Laterally heterogeneous seismic vulnerability of the Himalayan arc: A consequence of cratonic and mobile nature of underthrusting Indian crust

The Chamoli earthquake of 29 March has again focused the attention of scientists, engineers and the government on the imminent vulnerability of the Himalayan belt. The general understanding about the Himalayan earthquakes has been that over the past 100 years or so the western (from Kashmir to Kumaun) and eastern (from Assam to Bihar) parts of the Himalayan belt have been seismically active and releasing the built-up seismic energy as evidenced from at least three great earthquakes (i.e. $M > 8$ on the Richter scale). These are Kangra (1905), Bihar–Nepal border (1934) and Assam (1950)[1–3] (Figure 1 *a*, *b*). Both eastern and western sectors have been releasing the built-up seismic energy from time to time. Although the Meghalaya (or Shillong) great earthquake of 1897 is also included among the Great Himalayan earthquakes, its epicenter is located significantly south of the major Himalayan thrust belts, and hence it may not be strictly a 'pure' Himalayan earthquake.

However, the central Himalayan arc (CHA) – a region intervening between the eastern Himalayan arc (EHA) and western Himalayan arc (WHA) and lying between ~ 80 and 86°E – has largely remained 'seismically sleepy'. The dormant nature of the CHA has been widely termed as the seismic gap[1,4] (Figure 1 *b*) implying that although the stress is continuously building up all along the Himalayan arc due to the ongoing convergence between India and Eurasia[5] it has not relaxed in the central Himalayan region through the earthquake process. No great earthquake ($M > 8$) has taken place in the central Himalaya over the past 300 years or more except the historically assessed major events ($M \sim 7$) of 1803 (Uttarkashi) and 1833 (Nepal), in spite of the requisite strain build-up[6,7]. At present the CHA possesses a very high probability[8] of an imminent great earthquake. Within the CHA one or more great earthquakes ($M > 8$) are anticipated[9] for quite sometime now (or overdue!). Some recent studies at much finer scales indicate more seismic gaps even within the eastern and western Himalayan sectors[9,10].

In view of the 'inordinate delay' in occurrence of the imminent great earthquake(s), it may be reasonable to examine whether there might exist some hitherto unnoticed factors which could be responsible for this 'long-stretching' of the recurrence interval between two great earthquakes within the CHA. Since great earthquakes in Himalaya appear to be the result of the underthrusting of the Indian continental lithosphere beneath Southern Tibet[10–12] (Figure 2), it may be appropriate to check if the nearly 2500 km long front of the Indian crust entering under the Himalaya is homogenous (uniform) all along the east–west strike of the collision zone. And if a significant arc-parallel variation exists in the physico-elastic properties of the Indian crust underthrusting the Himalayan arc, then the associated recurrence period (t) may also be similarly affected and could be substantially different for different sectors of the Himalaya. Societally also, the recurrence period or the time interval between two successive large earthquakes is indeed a very important factor, because as Chander[13] has pointed that in case such a great earthquake occurs in the central Himalayan region, then a large part of the adjoining and very densely populated Indo-Gangetic plain may be severely affected (Figure 1 *a*).

From the surface geology and tectonics[14] (Figure 3), it is clear that the Indian crust interfacing the Himalayan front is made up of three broad zones, the Delhi–

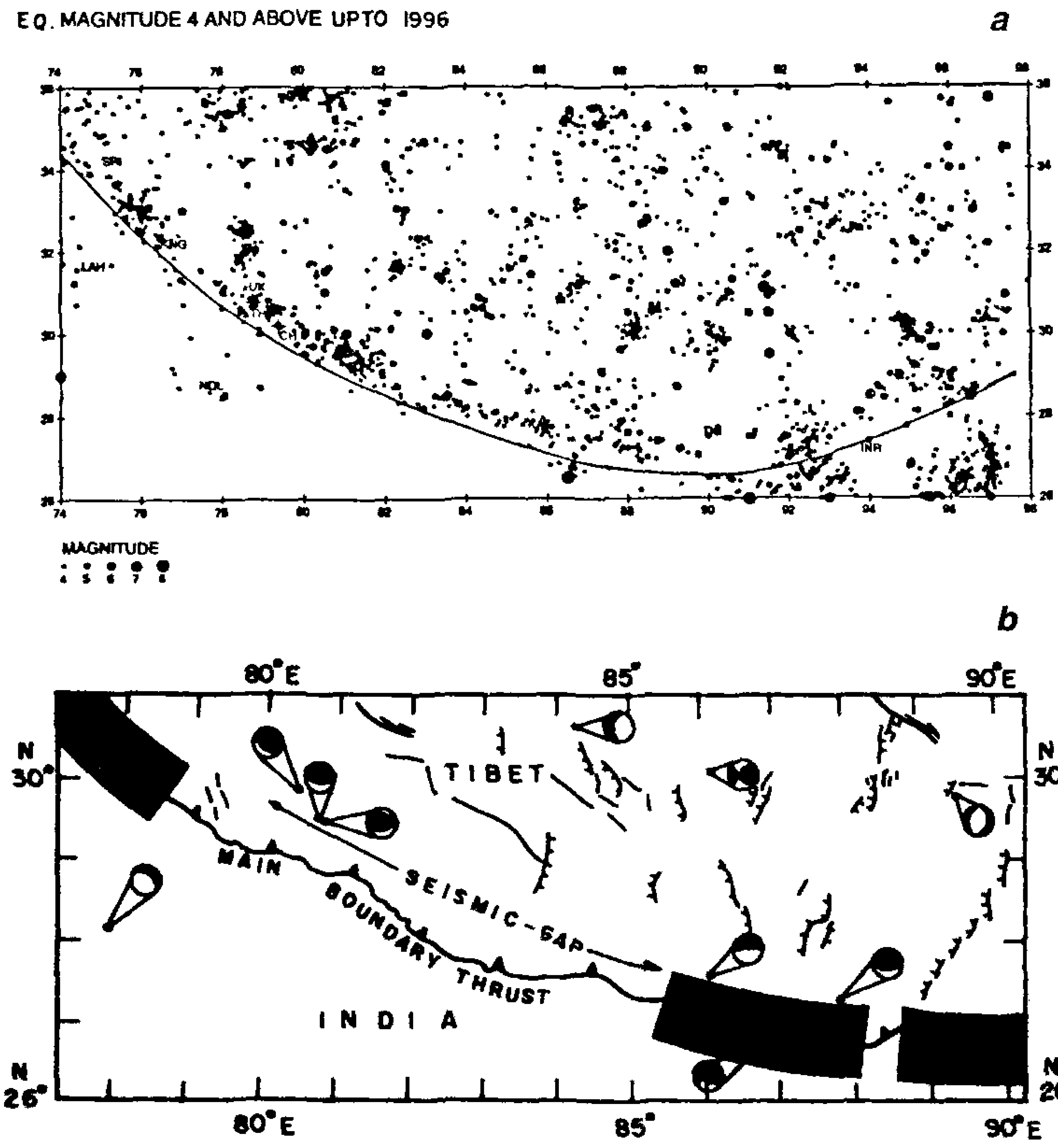

Figure 1. *a*, Spatial distribution of earthquake epicenters along the Himalayan arc (NGRI Earthquake Group, 1999). The lack of high energy release between 80° and 86°E is noticeable; *b*, Great earthquakes of magnitude > 8 along the Himalayan collision belt. Seismic gap in the central part of the Himalayan arc is also shown (Pandey *et al.*[40]).

Aravalli mobile belt (DA-MB), the Bundhelkhand craton (B-C) and the Satpura mobile belt (ST-MB), which seem to enter the WHA, CHA and EHA, respectively. Each of these units also has certain anti-clinal and syn-clinal structures as deduced from potential field data[15] over the fore deep basins. From palaeocurrent studies Valdiya[16] has postulated a continuity of structural elements[17,18] of the northern part of the Indian shield below the Himalaya. This is also clearly depicted by Gaur[19] (see figure 3 in his article). Similarly, the gravity anomalies[20,21] and surface wave studies[22] also bring out the distinct lateral variation in the geophysical parameters of the crust beneath the peninsular shield adjoining the Himalayan front. The Bouguer gravity anomaly map of India[20] clearly shows a gravity low in the central part of the Indo-Gangetic plain. This relative low is similar to that over the Dharwar craton and hence corresponds to the B-C and its northward extension. This implies that the properties of the Indian continental lithosphere slipping under the collision zone would vary along the strike of the Himalayan front in different sectors[23] of the Himalayan arc.

With regard to the above, it is also pertinent that the recent Global Positioning System (GPS) studies[6,7], particularly along the Kathmandu–Bangalore line have provided quantitative constraints[24] of certain parameters of the ongoing collision process. This study deduces 'strain' in the central Himalayan gap by combining it with the 'slip' for the 1934 Bihar–Nepal earthquake[6], obviously implying an arc-parallel homogeneity. A number of recent studies[10] have also tried to constrain the slip rates along the Himalaya. For example, (i) in the Potwar plateau the slip rates[25] are 9–14 mm/yr in the western region, 13 mm/yr in the central region and 7 mm/yr in the eastern region[26], (ii) at the Kangra reentrant the shortening rate is 14 ± 2 mm/yr (ref. 27), and (iii) in Nepal and Assam it is 18 mm/yr (refs 12, 28). Another observation is that the difference in the convergence vector and earthquake slip vector increases westward from 0 at 89°E to 300 in Pakistan[9].

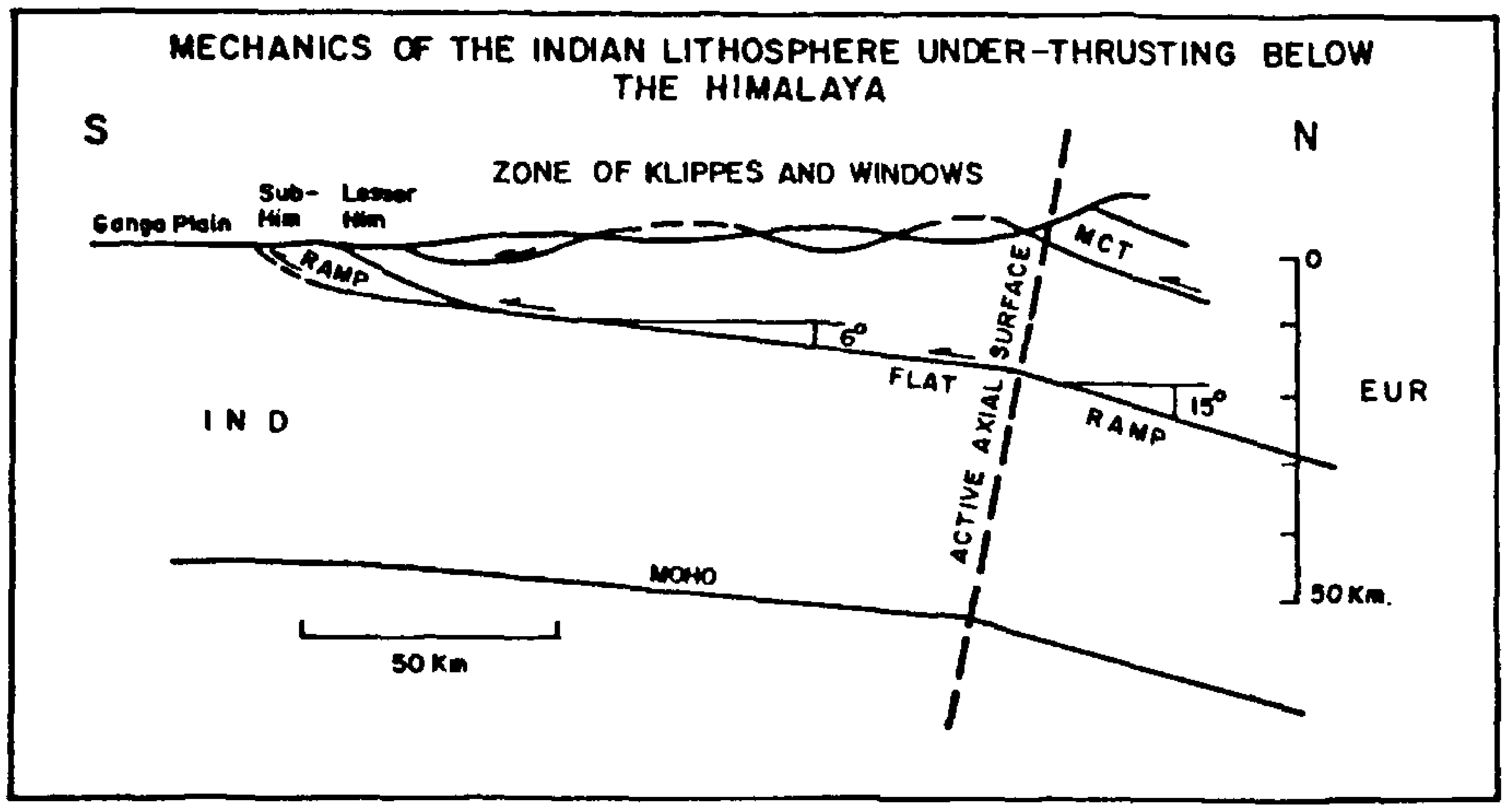

Figure 2. Model of the underthrusting of the Indian lithosphere beneath the Eurasian plate. The great magnitude earthquakes are expected due to slip along the flat shown in the figure (Yeats and Thakur[10]).

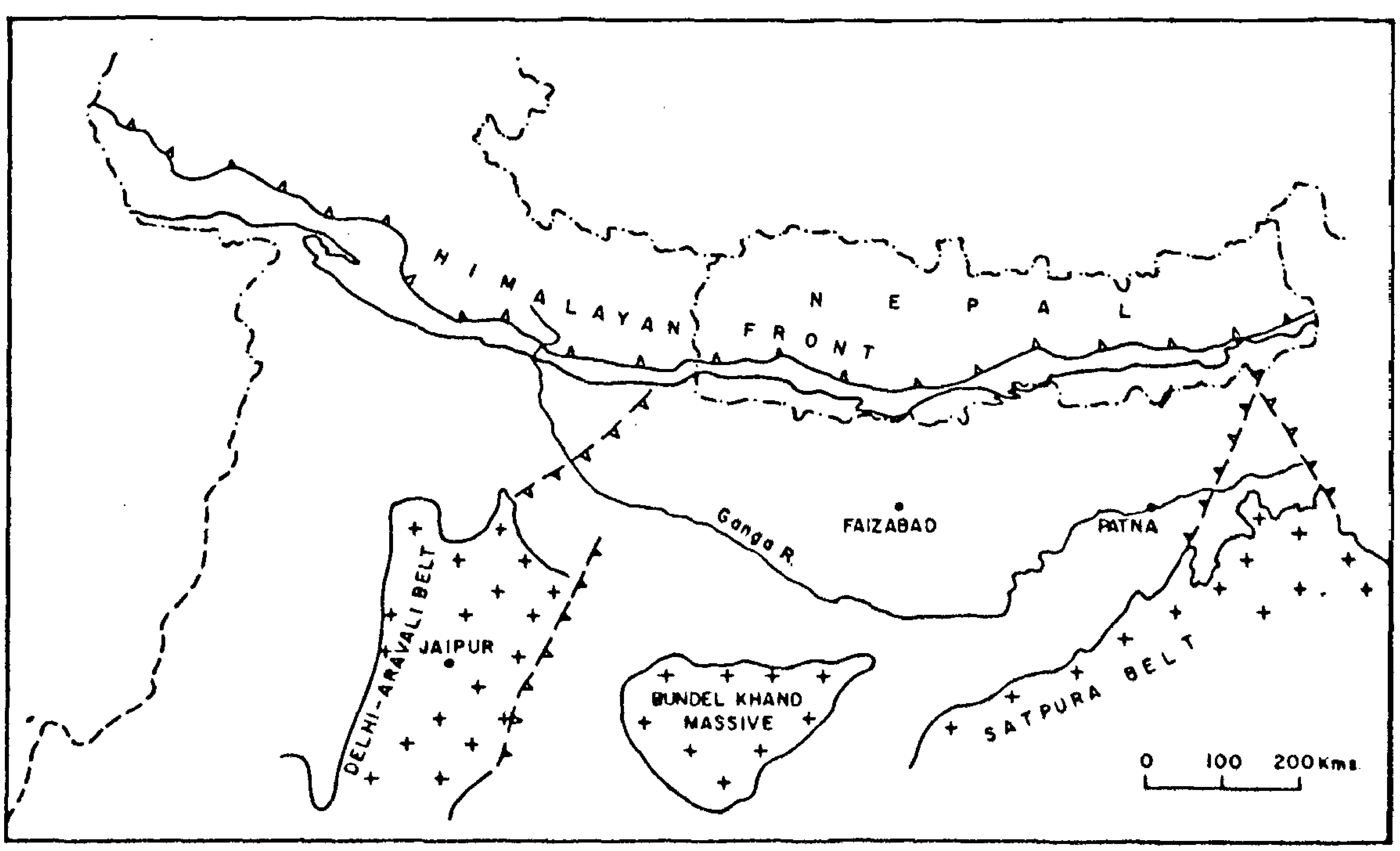

Figure 3. Himalayan collision front and the three major geological and tectonic zones (Delhi–Aravalli belt, Bundelkhand craton and Satpura belt) which seem to be entering below the Himalayan front (modified after Raiverman et al.[15]). It may be noted that the Bundelkhand craton correlates with the central Himalayan arc (or seismic gap).

A recent model study[29] also favours an arc-parallel variation in the slip. Although the slip rates estimated from geology (long-term) and seismicity/geodesy (short-term) are nearly consistent, those from tectonic morphology[10] are much smaller (5 mm/yr) in Nepal. The substantial differences in the measured values re-emphasize arc-parallel non-uniformity. Bilham *et al.*[9] have emphasized the need for extensive GPS studies to illuminate the subsurface distribution and rate of strain in southern Tibet and the Himalaya for both arc-normal and arc-parallel directions.

As a matter of fact, along-the-strike lateral variability of the convergence zones of the plate tectonic scenario and its consequences on the earthquake processes are being increasingly recognized[30]. Similar and significant variation in the crustal strength along the strike of the Himalayan collision (compressional belt) has also been strongly brought out[18,31,32]. As noted above, the northern part of the Indian continental crust underthrusting the Himalayas seems partly cratonic (in the CHA) and partly of the mobile type (under the EHA and WHA). This difference could be critical as Johnston[33] proposed that the order of magnitude difference may exist in the strain rates $\dot{\varepsilon}$ of cratons (10^{-8}–10^{-9} yr^{-1}) and mobile belts (10^{-7}–10^{-8} yr^{-1}). For example, it has been estimated from cumulative seismic earthquake moment[34] that the average seismic strain rate ($\dot{\varepsilon}$) for the central and eastern United States is ~ 10^{-12}–10^{-11} yr^{-1}, which evidently is less compared to those at the plate boundaries (10^{-6}–10^{-7} yr^{-1}). However, even within the mid-continental region Anderson[35] has identified pockets of relatively higher seismic strain rates of ~ 10^{-8} and 10^{-9} yr^{-1} in the New Madrid Seismic Zone (NMSZ) and Middleton Place Sumerville Seismic Zone (MPSSZ) near Charleston, South Carolina respectively . Thus, strain rates may significantly vary over continents. The recurrence interval (τ) seems to depend inversely on the strain rate ε provided other factors such as slip and length involved are same[36]. Hence, if ($\dot{\varepsilon}_{c,m}$, $\tau_{c,m}$) represent the pair of strain rate and recurrence interval in the cratonic (c) and mobile (m) type continental crusts, then $\tau_c = 10\ \tau_m$ for $\varepsilon_c = 10^{-1}\ \varepsilon_m$. Since the CHA seems to overly the B-C (Figure 3), while the basements beneath the EHA and WHA are most likely similar to the DA-MB and ST-MB mobile belts[34] respectively, the recurrence interval in the CHA could stretch up to an order of magnitude greater than those for EHA and WHA (Figure 4). Thus if the recurrence period for mobile type crust is 300 years, then for a cratonic crust it may be as long as 3000 years, and such a situation could cause the observed *temporal delay* of the so-called *seismic gap*.

In addition to the mobile type crust, another geodynamical event may also reduce the crustal strength of the underthrusting Indian crust beneath the EHA and WHA. It is the outburst of the Reunion plume at ~ 65.5 Ma near the central western margin of the subcontinent (Figure 5). Klootwijk *et al.*[37] have suggested that this event had extremely closely preceded the indentation of India with Eurasia. Due to the difference in lithospheric properties beneath cratons and mobile belts, the vertical and lateral diffusion of thermomagmatic flux spreading due to plume outburst, at the base of the continental lithosphere, would be facilitated under the MBs (DA-MB and ST-MG) but will be resisted by the B-C (see Figure 5). This scenario is duly supported by gravity signatures[20], seismic shear-wave velocity in the Ganga basin[38] and seismic tomographic imaging across Narmada-Son trend and Vindhyan[39].

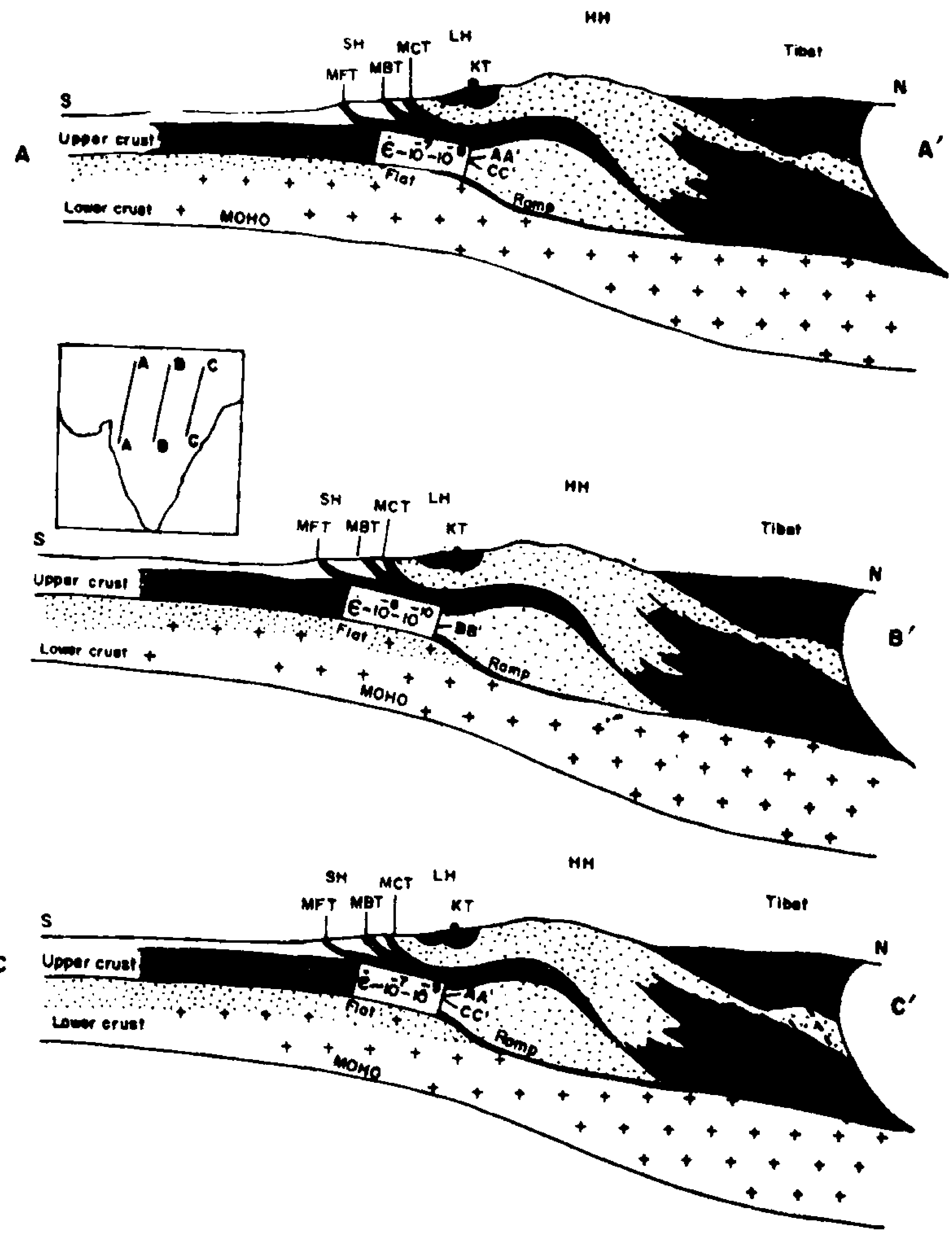

Figure 4. Three north–south sections of the Indian lithosphere underthrusting Tibet. AA', BB', and CC' represent sections with regard to the western, central and eastern Himalayan arc respectively (modified after Pandey *et al.*[40]). Possibility of lateral variations in the crustal strain rate ($\dot{\varepsilon}$) particularly along flats may be noted. It arises due to very low values for the cratonic part under BB' (in the seismic gap or CHA) relative to higher strain rates in the mobile type crusts under AA' and CC' (in WHA and EHA).

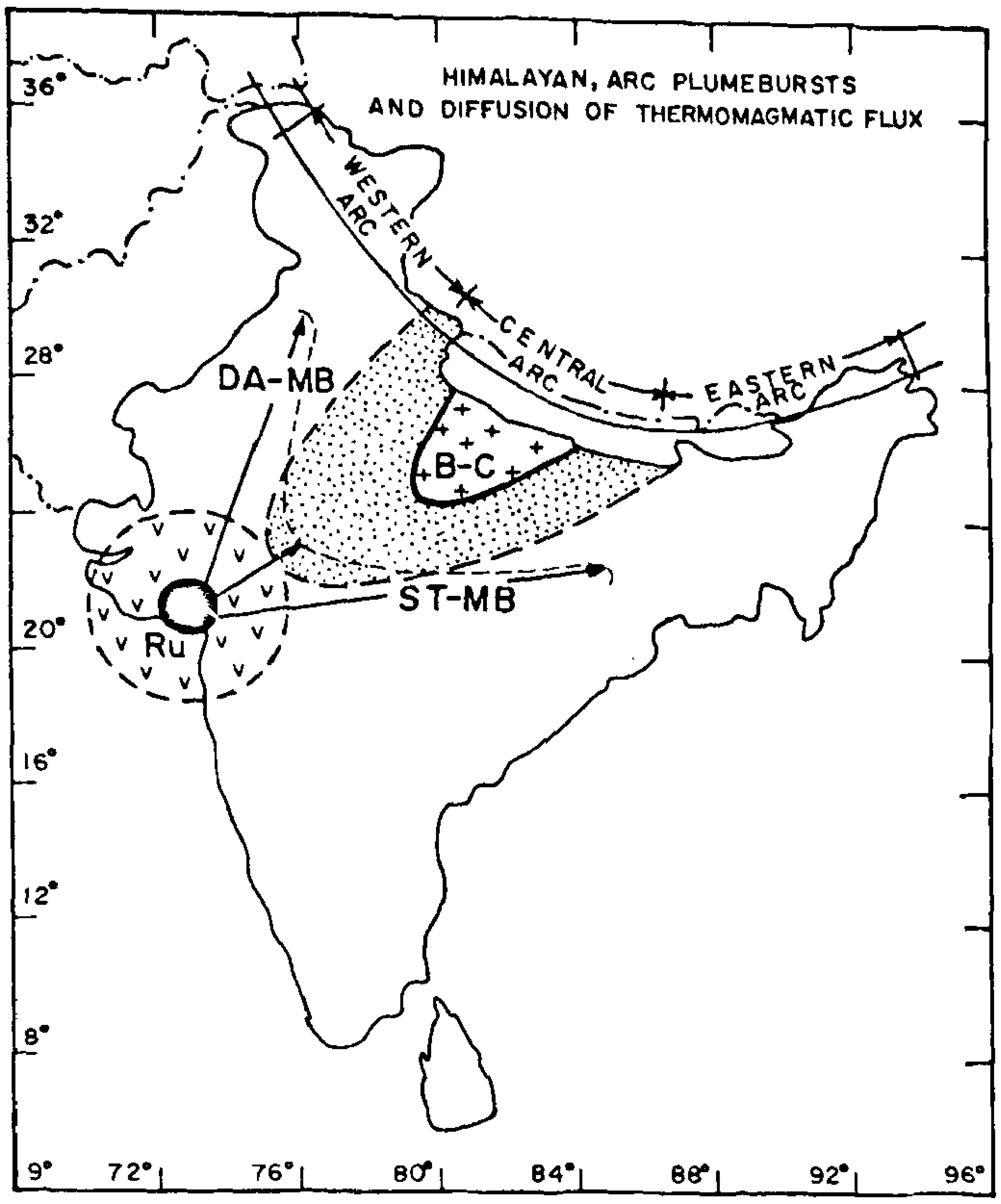

Figure 5. Outward flow of the thermomagmatic flux due to outburst of Reunion plume (at ~ 65–66 Ma). The thermomagmatic flux flow relatively much easily below the Delhi-Aravalli (DA-MB) and Satpura (ST-MB) mobile belts while being resisted by the Bundelkhand craton (B-C). This implies relative weakening of the western and eastern sectors when compared to the central Himalayan arc.

Such a differential diffusion might also contribute in shaping the Himalayan arc including its syntaxial regions.

It is interesting to note that Chamoli and Uttarkashi regions (Figure 1 *a*) may be lying near the boundary between the cratonic and mobile parts and may therefore experience large lateral gradients in the strain field. A well-planned palaeoseismological investigation may be used to check whether the recurrence period in central Himalaya is significantly greater than on its either side. Delineation and estimates of crustal heterogeneity, specially in rheology, of different segments of the northern part of the Indian crust underthrusting the Himalaya are needed. Deep seismic sounding, seismic tomography and magnetotelluric investigations need to be deployed to delineate the nature of the western, central and eastern segments.

As suggested by many workers, a well-planned approach needs to be evolved and adopted owing to peculiar geoecological problems of the hilly region. A well-focused natural hazard programme must be an essential part of such a package.

1. Khattri, K. N. and Tyagi, A. K., *Tectonophysics*, 1983, **96**, 19–29.
2. Seeber, L., Arumbruster, J. G. and Quittmery, R. C., *AGU Monogr.*, 1981, **3**, 215–242.
3. Molnar, P., *Ann. Geophys. B*, 1987, **5**, 663–670.
4. Khattri, K. N., *Tectonophysics*, 1987, **138**, 79–92.
5. Raval, U., *Mem. Geol. Soc. India*, 1995, **30**, 203–224.
6. Bilham, R., Larson, K., Ferymueller, J. and Project Idylhim members, *Nature*, 1997, **386**, 61–64.
7. Freymueller, J., Bilham, R., Burgmann, R., Larson, K. M., Paul, J., Jade, S. and Gaur, V. K., *Geophys. Res. Lett.*, 1996, **23**, 3107–3110.
8. Khattri, K. N., *Curr. Sci.*, 1999, **77**, 967–972.
9. Bilham, R., Blume, F., Bendick, R. and Gaur, V. K., *Curr. Sci.*, 1998, **74**, 213–229.
10. Yeats, R. S. and Thakur, V. C., *Curr. Sci.*, 1998, **74**, 230–233.
11. Hauck, M. L., Nelson, K. D., Brown, L. D., Zhao, W. and Ross, A. R., *Tectonics*, 1998, **17**, 481–500.
12. Gahalaut, V. K. and Chander, R., *Tectonophysics*, 1992, **204**, 163–174.
13. Chander, R., *Tectonophysics*, 1989, **170**, 115–123.
14. Valdiya, K. S., *Geophys. Res. Bull.*, 1973, **11**, 79–114.
15. Raiverman, V, Kunte, S. V. and Mukherjea, A., *Pet. Asia J.*, 1983, **6**, 67–92.
16. Valdiya, K. S., *Tectonophysics*, 1976, **32**, 353–386.
17. Valdiya, K. S., *Geol. Soc. Am. Bull.*, 1970, **81**, 451–468.
18. Valdiya, K. S., *Curr. Sci.*, 1994, **67**, 313–323.
19. Gaur, V. K., *Curr. Sci.*, 1994, **67**, 324–329.
20. Bouguer Gravity Anomaly Map of India, NGRI/GPH-2, 1975.
21. Qureshy, M. N., *Tectonophysics*, 1969, **7**, 137–157.
22. Singh, D. D., *J. Geodynamics*, 1999 (in press).
23. Ni, J. and Barazangi, M., *Tectonophysics*, 1985, **112**, 277–295.
24. Jackson, M. and Bilham, R., *J. Geophys. Res.*, 1994, **99**, 13897–13912.
25. Baker, D. M., Lillie, R. J., Yeats, R. S., Johnson, G. D., Yousuf, M. and Zamin, A. S. H., *Geology*, 1988, **16**, 3–7.
26. Leathers, M., MS dissertation, Oregon State University, Corvallies, Oregon, USA, 1987, p. 271.
27. Powers, P. M., Lillie, R. J. and Yeats, R. S., *GSA Bull.*, 1998, **110**, 1010–1027.
28. Avouac, J-P. and Tapponnier, P., *Geophys. Res. Lett.*, 1993, **20**, 895–898.
29. Peltzer, G. and Saucier, F., *J. Geophys. Res.*, 1996, **101**, 27943–27956.
30. Cloos, M., *Geology*, 1992, **20**, 601–604.
31. Raval, U., 1993, Proc. Indian Geophys. Union, Annual convention, 1991, pp. 129–140.
32. Raval, U., *J. Geol. Soc. India*, 1994, **43**, 629–646.
33. Johnston, A., *Nature*, 1992, **355**, 213–214.
34. Raval, U., *Mem. Geol. Soc. India*, 1995, **31**, 37–61.
35. Anderson, J. G., *Bull. Seismol. Soc. Am.*, 1986, **76**, 273–290.
36. Talwani, P., pers. commun.
37. Klootwijk, C. T., Gee, J. S., Peirce, J. W., Smith, G. M. and McFadeen, P. L., *Geology*, 1992, **20**, 395–398.
38. Chun, K, Y., *Bull. Seismol. Soc. Am.*, 1986, **76**, 1687–1698.
39. Rai, S. S., pers. commun.
40. Pandey, M. R. *et al.*, *Geophys. Res. Lett.*, 1995, **22**, 751–754.

Received 28 April 1999; revised accepted 28 December 1999

U. RAVAL

National Geophysical Research Institute, Hyderabad 500 007, India
(e-mail: postmast@csngri.ren.nic.in)