

Himalayan mid-crustal ramp

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The presence of the Himalayan mid-crustal ramp under the southern Higher Himalaya has been proposed by several investigators, on the basis of analyses of microseismicity¹⁻³, seismic reflection⁴, gravity anomaly⁵, uplift rate^{6,7} and inferred subsurface geological data⁸⁻¹². We analyse focal depths and fault plane solutions of the moderate thrust earthquakes of the Himalayan seismic belt derived from body wave inversion, along with the hypocentral parameters of reliably located earthquakes whose focal depths have been estimated on the basis of ISC-reported surface reflected phases. These earthquakes occurred in a narrow belt of about 25 km width along the northern Lesser and southern Higher Himalaya. A more or less systematic increase in the focal depths and dips of the inferred fault planes in north-northeast direction along the four cross-sections across the Himalaya along with the available evidences, supports the presence of this ramp under the southern Higher Himalaya. These earthquakes occur on and above the mid-crustal ramp that lies in the transition zone between the seismically active detachment under the Outer and Lesser Himalaya and the aseismically slipping detachment under the Higher and Tethys Himalaya.

IN the past few years, our understanding of earthquake occurrence processes and other geodynamic phenomena in the Himalaya and adjoining regions has increased significantly. It is mainly because of the initiation of various projects dealing with the data acquisition and their analyses and also due to the increase in our scientific capabilities to analyse the existing data. The joint American–Chinese–Nepalese^{6,13,14} and French–Nepalese¹⁵ GPS, French–Nepalese seismological^{1,2} and multi-institutional seismic reflection INDEPTH⁴ projects are amongst the most notable, apart from other small projects taken up in the Himalaya. Analyses of earthquakes occurring in the Himalaya due to the Indo-Eurasian plate convergence process, have provided useful information about the source processes of the earthquakes. Further, a mid-crustal ramp under the southern Higher Himalaya has been proposed on the basis of various seismological^{1,2}, geological⁸⁻¹² and geodetic studies^{6,7,14-16}. In this communication, we analyse the available earthquake focal mechanisms, focal depths and their spatial distribution, to see whether additional constraints about the presence of a mid-crustal ramp under the Himalaya may be provided by these data.

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ACKNOWLEDGEMENTS. We thank Drs Manju Banerjee, B. D. Sharma, P. K. Khare, David Dilcher, David J. Batten, Gary Upchurch and Peter Bass for their valuable suggestions, meaningful observations and discussions, and Prof. Anshu Kumar Sinha, Director, Birbal Sahni Institute of Palaeobotany for providing the necessary facilities to carry out the investigations.

Received 14 December 2000; revised accepted 1 October 2001

On the basis of geological and geophysical observations, several investigators have indicated the presence of a mid-crustal ramp under the Himalaya, which connects the shallower seismically active detachment under the Outer and Lesser Himalaya and the deeper aseismically slipping detachment under the Higher and Tibetan Himalaya. We discuss them here in brief.

Pandey *et al.*^{1,2} reported the results of seismic data collected by the seismological network of Nepal under a French–Nepalese collaborative project. Majority of the earthquakes occurred at a depth of 15–20 km, coinciding with the location of the ramp. They attributed the strain and stress accumulation at mid-crustal ramp as the cause for intense microearthquake activity. We find that the location of the ramp inferred by Pandey *et al.*¹ is consistent with the focal mechanisms and depths of moderate earthquakes in that region.

Khattari *et al.*¹⁷ reported the results of a microearthquake survey in Garhwal Himalaya. The microearthquakes located by the network occurred close to the Main Central Thrust (MCT), at depths shallower than 15 km. They also estimated the composite focal mechanism of these earthquakes, which indicated thrust motion on a 30° north-easterly dipping plane. Although a clear evidence for the presence of the ramp may not be seen in this study, the slip on the steep plane is consistent with the available fault plane solutions. Similar results have been reported from the Kangra–Chamba region by Thakur *et al.*³. The observed seismicity in this region appears to be diffused, but the earthquakes are confined in the upper 18 km of the crust. Although seismicity does not constrain the location and geometry of the ramp in this region, the authors³ have indicated a ramp under the Dhauladhar range and Chamba region based on geological considerations¹².

A few geological cross-sections constraining the subsurface structure across the Himalaya are available. DeCelles *et al.*⁸ reported a cross-section across the far western Nepal Himalaya, showing a ramp at a depth of 15–20 km. Further east, three cross-sections reported by Brunel⁹, Schelling¹⁰, and Schelling and Arita¹¹ distinctly show the presence of the ramp under the central and eastern Nepal Himalaya. The location of the ramp in each case coincides with the intense microearthquake activity in the region². Srivastava and Mitra¹⁸ indicated the ramp south of the MCT at a depth of 15–20 km in their balanced cross-section across the Garhwal Himalaya. Mukhopadhyay and Mishra¹⁹ and Powers *et al.*²⁰ constructed balanced geological cross-sections across the Punjab Himalaya, along a similar profile. However, there is a significant difference between the two cross-sections, e.g. the depth of the detachment under the MBT in the former is 26 km, while in latter it is only 8 km. Further, since these sections do not extend sufficiently northward, no constraint can be provided for the presence of a ramp in the region.

Yeats and Thakur¹² opined that the Himalaya moves southward as a fault bend fold due to slip by earthquakes which nucleate on the ramp and whose rupture lies on the detachment under the Outer and Lesser Himalaya. The axial surface at the inflection between the ramp and the flat projects northward to the surface and separates predominantly inactive north-dipping thrusts with highly convoluted map traces, klippe and windows¹².

Seismic reflection profiles are available across the frontal Himalaya²¹ and southern Tibet⁴, but not across any part of the Lesser and Higher Himalaya. Thus, the available seismic profiles do not directly constrain the location and geometry of the crustal ramp. The seismic profiles across the frontal Himalaya suggest that the detachment under the southern limit of the Outer Himalaya lies at 4–5 km and dips gently under the Himalaya at an angle of 4–6°. The seismic reflection profiles in southern Tibet indicate the depth of detachment (or the Main Himalayan Thrust, MHT, as referred by Hauck *et al.*⁴) at about 25 ± 3 km. The subsurface position of the detachment, when extrapolated towards south requires a ramp so that it can be joined with the detachment under the Outer and Higher Himalaya at a depth of about 15 km (ref. 4). Thus although the interpretation of the reflection data requires a ramp under the Higher Himalaya, its location and dip are not well constrained by the data.

Cattin and Avouac⁷ used a two-dimensional mechanical model to analyse the Nepalese geodetic, and river incision data. They found that the interseismic levelling and GPS observations from the Nepal Himalaya^{6,7,15,16} do not provide any constraint for the presence of the ramp, as they can be modelled with^{6,15} or without^{7,22,23} the ramp. However, the modelling of river incision rate profile requires the presence of a ramp under the northern Lesser Himalaya^{7,24}. Thus, the long-term deformation rates from the Nepal Himalaya are consistent with the presence of the ramp, but the interseismic deformation rates are insensitive to it. Lyon-Caen and Molnar⁵ analysed the gravity anomalies across the Himalaya and inferred steeper dip of the Moho under the Higher Himalaya than under the Outer and Lesser Himalaya, which may indirectly suggest the presence of the ramp under the Higher Himalaya.

Figure 1 shows the epicentres of the earthquakes estimated by USGS during 1973–1999, which have been recorded at 20 or more stations. Over most of the Himalaya, especially between 75 and 90°E longitude, the earthquake epicentres lie in a narrow belt along the topographic front between the Higher and Lesser Himalaya²⁵. Hereafter we shall refer to this belt as the Himalayan Seismic Belt (HSB). The seismicity further north of this belt is quite diffused. Although a large number of moderate-magnitude earthquakes have occurred in the HSB, reliable focal mechanisms and focal

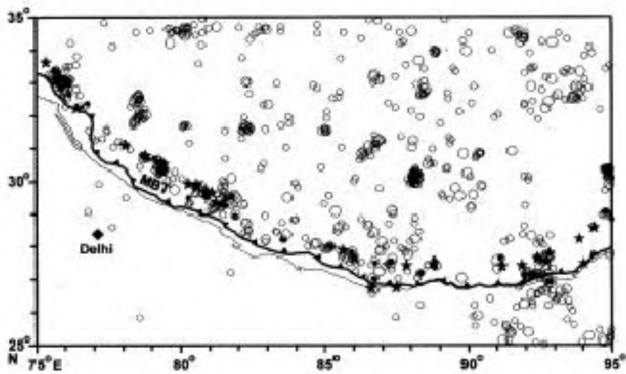


Figure 1. Epicentral map of Himalaya (January 1973–March 2000). Epicentres of only those earthquakes have been plotted that were recorded at 20 or more stations, as reported by PDE-USGS. Three sizes of the circles denote earthquakes in the magnitude (m_b) range of 4–5, 5–6 and 6–7. The Southern limit of the Outer Himalaya is also shown. Solid circles represent the epicentres of those Himalayan earthquakes (1964–1997) whose focal depths have been reported by ISC on the basis of four or more consistent P – pP observations. Stars indicate the Himalayan earthquakes (1964–1999) whose fault plane solutions and focal depths are available from the body waveform inversion (see Table 1). MBT, Main Boundary Thrust.

depths of very few earthquakes are available. Several studies on the analyses of focal mechanisms and focal depths of the thrust earthquakes of HSB have been reported to derive constraints on the earthquake occurrence processes and other geodynamic phenomena. We now provide a brief review of these studies.

A first serious attempt to estimate the focal mechanisms of Himalayan earthquakes was made by Fitch²⁶, using the first motion P and S wave data recorded by long-period instruments. He inferred thrust motion on the planes having north to north-easterly dip, as due to the underthrusting of the Indian plate beneath the Himalayan mountain front. Chandra^{27,28} estimated focal mechanisms of 15 Himalayan earthquakes using the first motion data and expressed similar views. Seeber and Armbruster²⁵ proposed a steady state subduction model for the Himalaya in which they proposed that the convergence between the Indian and Eurasian plates, accommodated within the Himalaya, occurs through slip on the detachment, the contact surface between the underthrusting Indian shield rocks and overthrust Hima-

Table 1. Hypocentral locations, focal mechanisms of Himalayan earthquakes (1964–1999)

| Date | Latitude | Longitude | m_b | Depth | Strike dip slip | | | Strike dip slip | | | Reference |
|-----------|----------|-----------|-------|-------|-----------------|----|-----|-----------------|----|-----|-----------|
| 64.02.18 | 27.40 | 91.18 | 5.6 | 22 | 302 | 40 | 90 | 122 | 50 | 90 | 27, 28 |
| 64.09.01 | 27.12 | 92.26 | 5.7 | 09 | 224 | 20 | 90 | 46 | 70 | 90 | 27, 28 |
| 64.09.26# | 29.91 | 80.55 | 6.2 | 18 | 310 | 23 | 90 | 130 | 67 | 90 | 31 |
| 64.10.21# | 28.22 | 93.87 | 5.9 | 15 | 265 | 3 | 90 | 85 | 87 | 90 | 31 |
| 65.01.12# | 27.41 | 87.85 | 6.1 | 15 | 270 | 15 | 90 | 90 | 75 | 90 | 31 |
| 66.06.27# | 29.70 | 80.89 | 6.0 | 15 | 277 | 27 | 70 | 119 | 65 | 100 | 31 |
| 66.09.26# | 27.53 | 92.73 | 5.5 | 17 | 253 | 20 | 90 | 73 | 70 | 90 | 27, 28 |
| 66.12.16# | 29.66 | 80.84 | 5.8 | 12 | 290 | 24 | 90 | 110 | 66 | 90 | 31 |
| 67.02.20 | 33.63 | 75.33 | 5.6 | 10 | 341 | 55 | 105 | 136 | 38 | 70 | 31 |
| 67.03.14# | 28.57 | 94.37 | 5.8 | 15 | 273 | 10 | 90 | 93 | 80 | 90 | 31 |
| 67.09.15 | 27.42 | 91.86 | 5.8 | 16 | 263 | 30 | 90 | 83 | 60 | 90 | 27, 28 |
| 70.02.19# | 27.47 | 94.02 | 5.5 | 10 | 257 | 5 | 90 | 77 | 85 | 90 | 35 |
| 74.03.24 | 27.66 | 86.00 | 5.7 | 16 | 275 | 2 | 90 | 95 | 88 | 90 | 31 |
| 79.05.20 | 29.93 | 80.27 | 5.8 | 16 | 251 | 16 | 53 | 109 | 77 | 100 | 30, 36 |
| 79.06.19* | 26.74 | 87.50 | 5.1 | 20 | 75 | 45 | 277 | 245 | 46 | 263 | 30 |
| 80.07.29 | 29.34 | 81.21 | 5.7 | 14 | 279 | 29 | 94 | 95 | 61 | 88 | 30, 36 |
| 80.07.29# | 29.64 | 81.08 | 6.1 | 18 | 288 | 25 | 86 | 113 | 65 | 92 | 30, 36 |
| 80.08.23# | 33.07 | 75.69 | 5.2 | 14 | 265 | 14 | 45 | 130 | 80 | 100 | 30, 36 |
| 80.08.23# | 32.89 | 75.83 | 5.2 | 13 | 320 | 5 | 90 | 140 | 85 | 90 | 30, 36 |
| 80.11.19# | 27.47 | 88.80 | 6.0 | 14 | 214 | 71 | 12 | 120 | 78 | 160 | 37 |
| 86.04.26# | 32.23 | 76.39 | 5.5 | 13 | 254 | 16 | 22 | 143 | 84 | 105 | 30, 36 |
| 86.07.16# | 31.10 | 78.08 | 5.6 | 13 | 305 | 8 | 90 | 125 | 82 | 90 | 30, 36 |
| 88.08.20* | 26.72 | 86.63 | 6.4 | 35 | 137 | 89 | 113 | 230 | 23 | 2 | CMT |
| 88.10.29 | 27.87 | 85.64 | 5.4 | 18 | 309 | 30 | 109 | 106 | 62 | 79 | CMT |
| 91.10.19 | 30.77 | 78.79 | 6.5 | 16 | 298 | 9 | 97 | 141 | 81 | 68 | 38 |
| 95.02.17 | 27.64 | 92.37 | 5.2 | 35 | 322 | 46 | 188 | 226 | 84 | 216 | CMT |
| 97.01.05 | 29.87 | 80.56 | 5.6 | 15 | 279 | 19 | 68 | 122 | 73 | 97 | CMT |
| 98.09.26 | 27.77 | 92.81 | 5.4 | 33 | 233 | 26 | 118 | 22 | 67 | 77 | CMT |
| 99.03.28 | 30.51 | 79.40 | 6.4 | 15 | 279 | 10 | 76 | 113 | 80 | 92 | CMT |
| 99.03.28 | 30.31 | 79.39 | 5.4 | 15 | 280 | 7 | 75 | 115 | 83 | 92 | CMT |

The first nodal plane is considered as the fault plane, except those marked with*; for these earthquakes any of the nodal planes could be the fault plane. The earthquakes marked with # indicate the epicentral location of Zhao and Helmberger³³. For the rest of the earthquakes, epicentral locations reported by ISC are used.

layan wedge. The detachment lying under the Outer and Lesser Himalaya slips during the occurrence of great earthquakes on it, whereas the detachment under the Higher and Tethys Himalaya slips aseismically. In their model, the moderate-magnitude thrust earthquakes of the HSB occur in the region between the seismically active and aseismically slipping parts of the detachment. They referred to it as the Basement Thrust Front (BTF) and proposed that the ruptures of thrust earthquakes of the BTF lie on the brittle components of the MCT²⁹. Ni and Barazangi³⁰ considered some additional focal mechanisms of the Himalayan earthquakes and suggested that all these earthquakes occurred on the detachment. Baranowski *et al.*³¹ estimated the focal depths and focal mechanisms of nine earthquakes. They suggested that in the eastern part of the Himalaya, the earthquakes having gentle dips occurred on the detachment. The earthquakes in western Nepal and neighbouring India indicated slip on steep planes. They suggested that there could be two possibilities: (i) all these earthquakes occurred on the detachment, which also consists of a ramp under the Higher Himalaya, and (ii) these earthquakes occurred on faults shallower than the detachment level and represent the deformation of the overriding plate. Molnar³² suggested that either the earthquakes with steeper dip did not occur on the detachment or the detachment dips steeply where these earthquakes occurred.

With the availability of some more Harvard Centroid Moment Tensor (CMT) focal mechanism solutions and also the results of other studies relevant to the theme of this communication, we analyse the occurrence of these earthquakes. Table 1 shows all the available focal mechanisms for the moderate earthquakes in the Himalaya. In our analysis, we have preferred the focal mechanisms and focal depths obtained from the conventional body waveform inversion over the automated waveform inversion as done in CMT solutions. Thus, it may be seen in Table 1 that prior to 1988, earthquake focal mechanisms obtained from conventional body waveform inversion are used, whereas for the later period CMT solutions are used. Further, we noticed that for majority of the Himalayan earthquakes, the epicentral locations given in CMT catalogue are generally south of the locations given by ISC or USGS, sometimes off by 50–70 km. For example, for the 1986 and 1991 earthquakes in the Garhwal Himalaya, CMT-derived respective epicentres are about 70 km south of those estimated by ISC, USGS or local agencies such as India Meteorological Department (IMD). Hence, we do not use the estimates of epicentral locations given in CMT catalogue. Zhao and Helmberger³³ relocated some of the Himalayan and Tibetan earthquakes using the travel time determinations from the short-period data. We consider these locations to be more accurate and prefer them over ISC and USGS locations. The epicen-

tral distribution and the focal mechanism solutions are shown in Figure 2. It appears that the thrust earthquakes of HSB occurred in a very narrow belt, not wider than 20–25 km. This feature emerged only when epicentres determined by Zhao and Helmberger³³, ISC and USGS, in that order of preference, were used in Figure 2. If we use the estimates of epicentres as reported by Baranowski *et al.*³¹, Ni and Barazangi³⁰ and CMT catalogue, the earthquake belt appears wider (about 40–50 km) as inferred by these authors. In Figure 3, we show the cross-sections across four segments (a, b, c and d in Figure 2) of the Himalaya and plot the focal depths and the dips of the inferred fault planes of earthquakes with thrust-type focal mechanisms. The gently dipping north to northeastward nodal plane is assumed to be the fault plane as most of the mapped geological faults dip in that direction. In Figure 3, we also plot the focal depths of earthquakes of HSB from ISC Bulletin (1964–1997), estimated from more than four consistent *P*–*pP* observations. During 1964 to 1997, we identified 40 such earthquakes in the Himalaya, apart from those listed in Table 1. Majority of these earthquakes occurred at depths shallower than 30 km. In all the four cross-sections, it can be seen that the fault planes of the earthquakes that are located farthest in the north or northeast direction have steeper dip and generally, the focal depths are more. We assume that the detachment under the southern limit of the Outer Himalaya has a depth of about 5 km and dips gently towards the north or northeast^{21,34}. We infer the dip of the detachment and the location and geometry of the ramp in each cross-section from the depth and dip of the fault planes of thrust earthquakes in that segment and from the other available constraints (see above). The flat in each panel of Figure 3 denotes the seismically active detachment under the Outer and Lesser Himalaya, which slips episodically during the great Himalayan earthquakes. In Figure 3a the distribution of focal depths suggests that

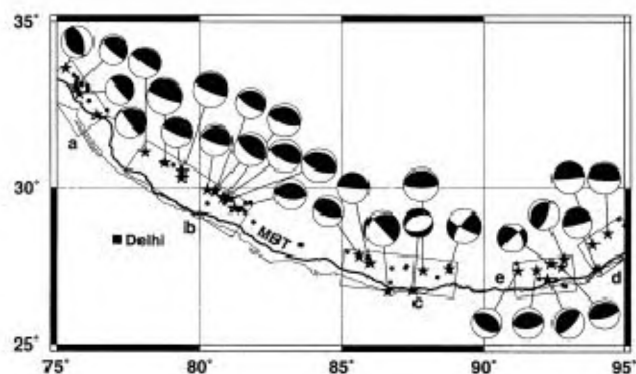


Figure 2. Available focal mechanisms in the Himalaya. Focal depths and the inferred fault planes of the earthquakes of five segments (a to e) of the Himalayan arc are projected in cross-sections of Figure 3. The four fault plane solutions in segment e, based on first motion data only²⁸, are shown south of the MBT.

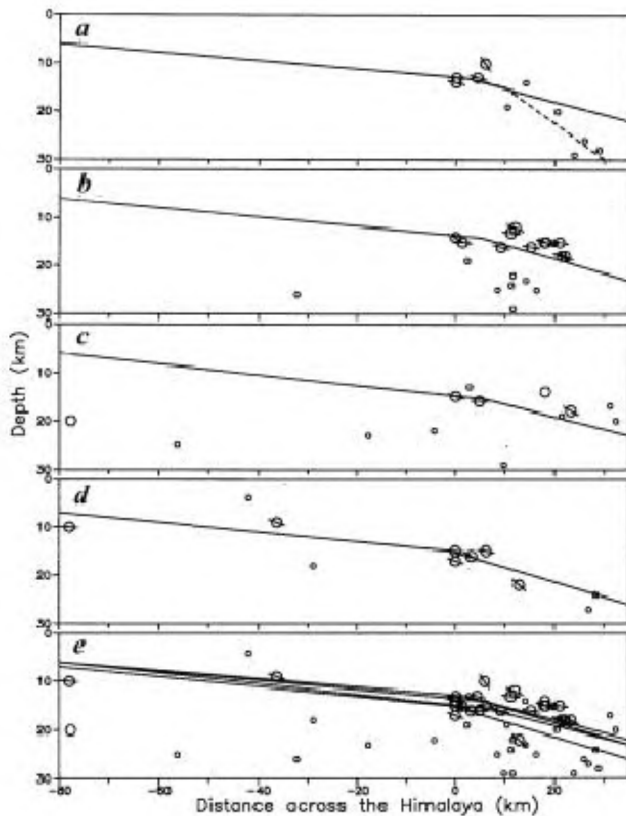


Figure 3. Focal depths and the inferred fault planes of the earthquakes in five Himalayan segments of Figure 2 are plotted in four vertical cross-sections. The earthquakes of segments (d) and (e) of Figure 2 are plotted in panel *d*. The lowest panel is a composite cross-section of all four individual sections. Lines through circles denote the dip of the fault plane of thrust earthquakes. Bigger circles denote the hypocentres of the earthquakes of focal mechanism other than thrust type. Smaller circles denote the hypocentres of earthquakes whose focal depths have been estimated on the basis of surface reflected phases. The flat in each panel denotes the portion of the detachment that lies under the Outer and Lesser Himalaya. The dip and location of the ramp in each panel is largely constrained by the focal depths and fault plane solutions of the earthquakes.

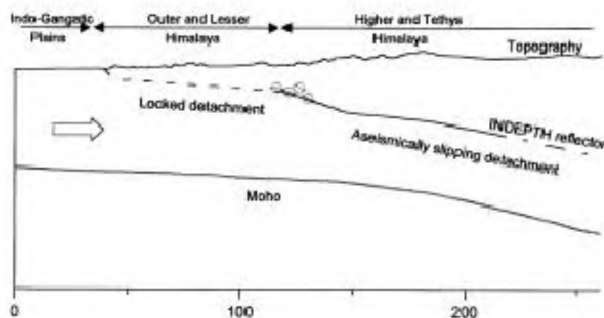


Figure 4. General cross-section across the Himalaya. The detachment under the Outer and Lesser Himalaya, i.e. updip of the ramp, remains locked during the interseismic period (shown with dashed line), whereas the detachment under the Higher and Tethys Himalaya, i.e. downdip of the ramp, slips aseismically (shown with continuous line). Thus the ramp lies in the transition zone between the seismically active and aseismically slipping detachment. Moderate thrust earthquakes of HSB occur on and above the ramp, as the detachment lying updip remains locked. The detachment under the Tethys Himalaya, shown with dashed and dotted line, roughly coincides with the reflector seen in the INDEPTH profile.

the ramp could be steeper in this segment (shown with dashed line in Figure 3*a*). This appears to be consistent with the available fault plane solutions of earthquakes lying further west of this cross-section³², which have steeper dips (about 40–50°). The reason for the steep dip of the ramp could be the proximity of this region to the western syntaxial bend. The location of the ramp in Figure 3*c* is mainly constrained by the hypocentral distribution of microearthquakes in the Nepal Himalaya (figures 4 and 6 of Pandey *et al.*²), as there are not many earthquake focal mechanisms available in the corresponding segment (c) of Figure 2. In the cross-section shown in Figure 3*d*, we plotted fault planes corresponding to four additional earthquakes and their ISC-reported focal depths, based on reflected phases³⁰. These earthquakes occurred in segment (e) of Figure 2 that lies between segments (c) and (d). The fault plane solutions of these earthquakes (Table 1) are based on first motion data and hence probably are not well constrained. In fact, a preliminary examination of the observations used for construction of fault plane solutions suggests a relatively gentler north-northeastward dipping plane for the earthquakes of 18 February 1964, 1 September 1964 and 26 September 1966 (see Chandra²⁸, p. 267).

In Figure 3, a more or less systematic increase in focal depths and dips of the fault planes of the earthquakes of the HSB in north-northeast direction may be observed, which makes it plausible that the detachment there dips steeply, indicating the presence of the ramp. Further, these cross-sections reveal that most of the earthquakes generally occurred on and above the inferred crustal ramp.

Thus the available thirty focal mechanisms and focal depths of the moderate earthquakes derived from the inversion of body waveforms and focal depths of forty additional Himalayan earthquakes derived from the ISC-reported surface-reflected phases, provide further support for the presence of a mid-crustal ramp under the Himalaya, which has also been reported on the basis of analysis of gravity data, uplift rates derived from the heights of uplifted terrace, microseismicity, wide-angle seismic reflection data and geological cross-sections. It lies under the northern Lesser and southern Higher Himalaya, at a depth range of about 15–25 km and has a dip of about 15–20°. The dip of the ramp may be steeper in the region close to the western and eastern Himalayan syntaxial bends.

We suggest that moderate-thrust earthquakes of the HSB occur in a narrow belt of 25 km width. Some of these earthquakes occurred on the mid-crustal ramp that lies in the transition zone between the seismically active and aseismically slipping detachment, whereas a few seem to have occurred on fault planes parallel to the mid-crustal ramp, but lying above it. Thus, these earthquakes represent the internal deformation of overthrust-

ing Himalayan wedge in response to the locking of the updip detachment (Figure 4).

It is conceivable that at the Himalayan convergent plate margin the direction of maximum principal stress (σ_1) lies in the same direction as that of the Indian plate motion, i.e. north to northeast, and dips gently under the Himalaya. Thus it seems reasonable that relatively steep planes having dip of about 15–20°, the same as that of the mid-crustal ramp, should be relatively more favourably oriented with respect to σ_1 for failure, than those dipping gently (>10°). Out of 26 focal mechanisms of thrust earthquakes (Table 1), 18 earthquakes occurred on relatively steeper planes (dip $\geq 14^\circ$). Thus it appears that in the Himalaya, majority of thrust earthquakes occur either on the ramp or on shallower fault planes parallel to it.

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ACKNOWLEDGEMENTS. We thank the Director, NGRI for permission to publish this paper. Comments of an anonymous reviewer are greatly appreciated. We thank Ajay, Ravi and PC for their help and suggestions. We acknowledge support from H. C. Tewari, M. Kousalya and E. C. Malaimani. Financial support from CSIR to Kalpna is acknowledged. Figure 2 was made using the GMT software³⁹.

Received 11 June 2001; revised accepted 27 September 2001