Eastern Ghats support the above data. Thus, sapphirine formation in the Eastern ghats and in the SGT probably took place at different times and this has a great bearing on the tectonic evolution of these two granulite terrains.

From Figure 1, it can be seen that all the sapphirine localities from eastern Kodaikanal ranges cluster around the Kambam fault extending from Kambam and cutting across the eastern Kodaikanal ranges. The present carbonatite and sapphirine locality lies at the southern extremity of the Kambam fault which trends in a NNE to NE direction.

It is to be noted that in northern Tamil Nadu, the carbonatite–syenite associations also occur along NNE trending major faults[22]. Hence, Kambam fault is comparable to the above major faults and sapphirine formation is closely linked to the Pan-African rifting and high temperature magmatism.

Thus, the present study describes a new sapphirine occurrence from Kambam valley which forms part of the SGT. This study also brings out the fact that most of the sapphirine assemblages of the Kodaikanal ranges, including the well-described Ganguvarpatti and Perumalmalai ones occur in a rather narrow tract, paralleling the NNE trending Kambam fault. The other well-known reports of Kiranur, Ellamankovilpatti and the Sittampundi also occur in the Palghat–Cauvery fundamental break.

The Kambam fault is akin to the major NNE trending deep crustal faults in northern Tamil Nadu and can be extended further northward to the Attur fault zone of Grady[22], which lies east of Tiruvannamalai. Incidentally, sapphirine-bearing assemblages have also been reported from Ponnakadu, 7 km west of Tiruvannamalai[2]. Carbonatite–syenite–shonkinite intrusives closely associated with these major crustal breaks, range in age from 800 to 670 Ma. Hence, these faults could well represent intracratonic lineaments of the Pan-African age.

The close spatial and temporal association of the sapphirine granulites to the deep crustal Kambam fault, which hosts carbonatite and syenite, strongly suggests that the sapphirine formation in the Kodaikanal ranges can be linked to the Pan-African tectonothermal event.

1. Muthuswamy, T. N. and Gnanasekaran, R., *J. Annamalai Univ.*, 1968, **23**, 183–196.
2. Grew, E. S., *J. Geol. Soc. India*, 1982, **23**, 469–505.
3. Mohan, A. and Windley, B. F., *J. Metamorphic Geol.*, 1993, **11**, 867–878.
4. Grew, E. S., *J. Geol. Soc. India*, 1984, **26**, 117–119.
5. Sivasubramanian, P., Natarajan, R. and Janardhan, A. S., *J. Geol. Soc. India*, 1991, **38**, 552–537.
6. Sivasubramanian, P., Natarajan, R. and Janardhan, A. S., *J. Geol. Soc. India*, 1992, **40**, 287–290.
7. Mohan, A., Prakash, D. and Motoyoshi, Y., *J. SE Asian Earth Sci.*, 1996, **14**, 221–243.
8. Subba Rao, D. V., Nirmal Charan, S. and Moeen, S., *J. Geol. Soc. India*, 1997, **49**, 7–12.
9. Ellis, D. J., *Contrib. Mineral. Petrol.*, 1980, **74**, 201–210.
10. Motoyoshi, Y. and Hensen, B., *Eur. J. Mineral*, 1989, **1**, 467–471.
11. Vielzeuf, D., *Contrib. Mineral. Petrol.*, 1983, **82**, 301–311.
12. Aranovich, L. Ya, Lavrent'eva, I. V. and Kosyakeva, M. A., *Geokhimiya*, 1988, N5, pp. 668–676.
13. Sengupta, P., Dasgupta, S., Bhattacharya, P. K. and Mukherjee, M., *J. Metamorphic Geol.*, 1990, **8**, 191–197.
14. Berman, R. G., *Can. Min.*, 1991, **29**, 833–855.
15. Jayananda, M., Janardhan, A. S., Sivasubramanian, P. and Peucat, J. J., *J. Geol. Soc. India*, 1995, **34**, 373–390.
16. Unnikrishnan-Warrier, C., Santosh, M. and Yoshida, *Geol. Mag.*, 1995, **132**, 253–260.
17. Anilkumar and Gopalan, K., *Curr. Sci.*, 1991, **60**, 653–655.
18. Odom, L. A., India, Rept UN Case 81-100084, 1982, pp. 1–9.
19. Rogers, J. J. W., Miller, J. S. and Clements, A. S., *Mem. Geol. Soc. India*, 1995, **34**, 11–23.
20. Grew, E. S. and Manton, W. I., *Precam. Res.*, 1986, **33**, 123–127.
21. Shaw, R. K., Arima, M. and Kagami, H., Abst. International workshop on the Proterozoic continental crust of southern India, Center for Earth Science Studies, Trivandrum (eds Santosh, M. and Yoshida, M.), 1966, pp. 123.
22. Grady, J. C., *J. Geol. Soc. India*, 1971, **12**, 56–62.

ACKNOWLEDGEMENTS. We thank Dr Steele of Chicago University, for the probe data. Prof. S. Sathyanarayan, Chairman, Dept of Geology is thanked for the facilities. Anto thanks UGC, New Delhi for financial support. A.S.J. acknowledges the IFCPAR programme under which the garnet ages were obtained. P.S. thanks the DST, New Delhi for financial assistance under the Young Scientists Programme.

Received 12 May 1997; revised accepted 25 August 1997

On the seismic vulnerability of Jabalpur region: Evidence from deep seismic imaging

P. R. Reddy, Kalachand Sain and A. S. N. Murty

National Geophysical Research Institute, Hyderabad 500 007, India

In light of our limitations in 'short-term earthquake prediction', detailed structural results from seismic studies could act as parametric inputs, in our pursuit for better understanding the seismicity of a region. A synthesis of seismic refraction/wide-angle reflection results of Hirapur–Mandla profile with other geological and geophysical signatures in central India, occurrence of seismic activity indicate presence of neotectonic activity. This assumes significance in light of the recent earthquake in Jabalpur region. Intense fracturing associated with the boundary fault near Jabalpur might have been responsible for the release of stress accumulated due to continuous northward movement of the Indian plate. It is suggested that detailed seismic surveillance is undertaken in and around the Narmada–Son lineament to more specifically pinpoint seismic vulnerability of the region.

THE controlled source seismic experiment is a powerful tool to image the crustal structure (faults/fracture zones) and subsurface velocity structure. It is well known that for a comprehensive understanding of a region's seismicity, one needs to know its genesis by understanding the role of faults/fractures present in the region.

A 240 km long deep seismic sounding (DSS) profile (Figure 1) was shot, from Hirapur to Mandla, to acquire analogue seismic refraction/wide angle reflection data. Processing of this data[1] has revealed that the crust is divided into four major blocks around deep faults at Narsinghgarh, Katangi and Jabalpur, and the block between Katangi and Jabalpur is uplifted.

Subsequently, travel time and amplitude modelling has been carried out using digitized record sections of the analogue data. For Katangi and Jabalpur region in the zone of Narmada–Son lineament (NSL), the forward modelling (Figure 2) by Murty *et al.*[2] has brought out (i) a horst structure and (ii) a prominent upwarp in the Moho horizon. Using travel time inversion of wide angle seismic data, shallow velocity structure (Figure 3) has been built up[3], which also corroborates presence of the uplifted block beneath Katangi–Jabalpur section. High velocity (6.5 km/s) lower crustal material appears to have come up to a depth of less than 2 km. There is a general qualitative agreement between the velocity structure and the Bouguer gravity anomaly (plotted on the top of Figure 3). The study also brings out the presence of low-velocity materials at the flanks of the horst structure. The intense fracturing associated with the boundary faults flanking the horst indicates that the block tectonics might have been active in this region. The Narmada–Son lineament has been the subject of investigating various geological and geophysical features and many such important results have been reviewed by Reddy *et al.*[4]. It is evident from their work that the crustal structure along and across the NSL is very heterogeneous and complicated in nature. As such this zone is susceptible for seismic activity. In a review note on NSL, Krishnabrahmam[5] has also pointed out that the Narmada region is far from being seismically quiet. ENE–WSW trending NSL (SONATA) in central India is a remarkable lineament zone – 1600 km long and 150–200 km wide – traceable across the Indian Peninsula between 72° and 88° longitudes and may further extend in either direction[6]. In the area of our present study this zone (Figure 1) seems to be lying between north of Katangi and south of Jabalpur. From the geological and tectonic signatures[7,8] it is evident that the deep seated fault south of Jabalpur is more or less forked into two branches from Jabalpur northeastward. As such the region closer to Jabalpur, which is at the boundary of the Katangi–Jabalpur block, is weak and susceptible for seismic activity. The epicenter (shown in Figure 1) of the recently occurred Jabalpur earthquake (May 22, 1997) is 30 km southeast of Jabalpur and falls on seismically active NSL in the central India. The isoseismal map of this earthquake prepared by Gupta *et al.*[9] shows NE–SW trend which, in general, agrees with the focal mechanism solution, indicating a dominant thrust component along a ENE–WSW nodal plane with a minor strike-slip component. The maximum intensity is assessed to be VIII on a MM scale and is observed in Jabalpur and surrounding region. Gupta *et al.*[9] reported only a few aftershocks but no foreshocks. Mittal *et al.*[10], while analysing crustal structure along Hirapur–Mandla and micro-earthquake information of the region have pointed out that the region west of Jabalpur could be identified as a pocket of higher seismicity. They also suggested that the concentration of micro-earthquake activity indicates probable recurrence of an earthquake of magnitude 6 to 6.5 near Jabalpur.

Studies in the Deccan Trap-covered area south of Katangi–Jabalpur zone have also yielded interesting results. This zone falls in the NSL region which is part of a suture between Bundelkhand and Deccan Protocontinents. NSL has been rejuvenated periodically since the Precambrian times. Hwang and Mitchell[11] noticed low Q_b (high attenuation) values for the central Indian crust and this has been attributed to the thermal effect of Deccan volcanism on the central Indian crust. Geomagnetic depth sounding (GDS) experiment[12] provided strong evidence for the existence of an elongated conductivity zone south of Jabalpur beneath the Satpura range (Satpura conductivity anomaly – SCA). The SCA embedded in a high heat flow zone[6] coincides with a prominent gravity high both on Bouguer and Isostatic anomaly map[13–15]. The area of conductivity anomaly is characterized by an uplifted Moho with a high velocity layer at mid crustal depth[16].

In addition to the above, results of surface wave studies[17] show an estimated thickness of 100 km for the lithosphere below central India based on the presence of low velocity zone and high attenuation at that depth. Reddy[18], while studying the low-velocity layers present beneath the Koyna, Latur and Central India, has suggested that a large part of Central India has been affected by mantle-plume activity. The region has a number of weak zones that might have acted as feeders for hot material injected into the crust-lithospheric system due to asthenospheric upwelling during the Deccan volcanism. Further, Reddy *et al.*[19] have also suggested the existence of deep rooted N–S trending sinusoidal structure between 70° and 90°E with undulations at every 5°. Accordingly a regional N–S extending ridge-like structure runs through Jabalpur, i.e. 80°E meridian. This would imply a major intersection between E-NE NSL and the N–S trend. The morpho-structural zoning scheme of Himalayan belt, foredeep and Indian shield[20] also indicates a first order N–S directed and approximately 1000 km long mega lineament along the 80°E meridian passing from Ongole to north of Jabalpur.

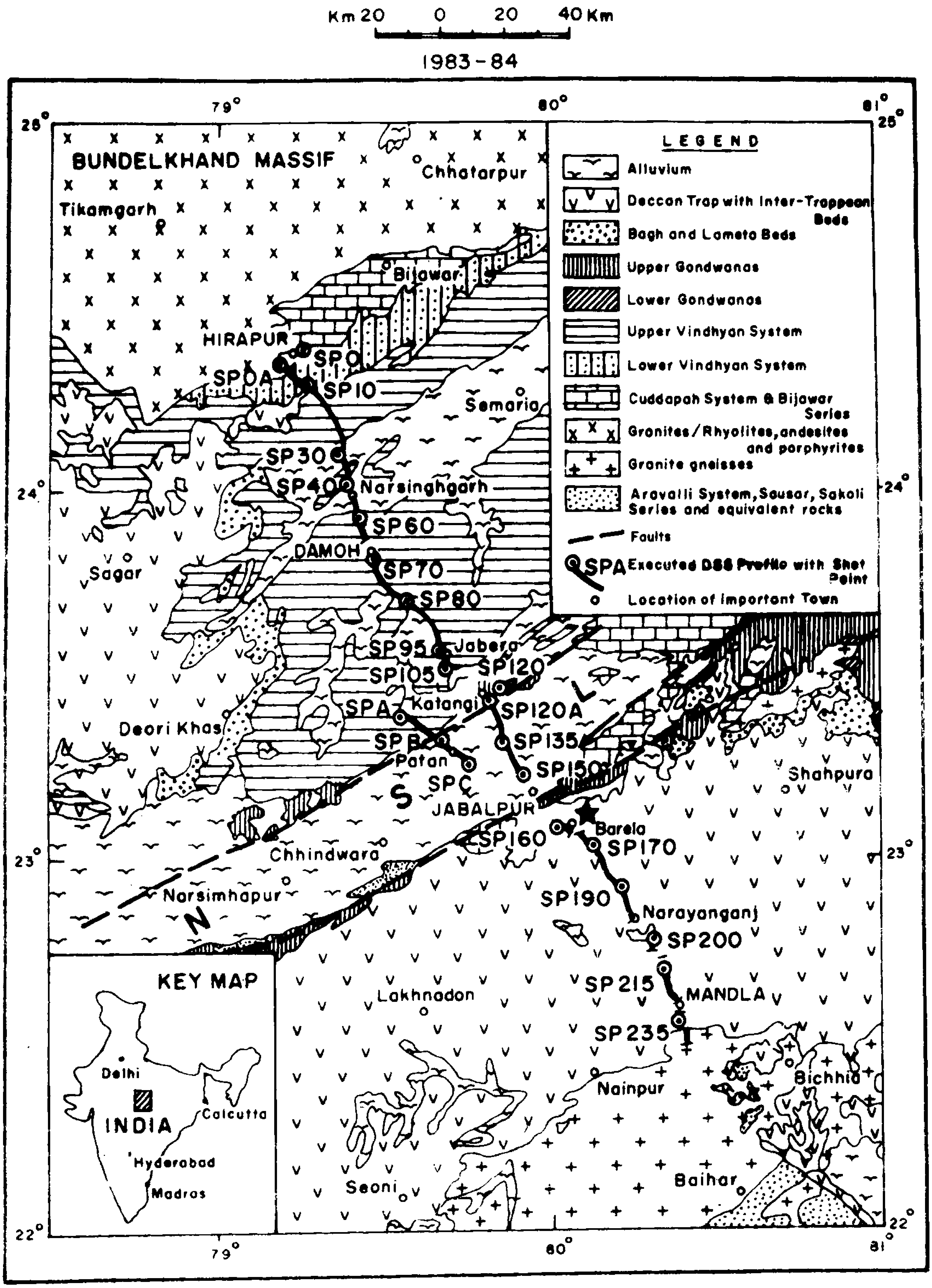

Figure 1. Location of the Hirapur-Mandla DSS profile in central India, shown on geological map. Star mark indicates the epicenter of Jabalpur earthquake (22 May 1997).

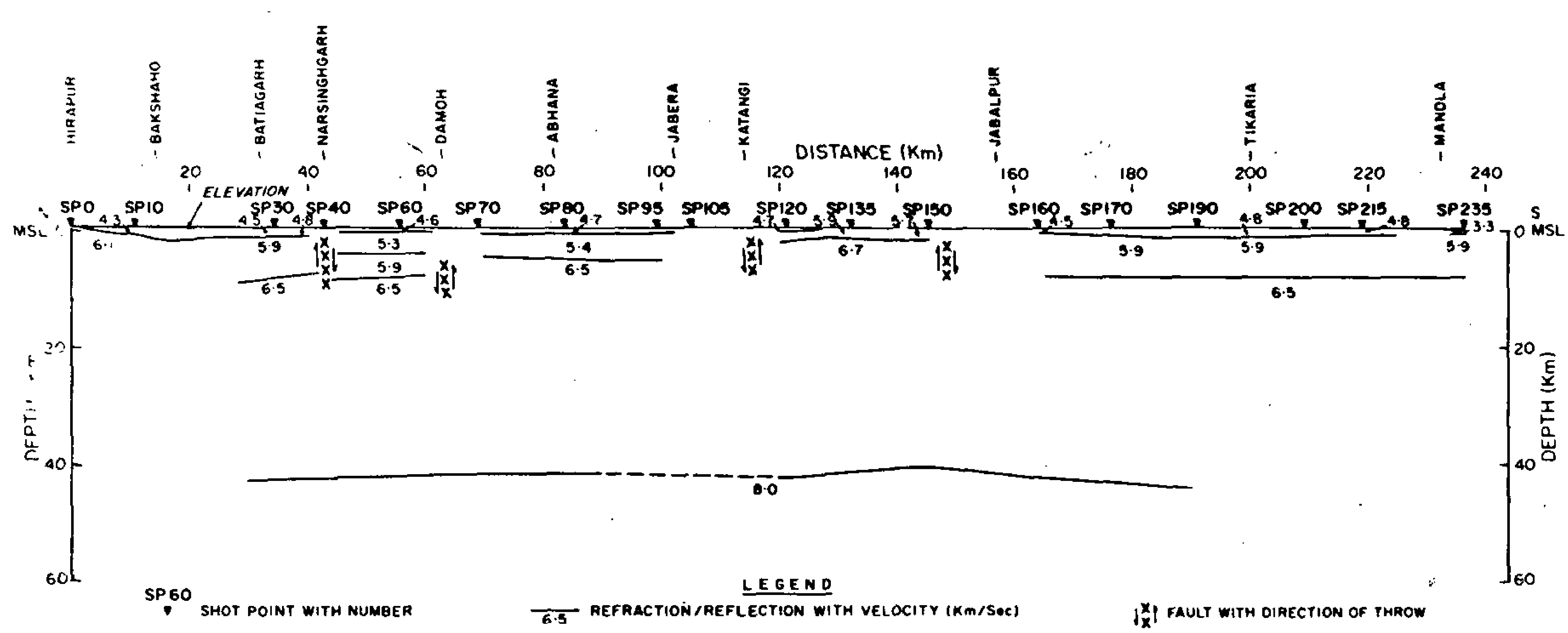

Figure 2. 2-D crustal velocity structure along the Hirapur–Mandla profile (after Murty *et al.*[2]).

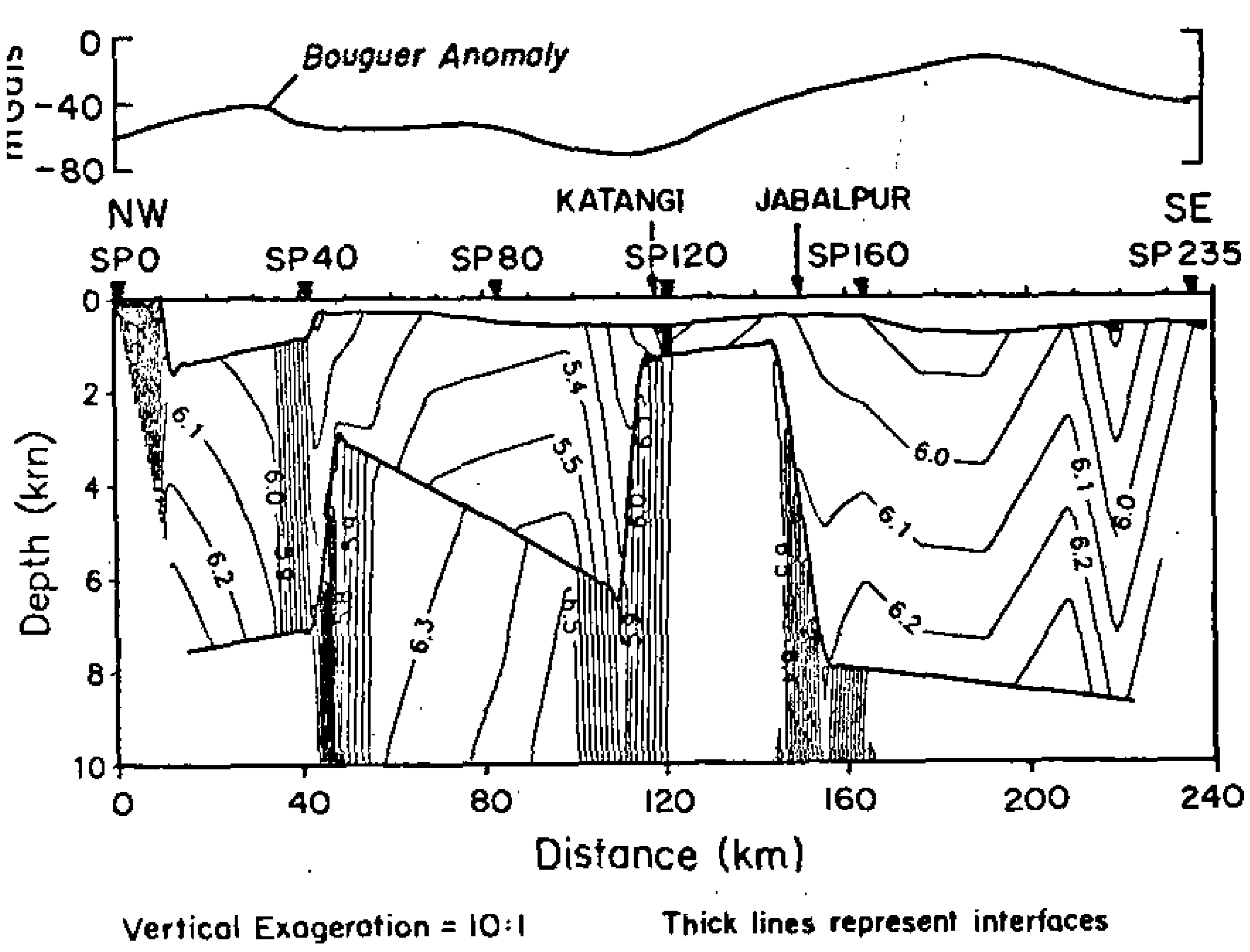

Figure 3. Shallow velocity (contour) structure along the Hirapur–Mandla profile. Thick lines represent interfaces (after Sain *et al.*[3]).

Short-range prediction of an earthquake namely exact time, location and magnitude is, as on today, not possible. However, in our pursuit to unravel the hidden mysteries associated with the worst natural calamity – earthquake, one needs to take into consideration various observations and data sets. The refraction and wide-angle reflection studies carried out in different parts of Indian sub-continent have brought out velocity–depth structural variations present at the upper, middle and lower crustal columns. It is noticed from different velocity–depth models that such zones, where prominent block structural movements are noticed with conspicuous presence of fault zones, need to be studied critically as these locales could probably be sources for future seismic activity. In these, especially those zones where clear block movements are noticed, with upward movement of middle and lower crustal formations to shallower depths, are important. The deductions made in our present study, after duly considering various geological and geophysical inputs could be used as parametric inputs while analysing signatures from different areas. In any region where vertical tectonics is noticed, as a part of neotectonic activity, one needs to study carefully the pattern and role of faults, fractures and joints. However, it is relevant to note that as the continental crust contains innumerable number of criss-cross faults, fractures and joints, one needs to have a systematic seismic surveillance before arriving at any definite idea about the seismicity character of a region. So, the useful structural details as brought out from seismic studies could be synthesized with other geological and geophysical signatures, especially the stress pattern, for better understanding of the seismicity of a region, but not for short-range prediction.

Coincident deep reflection/refraction studies in central India[21] have shown presence of upper and lower crustal low-velocity layers. These layers, high heat flow, hot springs, significant reflectivity character north and south of central Indian suture and mild seismic activity in the central India strongly suggest neo-tectonic activity in the region, including the horst structure between Katangi and Jabalpur.

In view of the details given above, the region north of Jabalpur to Seoni deserves a detailed integrated geophysical investigation on a much finer scale. Such a study will help in more clearly pinpointing the causes of recurring seismic activity which manifested in the form of Jabalpur earthquake on 22 May 1997. The fracture zone represented by low-velocity materials (Figure 3) associated with the boundary fault near Jabalpur might have got disturbed by the fall of the water level in the driest period of the year and the blocking of natural drainage by the Bagdi dam[22] resulting in the crustal movement and hence the earthquake. More than 30 earthquakes[9] in the magnitude range 3.0 and 6.5 are reported for the seismically active NSL. The occurrence of Son valley earthquake (1927) of magnitude 6.4 in the eastern part of the NSL cannot surprise recurrence of an earthquake with magnitude 5.8 near Jabalpur. The fracturing associated with the northern boundary fault (near Katangi) of the Katangi–Jabalpur horst feature may be a weak zone for future release of the stress energy. So, as a part of disaster-management programme it is essential to continuously monitor the seismic activity in the surrounding region of the horst feature, if such a surveillance along the entire NSL is difficult due to various constraints.

1. Kaila, K. L., Murty, P. R. K. and Mall, D. M., *Tectonophysics*, 1989, **162**, 277–289.
2. Murty, A. S. N., Mall, D. M., Murty, P. R. K. and Reddy P. R., *Pure Appl. Geophys.*, 1997, communicated.
3. Sain, K., Bruguier, N., Murty, A. S. N. and Reddy P. R., *Geophys. J. Int.*, 1997, communicated.
4. Reddy, P. R., Rao, P. K. and Sain, K., 1997, *Mem. Geol. Soc. India*, 1997, in press.
5. Krishnabrahmam, N., *Curr. Sci.*, 1990, **59**, 1209–1211.
6. Ravi Shanker, Extended Abstracts, Group Discussions on 'Suture zones – Young and old', Wadia Institute of Himalayan Geology & Geological Society of India, 1990, pp. 27–34.
7. Venkata Rao, K., Srirama, B. V. and Ramasastry, P., *Spl. Pub. No. 28*, Geological Society of India, 1990, pp. 99–117.
8. Jain, S. C., Nair, K. K. K. and Yedekar, D. B., Report of the Son–Narmada–Tapti Lineament Zone in Central CRUMSONATA, Geological Survey of India 1995,
9. Gupta, H. K., Chadha, R. K., Rao, M. N., Nara Mandal, P., Ravi Kumar, M. and Kumar, N., *J. Geo* 1997, **50**, 85–91.
10. Mittal, V. K., Bhattacharya, S. N. and Srivastava, H. 1990, **41**, 59–64.
11. Hwang, H. J. and Mitchell, B. J., *Geophys. J. R. Ast* **90**, 575–613.
12. Arora, B. R., Waghmare, S. Y. and Mahashabde, M *Geol. Soc. India*, 1995, **31**, 519–535.
13. Gravity Map Series of India, NGRI, 1971, GPH-4.
14. Qureshy, M. N., *J. Geophys. Res.*, 1971, **76**, 545–5
15. Mishra, D. C., *Tectonophysics*, 1992, **212**, 153–161.
16. Mall, D. M., Kaila, K. L. and Rao, V. K., 1st Seminar, Exploration Geophysics in 1990s, Associati ration Geophysicists, 1991, vol. 1, pp. 298–303.
17. Singh, D. D., *PAGEOPH*, 1991, **135**, 545–555.
18. Reddy, P. R., Abstract communicated to IASPEI Thessalonki, Greece, 1997.
19. Reddy, P. R., Rao, V. K. and Rao, P. P., Proceed Annual Convention of IGU, 1993, pp. 45–52.
20. Rantsman, E. Ya, Chetty, T. R. K., Rao, M. N., Gl Zhidkov, M. P. and Vovshkov, A. I., DST Report,
21. Reddy, P. R., Murty, P. R. K., Rao, I. B. P., Kha D. M., Rao, P. K., Rao, G. K., Raju, S., Sridher, V M. S., NGRI Technical Report, Department of Scie nology, New Delhi, 1996.
22. Bhattarcharjee, M., *Sci. Rep.*, 1997, pp. 4–6.

ACKNOWLEDGEMENTS. We are grateful to the Dir for his kind consent to publish this work. We thank the reviewer and Dr U. Raval for useful suggestions.

Received 9 June 1997; revised accepted 25 September 1