measurements of crustal deformation in the IBW were initiated in 2004 with the establishment of 23 survey-mode and 5 permanent GPS sites. The survey-mode sites were occupied annually from 2004 until 2011. Our GPS network occupies about half of the length of the IBW and is located in the region where the wedge is developed most extensively and the seismicity is most intense (Fig. 1). We did not consider sites close to the Himalayan Arc and Shillong plateau, in order to avoid the influence of the deformation associated with these geologic units. The sites are located either on hard rock or a constructed underground pillar that extends to the ground surface, anchored in the ground through 1-m-long iron rods. We occupied each site for 3–4 days on annual basis, and used bipods to minimize the height error. We processed these data, along with data from several International GPS Service (IGS) sites (HARO, MALI, BAHR, KIT3, POL2, SELE, URUM, KUNM, WUHN, COCO, DGAR, KARR, IISC, and HYDE) around the IBW region, using the GAMIT and GLOBK software (Herring et al., 2010a, 2010b) for the estimation of site velocity in the International Terrestrial Reference Frame (ITRF2005; Altamimi et al., 2007) by constraining IGS reference station positions and velocities in the region to their reported values in that frame with standard errors provided by the IGS. Site velocity in the India fixed reference frame (Table DR1) is estimated using the Euler rotation pole of the stable Indian plate (Banerjee et al., 2008). We corrected site velocities for the coseismic displacement due to the 2004 Sumatra-Andaman earthquake (M 9.2), which caused a southward motion of ~4 mm in this region

*E-mail: vkgahalaut@yahoo.com.

[1]GSA Data Repository item 2013057, details about modeling GPS data using ANSYS, Figures DR1–DR7, and Table DR1, is available online at www.geosociety.org/pubs/ft2013.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

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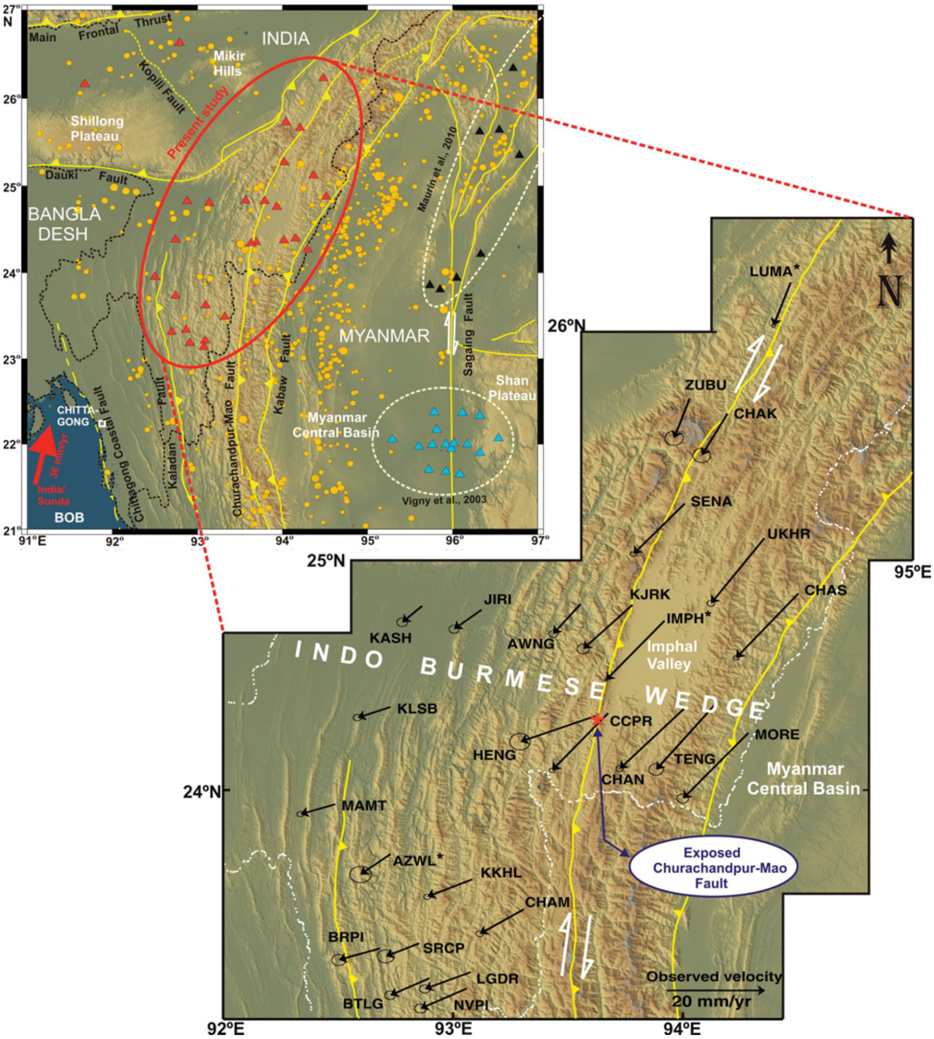

Figure 1. Global positioning system (GPS) networks in Indo-Burmese wedge and Sagaing fault region (Vigny et al., 2003; Maurin et al., 2010). Filled circles represent earthquakes in region. Lower panel shows our GPS network in Indo-Burmese wedge, and estimated site velocity in Indian reference frame. Permanent sites are marked by asterisks.

(Jade et al., 2007). The cumulative postseismic displacement due to the 2004 earthquake in this region (Maurin et al., 2010) is negligible (<1 mm, predominantly toward the south) and hence ignored (Fig. DR3; Table DR1).

The motion at these sites with reference to the Indian plate increases in the east direction and is predominantly toward the south (Fig. 1; Table DR1). There appears to be a sudden change in the magnitude of the motion at long ~93.5°E, which corresponds to the known NNE-SSW–oriented Churachandpur-Mao fault (CMF). Such a change is also evident in the strain derived from these velocity vectors (Fig. DR4). One of the immediate deductions from these observations is that the CMF is a dextral strike-slip fault. It is probably one of the older thrust sheets of this fold-and-thrust belt, which is now reactivated in the dextral motion. The fault is mostly either inaccessible due to security reasons or not exposed and covered under the alluvium. However, it is exposed at a location ~50 km south of Imphal, where an east-west–trending road cuts across the north-south–trending CMF. The fault zone width is ~400 m, and is marked with pulverized fault gouge material within the shaley sandstone (Fig. DR5). The two nearest sites located across it (HENG and CCPR, which are only 4 km apart) show a high velocity difference of 7–8 mm/yr. Although there is no change in the velocity across the Kabaw or Kaladan faults, the two most extensively mapped faults in the IBW (Alam et al., 2003) (Figs. 1 and 2), the deformation appears to be increasing gradually in the east direction, implying internal deformation of the wedge. The MCB does not appear to be deforming significantly, as the velocity of our easternmost GPS site is similar to the velocity of the westernmost site of the Sagaing fault network (Vigny et al., 2003) (Figs. DR3 and DR6).

MODELING OF GPS DATA

We resolved Indian reference-frame velocity estimates into the CMF-parallel and CMF-normal components. There is no significant variation in the fault-perpendicular motion across the CMF, implying that there is no subduction across the CMF or any other fault in the IBW (top left panel of Fig. DR6). However, a significant increase in the fault-parallel velocity from west to east implies that the slip along the CMF is accommodated predominantly through dextral strike slip, either through stick-slip behavior or aseismic creep. We assumed the steeply dipping CMF to be locked, and the plate boundary interface further downdip to be slipping freely (Savage, 1983). We used a grid search method in which we estimated the downdip width of the fault, its dip, and the slip deficit on it. Although the simulated strain accumulation curve corresponding to a downdip fault width of 25 km and a dextral slip deficit rate of 16 ± 0.5 mm/yr on a vertical fault simulates the overall pattern in the fault-parallel velocity, it fails to simulate the sudden velocity jump at the CMF (Fig. 2). The sudden jump in the velocity may actually imply that the deformation across the CMF may be due to aseismic slip involving very low friction. To test this, we used a finite element method (ANSYS software, www.ansys.com) in which friction may vary on the CMF (see the Methods discussion in the Data Repository). The deeper and gently eastward dipping part of the plate boundary interface was allowed to slip freely. We imposed a motion of 18.6 ± 0.5 mm/yr on the eastern margin of the IBW, corresponding to the motion at site MORE, the easternmost site of our network (Fig. DR7). The CMF is assumed as a near-vertical fault with a width of 25 km. We find that the resulting velocity estimates across the wedge using a friction coefficient of 0.17–0.18 on the CMF provide a better fit to the data and simulate the velocity jump reasonably well (Fig. 2). Model geometry and boundary conditions for the analysis are constrained from various data and observations (see the Data Repository); the result of low friction is robust, and does not change with a slight change in these boundary conditions. The very low friction coefficient and the jump in the fault-parallel velocity imply aseismic slip on the CMF. Low frictional behavior on the CMF appears to be related to the fault gouge. The extent of the creeping depth of the CMF was also verified using the formulation of Savage and Lisowski (1993). Corresponding to almost lithostatic pore pressure in the region (Steckler et al., 2008), the creeping depth for the CMF is estimated as ~20 km, implying that the CMF is creeping almost along its entire width. The near-lithostatic pore pressure should reduce the frictional stress, and may encourage creep behavior (Scholz, 1990). The CMF is also marked with frequent occurrences of landslides along its north-south extent

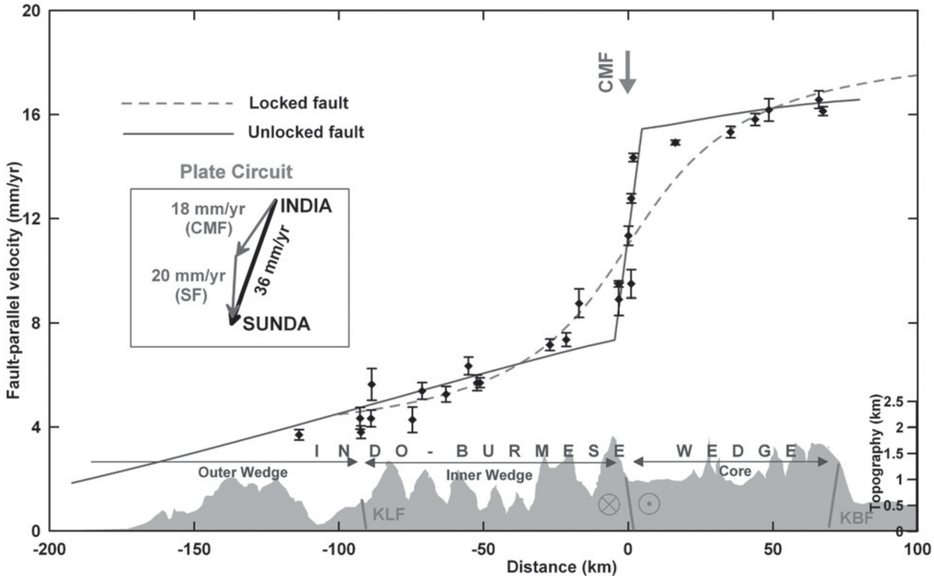

Figure 2. Profile perpendicular to Churachandpur-Mao fault (CMF) (approximately east-west at lat 24.5°N) showing fault-parallel site velocity. Dashed curve is simulated velocity profile (root mean square, rms, misfit ~0.15 mm/yr) due to locking on CMF at rate corresponding to dextral strike-slip motion of 16 ± 0.5 mm/yr. Continuous curve (rms misfit ~0.08 mm/yr) corresponds to relative motion of 18.6 ± 0.5 mm/yr across Indo-Burmese wedge (IBW), largely accommodated on CMF with very low friction of 0.18. KLF—Kaladan fault; KBF—Kabaw fault. Inset shows partitioning of India Sunda plate motion on CMF in IBW and Sagaing fault (SF).

(Singh et al., 2011), probably due to weakened rocks and the continuing slip across the fault. However, no significant earthquake activity (M > 2) has been associated with the CMF along its entire length during the recorded history of the past 50 yr.

GPS measurements in the IBW and across the Sagaing fault (Vigny et al., 2003; Maurin et al., 2010) suggest that, of the 36 mm/yr of India-Sunda motion, ~18 ± 0.5 mm/yr is accommodated through dextral motion along the CMF in the IBW, and ~20 ± 3 mm/yr is accommodated along the Sagaing fault. However, the motion across the CMF is aseismic, whereas it is through stick-slip behavior across the central part of the Sagaing fault (Vigny et al., 2003; Maurin et al., 2010). The northern part of the Sagaing fault appears to be creeping, as the estimated locking depth was less (6–8 km).

IMPLICATIONS OF ASEISMICALLY SLIPPING BOUNDARY

From available historical records of the past several hundred years, it appears that no great earthquake has occurred in the IBW (Kundu and Gahalaut, 2012), or more specifically on the CMF. The great A.D. 1897 Shillong plateau earthquake and the 1950 Assam earthquake in the Himalayan region are not linked with the tectonics of the IBW (Molnar, 1990; Bilham and England, 2001). In a history of more than 500 yr, only 2 strong earthquakes appear to have occurred in the IBW: the 1869 Cachar earthquake and the 1762 Arakan earthquake. The damage caused by the 1869 earthquake was confined in small regions where unconsolidated sediments were present, and so this earthquake cannot be categorized as a great or even major earthquake (Kundu and Gahalaut, 2012). Although Cummins (2007) reported the 1762 Arakan earthquake as a great tsunamigenic earthquake, the available information does not necessarily qualify it to be referred to as a great earthquake, and it was not tsunamigenic (Martin and Szeliga, 2010; Gupta and Gahalaut, 2009). Modern seismological history of the past 50 yr indicates that the earthquakes in the IBW occur at depths >40 km on steep planes within the subducted India plate, and are thus intraplate earthquakes. Even the largest magnitude earthquake (M 7.1), the 1988 Indo-Myanmar border earthquake, which occurred at 90–100 km, was also an intraslab earthquake; it is possible that the 1869 Cachar and the 1762 Arakan earthquakes were of a similar type. The contact surface between the base of the outer and inner wedge and the Indian plate, which is to the west of the CMF, is nonseismogenic. The CMF in the IBW is a low-friction boundary, where a significant part of the India-Sunda motion is accommodated mostly aseismically, and it is not associated with any earthquake activity. The CMF at depth joins the top surface of the Indian slab where slip occurs through stable sliding. Aseismic slip at the CMF has strong implications for seismic hazard assessment in the IBW. It is not necessary for creeping faults to be weak (Lockner et al., 2011). However, the absence of great and major interplate earthquakes in the IBW, the lack of small-magnitude seismicity on the CMF, and the aseismic behavior of the CMF suggest that the CMF is actually a weak fault, and therefore the earthquake hazard in the IBW due to great and major interplate earthquakes is very low. At the same time, the strong intraplate earthquakes that generally occur at depths >40 km within the Indian plate may cause damage in the unconsolidated sediment-filled valley regions, such as the Cachar and Imphal valleys in India and the Sylhet trough and Chittagong in Bangladesh. We acknowledge that although our GPS network spans about half of the length of the IBW, where plate motion is found to be aseismic, there could be some variation in the frictional properties of the CMF in the IBW; this needs to be ascertained from further studies and GPS measurements.

CONCLUSIONS

GPS measurements in the IBW suggest that subduction, which occurred in the geological past, is no longer active across this margin. Approximately 47% of the India-Sunda plate motion is accommodated in the IBW through dextral slip on the Churachandpur-Mao fault and does not lead to strain accumulation because it occurs aseismically. This is consistent with a general absence of great and major interplate earthquakes in the region. Thus the seismic hazard in the IBW due to great and major interplate earthquakes along this plate margin is very low. However, the moderate-magnitude intraplate or intraslab earthquakes, which occur at depths >40–50 km, may cause damage in unconsolidated sediment-filled valley regions.

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