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Seismotectonic Model of the Sikkim Himalaya: Constraint from Microearthquake Surveys

by Reena De and J. R. Kayal

Abstract The seismotectonic model in the Sikkim Himalaya does not fit well with the proposed steady state or evolutionary models. The main boundary thrust (MBT) is seismogenic and is a mantle-reaching fault. The earthquakes are not confined to shallower depths (<25 km) above the plane of detachment as proposed in the models, the seismic activity continues from surface to the lower crust (0–45 km) to the north of MBT, and earthquakes are produced by a thrust mechanism. The earthquakes to the east of Sikkim, in the Bhutan Himalaya, on the other hand, are produced along a 200-km-long northwest–southeast–trending lineament by transverse tectonics; the seismogenic lineament cuts across the Himalayan major thrusts and extends to the Goalpara wedge in the southeast. The earthquakes occur by strike-slip mechanism in the midcrust, at a depth range of 10–25 km, along this long active lineament.

Introduction

The Himalayan region, including the 2500-km-long Himalayan Seismic Belt from Kashmir in the west to Arunachal Pradesh in the east, can be divided into different seismotectonic blocks; the seismotectonic structures are different from west to east (Kayal, 2001). The Darjeeling–Sikkim tectonic block constitutes one of these where a good number of moderate magnitude earthquakes with $M \geq 5.0$ have been recorded. Figure 1 shows the major tectonic features, including the major thrusts/lineaments/faults and the earthquakes ($M \geq 4.0$) recorded by the World Wide Seismograph Station Network (WWSSN) since 1964 in the Sikkim and adjoining areas. Among the major thrusts, the main boundary thrust (MBT) is well demarcated; the main central thrust (MCT), on the other hand, takes a sinusoidal turn in the Sikkim Himalaya. The main Himalayan Seismic Belt is mostly confined within the MBT and MCT zones (Ni and Barazangi, 1984). The Himalayan frontal fault (HFF), to the south of MBT, separates the Siwalik formations to the north and the Gangetic Plain alluvium to the south; neotectonic activity is reported along this fault (Nakata *et al.*, 1990).

The great Bihar earthquake (M 8.4) of 1934, which claimed about 11,000 lives, was located to the south of the MBT, in the foothills region (Fig. 1), and it caused an intensity of VIII in the Sikkim Himalaya (GSI, 1939). The recent damaging earthquake of 1988 (M_S 6.7), which occurred near to the epicenter of the 1934 great earthquake (Fig. 1), was distinctly felt in the Darjeeling–Sikkim Himalaya, and the isoseismal VII passed through the towns of Darjeeling and Gangtok. The damages to hydroelectric projects and road alignments were mainly in the form of subsidences and landslides in this area (GSI, 1993). Several buildings, both in Darjeeling and Gangtok, were badly damaged. There were also two significant moderate-magnitude earthquakes, the 1965 (M 5.9) and the 1980 (M 6.0) events, that occurred in the study area (Fig. 1).

In view of this history, we from the Geological Survey of India made a few microearthquake surveys between 1993 and 1999, deploying closely spaced temporary networks in the Darjeeling–Sikkim Himalaya (De, 1996, 2000). The consolidated data are reanalyzed and presented here; they shed new light on understanding the seismotectonics in this tectonic block of the Himalaya.

Regional Earthquakes

The teleseismic/regional earthquakes recorded by the WWSSN and by the Indian national network between 1964 and 2002 (NEIC, USGS catalog) are shown in Figure 1. The figure clearly shows that the activity is not uniformly distributed; there is high activity in the eastern Nepal and in the Sikkim tectonic blocks and also in the Shillong Plateau in northeast India. A northwest–southeast lineament is mapped that extends from the Sikkim Himalaya to the southeast (GSI, 1993). We name it Goalpara lineament, as it appears to be the extension of the Goalpara wedge (Fig. 1). The seismic activity along this lineament looks sparse, except for the 1980 earthquake (M 6.0) and a few more events ($M \geq 4.0$) that occurred at the northwest end of the lineament.

Three moment tensor solutions (USGS) are available for the three significant earthquakes in the region, two (1965 and 1980) in the Sikkim Himalaya and one (1988) in the

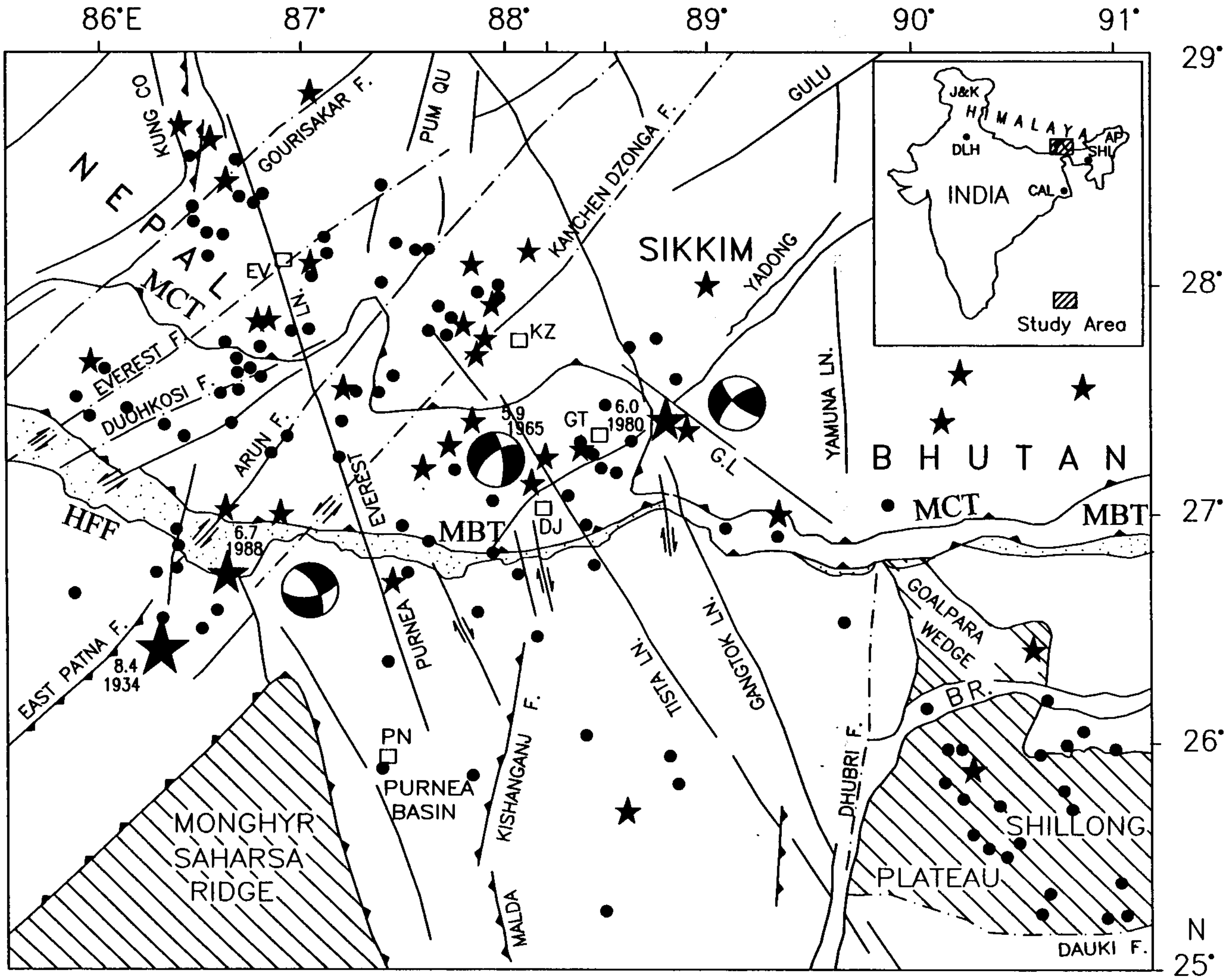

Figure 1. The map shows major tectonic features (after GSI, 1993) and epicenters of the earthquakes $M \geq 4.0$ (NEIC, USGS catalog, 1964–2002). Solid circles indicate earthquakes with $4.0 < M < 5.0$, smaller solid stars $5.0 < M < 6.0$, and larger solid stars $M \geq 6.0$. Available moment tensor solutions of the three significant earthquakes are shown; the shaded area shows the compressional zone and the open area the dilatational zone. The epicenter of the 1934 great Bihar earthquake is taken from GSI (1993). MCT, main central thrust; MBT, main boundary thrust; HFF, Himalayan frontal fault; GL, Goalpara lineament; BR, Brahmaputra River; EV, Everest; KZ, Kanchen Dzonga; DJ, Darjeeling; GT, Gangtok; PN, Purnia. Inset: Sketch map of India showing the study area; J&K, Jammu and Kashmir; A.P., Arunachal Pradesh; DLH, Delhi; CAL, Calcutta; SHL, Shillong.

foothills region (Fig. 1). The event (M 6.0) of 1980 shows a strike-slip solution; the near-vertical/south–dipping northwest–southeast nodal plane is comparable with the Goalpara lineament. The 1965 event (M 5.9) also shows a strike-slip solution; the near vertical/northeast–dipping northwest–southeast nodal plane is correlatable with the Tista lineament (Fig. 1). The 1988 earthquake (M_S 6.7) in the foothills region also shows a strike-slip solution; the southeast-dipping northeast–southwest nodal plane is comparable with the East Patna fault (Fig. 1). Based on these observations, Dasgupta *et al.* (1987) suggested transverse tectonics in the eastern Himalaya. The focal depth of the 1988 earthquake (M_S 6.7) was well estimated at 51–65 km (NEIC and ISC). Both the 1988 earthquake (M_S 6.7) and the 1934 great earthquake (M 8.4) occurred to the south of the MBT (Fig. 1). These two events occurred at the juncture of the Monghyr Saharsa Ridge, East Patna fault, and the Himalayan frontal fault. The tectonic domain that caused these two devastating earthquakes in the foothills region is different from those that occurred to the north of the MBT. A detailed discussion on the foothills region earthquakes is given in the GSI (1993) report.

Microearthquake Activity

Four microearthquake surveys were carried out between 1993 and 1999 in the Sikkim–Darjeeling Himalaya deploying a five-station closely spaced temporary network in each survey; recording was done for about 4 months in each investigation. About 500 events were recorded during these surveys. Two hundred events are relocated using the Hypo71 computer program of Lee and Lahr (1975). The relocations are done by the homogeneous station method (Kayal, 1984), which is also known as the common phase method (Lahr, 1992). In this method, relative locations are more precise and independent of crustal velocity model error (Kayal *et al.*, 2002). These locations were much improved with an average root mean square of 0.10 sec and epicenter and depth error within ±2 km. Epicenters of these events are shown in Figure 2. The epicenter map shows high activity in the Sikkim Himalaya and high activity along the Goalpara lineament, which continued to the Goalpara wedge. In the Sikkim Himalaya, there is not much activity to the south of the MBT; the activity is concentrated to the north. One significant earthquake (*M* 5.0), however, occurred in 1993 to the south of the MBT, in the Gangetic plain. The event was located by the U.S. Geological Survey (USGS) as well as by the temporary network; both the locations are shown in the map (Fig. 2). The USGS located the event with a fixed depth of 33 km. The event was well felt at the nearest camp/station (ISL) at Islampur, which recorded intensity V in the area (GSI, unpublished report, 1995). A critical examination of the epicenter maps of the regional earthquakes (Fig. 1) and the microearthquakes (Fig. 2) suggests that the Sikkim Himalayan earthquakes and the earthquakes along the Goalpara lineament belong to two different tectonic domains. To examine this, a depth section (T1) is prepared along the strike

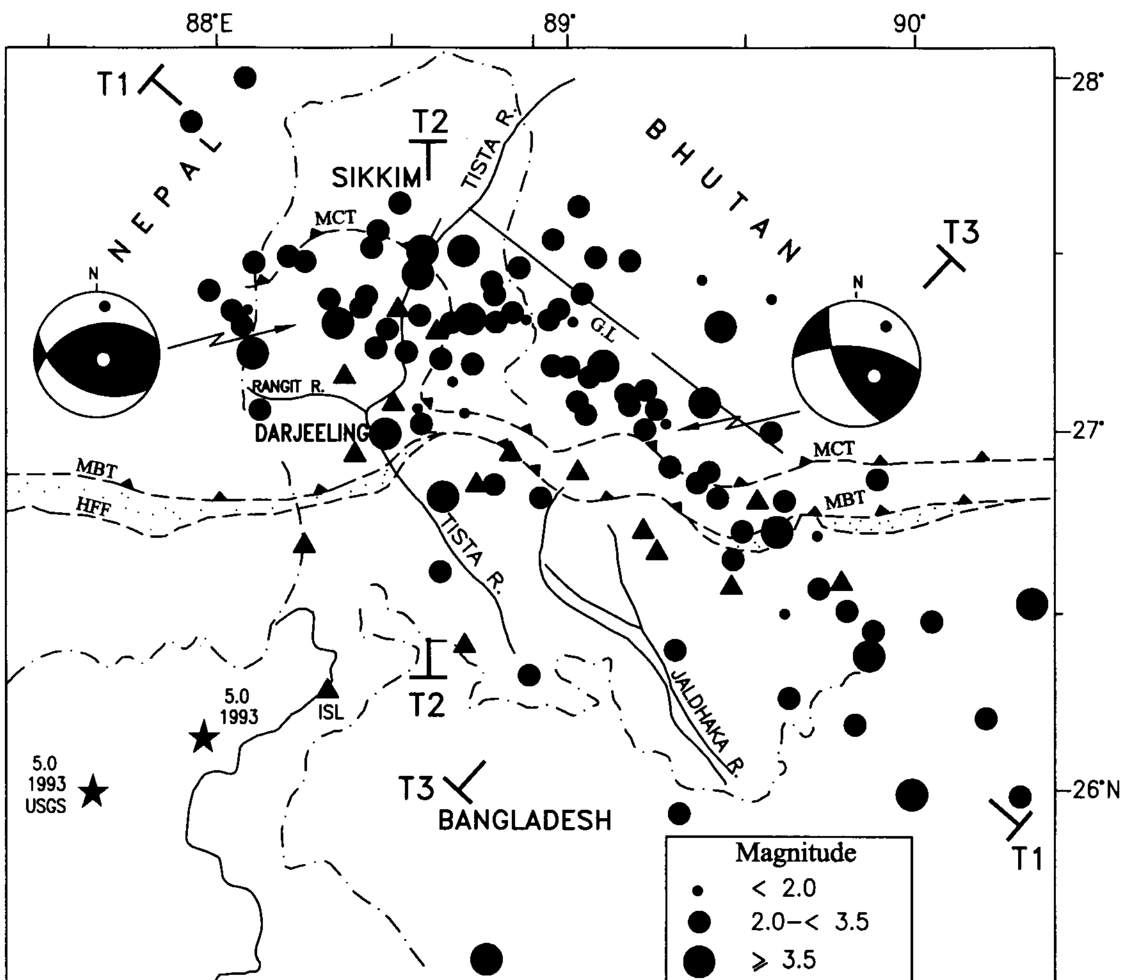

Figure 2. Map showing epicenters of the earthquakes recorded by the temporary microearthquake networks (1993–1999). Temporary seismic stations are shown by solid triangles. The composite fault-plane solutions (lower hemisphere) of the earthquakes in the two tectonic zones are shown (see text); the shaded area shows the compressional zone and the open area the dilatational zone, whereas the solid circle indicates the compressional (*P*) axis and the open circle the tensional (T) axis.

direction of the Himalayan belt in the area (Fig. 3a). In this section two tectonic zones are clearly evident; earthquakes along the Goalpara lineament are shallow (10–25 km) and the earthquakes along the Sikkim Himalaya are both shallower and deeper (0–45 km).

Depth sections of the earthquakes across these two tectonic zones are also examined: one north–south (T_2) section in the Sikkim Himalaya and one northeast–southwest section (T_3) across the Goalpara lineament. The north–south section (T_2) shows that the earthquake activity is continuous from the surface to the mantle depth (0–45 km) in the Sikkim Himalaya, and the earthquakes occur well below the plane of detachment, which is envisaged in the tectonic model of the Himalaya (Seeber *et al.*, 1981). The earthquakes also deepen to the north. The northeast–southwest depth section (T_3) across the Goalpara lineament, on the other hand, shows that the earthquakes are shallower; they are mostly clustered below the Goalpara lineament at a depth range of 10–25 km, within the middle crust.

Two composite fault-plane solutions using *P*-wave first motions are obtained for the two clusters of events in the two tectonic zones (Fig. 2). The solution for the cluster in the Sikkim zone shows thrust faulting; the north-dipping nodal plane is the inferred fault plane. The fault-plane solution and the depth section T_2 suggest that the MBT is seismogenic, and it is possibly a deep-rooted, mantle-reaching fault. The fault-plane solution of the cluster along the Goalpara lineament, on the other hand, shows a strike-slip solution; the near-vertical/southeast–dipping northwest–southeast nodal plane, comparable with Goalpara lineament, is the inferred fault plane.

Discussion and Conclusions

The seismotectonics of the Himalaya is very fascinating, and there have been many studies on this subject. Among the many tectonic models proposed for Himalayan earthquakes, the steady state model (Seeber *et al.*, 1981) and the evolutionary model (Ni and Barazangi, 1984) are the most referred. These models are based on geological and teleseismic data. The steady state model consists of a subducting slab (the Indian shield), an overriding slab (the Tethyan slab), and a sedimentary wedge that is decoupled from the two converging slabs. The interface between the subducting slab and the sedimentary wedge is termed the plane of detachment, and it is proposed that the MBT and MCT converge with the plane of detachment at depth. In this model, both the MBT and MCT are active thrusts. In the evolutionary model, on the other hand, it is suggested that the MBT and MCT are successive tectonic thrusts; the southern thrust zone (MBT) is the new boundary of the continental convergent zone, while the older thrust zone (MCT) is seismically less active, a dormant feature now.

The regional epicenter map reveals two intense active zones, the eastern Nepal–Sikkim Himalaya zone and the Shillong Plateau in northeast India (Fig. 1). These two active zones are linked by the Goalpara lineament. Although the regional seismic ($M \geq 4.0$) activity along this lineament is not intense, one significant earthquake (1980, *M* 6.0) occurred at its northwestern end (Fig. 1). The fault-plane solution of this moderate-size earthquake suggests that the northwest–southeast Goalpara lineament is the causative fault/lineament for this earthquake.

The epicenter map of the lower magnitude (*M* 2.0–4.0) earthquakes recorded by the closely spaced temporary networks, however, clearly indicates that the Goalpara lineament is seismically quite active, and the activity is transverse to the trend of the MBT. The activity continues from the Sikkim Himalaya to the Goalpara wedge along this lineament. The map further confirms that the Sikkim Himalaya region is equally active, but the activity concentrates mostly to the north of the MBT, except for one significant earthquake (*M* 5.0) of 1993, which was located by the USGS as well as by the temporary network to the south of the MBT, in the Gangetic Plain. The USGS location used the fixed depth of 33 km. The focal depth was determined at 25 km by the temporary network. However, the major seismic activity is observed to the north of the MBT in the Sikkim Himalaya, and this is important in terms of seismic hazard evaluation.

Since the focal depths of the regional earthquakes are not precise and mostly located using the fixed depth at 33 km (USGS), we have not prepared depth sections of the regional earthquakes. Three depth sections of the closely spaced microearthquake network data are critically examined. The depth section (T_1) along the strike of the Himalayan trend, or the activity trend, reveals an interesting observation (Fig. 3a). The activity is confined in the middle crust (depth 10–25 km) along the Goalpara lineament zone, but the activity is pronounced from the surface to the lower crust (depth 0–45 km) in the Sikkim Himalaya zone. This section very clearly indicates the two distinct, tectonically active zones. Depth sections across the Sikkim Himalaya and the Goalpara lineament (T_2 and T_3) further confirm the two tectonic zones (Fig. 3b,c). There is no dipping seismogenic structure across the Goalpara lineament; the activity is rather confined in the middle crust (depth 10–25 km), above the plane of detachment. Across the Sikkim Himalaya, on the other hand, a dipping seismogenic structure is evident, and the structure is deep rooted, down to the base of the lower crust. The tectonic model envisaged by Seeber *et al.* (1981) is shown in both of the sections. Across the Goalpara lineament (section T_3), two deeper earthquakes (depth >25 km) are recorded below the MBT zone, but the main seismic activity is confined in the middle crust, below the Goalpara lineament zone (Fig. 3c). Across the Sikkim Himalaya, it is striking to note that the earthquakes are not confined above the proposed plane of detachment; more or less uniform activity is observed from the upper crust to the lower crust, down to the Moho depth. This observation does not support the steady state tectonic model of Seeber *et al.* (1981), which suggested that the activity in the Himalayan Seismic Belt,

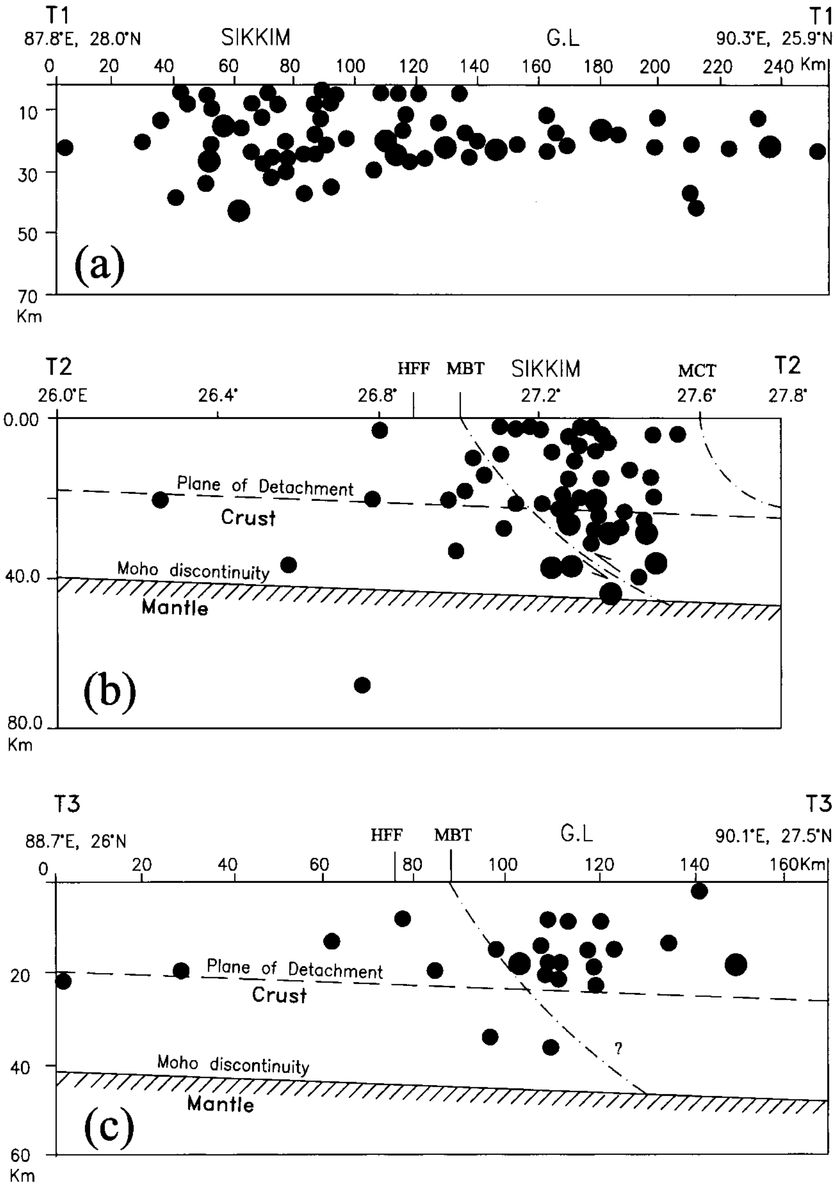

Figure 3. Depth sections of the earthquakes along (a) T_1T_1, (b) T_2T_2, and (c) T_3T_3, (Fig. 2); epicenters within 30 km on both sides of the section line are considered. Larger solid circles indicate magnitudes $M \geq 3.5$. The plane of detachment is taken from the steady state model of Seeber *et al.* (1981) and the Moho discontinuity from the gravity survey of Choudhury and Dutta (1975). (Horizontal scale = vertical scale.)

between the MBT and MCT, is confined above the plane of detachment. It may also be noted that there is almost no activity to the north of the MCT. The MBT is the active seismic zone. This observation supports the concept of the evolutionary model of Ni and Barazangi (1984), which suggested that the MCT is a dormant thrust now and the MBT is the zone/boundary of active convergence. The most remarkable observation is that the MBT does not converge with the plane of detachment in the Sikkim Himalaya, unlike in the western Himalaya (Kayal, 2001). De (2000) and Kayal (2001) suggested that the MBT is a mantle-reaching seismogenic thrust in the Sikkim Himalaya. Choudhury and Dutta (1975), based on gravity data, also suggested that the MBT is a mantle-reaching thrust in this area. The other exceptional geological feature in the Sikkim Himalaya is that the MCT and MBT are not parallel; the MCT arches in the form of a culmination, and the core region exposes a vast expanse of pre-Tertiary rocks arranged in a pile of thrust sheets (Ray, 2000). This unusual culmination may also be a controlling factor for deeper earthquakes in the Sikkim Himalaya. To the east of Sikkim, in the Bhutan Himalaya, on the other hand, the Goalpara lineament, a transverse structure to the MBT, is the main seismogenic structure (Figs. 2 and 3).

The fault-plane solution of the Sikkim Himalayan earthquakes, a cluster at a depth range 10–40 km, suggests that the north-dipping nodal plane, comparable with the MBT, is the preferred fault plane. The fault-plane solution of the cluster of events (depth 10–25 km) along the Goalpara lineament, on the other hand, shows a dominant strike-slip solution. The northwest–southeast–trending nodal plane is the preferred fault plane. The moment tensor solution of the 1980 earthquake (M 6.0), which occurred at the northwest end of the lineament, also shows strike-slip motion; the northwest–southeast–trending nodal plane is comparable with the Goalpara lineament. These observations suggest that the midcrustal (depth 10–25 km) earthquakes along the Goalpara lineament are the result of transverse tectonics and the active fault/lineament is transverse to the MBT. The earthquake trend is colinear, and it cuts across the MBT (Fig. 2). Although the activity along the southeast part of the Goalpara lineament is not prominent in the regional earthquake map (Fig. 1), it is very prominent in the microearthquake map (Fig. 2). The microearthquake data clearly identified this active lineament, which is about 200 km long and cuts across the MBT. The seismogenic structure is longer than the mapped lineament (Fig. 2); the seismic activity indicates that it continues to the Goalpara wedge in the southeast (Fig. 1).

We conclude that a single tectonic model does not explain the Himalayan earthquakes. In the western Himalaya the proposed models (Seeber *et al.*, 1981; Ni and Barazangi, 1984) fit fairly well (Kayal, 2001), but in the eastern Himalaya the tectonics is further complicated. The tectonics in the Sikkim–Darjeeling Himalaya is dominantly controlled by the deep-rooted MBT; the earthquakes are continuous from the surface to the lower crust at a depth range of 0–45 km. To the east of Sikkim, in the Bhutan Himalaya, an active lineament, about 200 km long, transverse to the Himalayan major thrust zones, plays the dominant role for producing shallower earthquakes in the midcrust (10–25 km). The lineament links the Goalpara wedge to the southeast and the Sikkim tectonic block to the northwest. We believe that identification of such active deep-rooted faults/transverse lineaments in the Himalaya is very useful to evaluate the seismic hazards in the Himalaya region. A present-day high-precision closely spaced digital network in the Himalaya would shed more light on understanding the earthquake source processes in the Himalaya.

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