and the coexistence as a mineral, calcite ($CaCO_3$), have been observed in this, indicating that the recrystallization of this quartz may have occurred during retrograde metamorphic processes.

1. Roedder, E., *Fluid Inclusions – Reviews in Mineralogy*, Mineralogical Society of America, 1984.
2. Lattanzi, P., *Fluids in Ore Deposits, Evidence from and Applications of Fis in Fluid Inclusions in Minerals* (eds De Viro, B. and Frezbotti, M. L.), Short course of the working group (IMA), Inclusions and Minerals, 1994. pp. 297–309.
3. Shephard, T. J., Rankin, A. H. and Alderton, D. H. M., *A Practical Guide to Fluid Inclusion Studies*, Blackie & Sons Ltd, 1985, p. 239.
4. Kerrich, R., *Miner. Deposita*, 1993, **28**, 362–365.
5. Phillips, *Miner. Mag.*, 1993, **57**, 365–374.
6. Bakker, R. J. and Jansen, J. B., *Geochim. Cosmochim. Acta*, 1991, **55**, 2215–2230.
7. Bakker, R. J. and Jansen, J. B., *Contrib. Mineral. Petrol.*, 1994, **116**, 7–20.
8. Vityk, M. O. and Bodnar, R. J., *ibid*, 1995, **121**, 309–323.
9. Prasad, P. S. R., *J. Raman Spectrosc.*, 1999, **30**, 693–696.
10. Prasad, P. S. R., Sarma, L. P., Gowd, T. N. and Krishnamurthy, A. S. R., *Curr. Sci.*, 2000, **78**, 729–734.
11. Cordier, P. and Doukhan, J. C., *Am. Mineral.*, 1997, **76**, 361–369.
12. Heamey, P. J., Premitt, C. T. and Gibbs, G. V., *Reviews in Mineralogy*, Mineralogical Society of America, 1994, vol. 29.
13. Suziki, S. and Nakashima, S., *Phys. Chem. Mineral.*, 1999, **26**, 217–225.
14. Manikyamba, C., Naqvi, S. M., Ram Mohan, M., Ramavati Mathur, Ramesh, S. L. and Dasaram, B., Annual Report, National Geophysical Research Institute, Hyderabad, 1997–98, pp. 82–83.
15. Manikyamba, C., *Visakha: Sci. J. A P Acad. Sci.*, 2000, **4**, 57–66.
16. Manikyamba, C., Naqvi, S. M., Ram Mohan, M. and Gnaneshwar Rao, T., *Ore Geol. Rev.* (communicated).
17. Naden, J. and Shepherd, T. J., *Nature*, 1989, **342**, 793–795.
18. Farmer, V. C., *Mineral. Soc. Monogr.*, 1974, **4**.
19. Wopenka, B., Pasteris, J. D. and Freeman, J. J., *Geochim. Cosmochim. Acta*, 1990, **54**, 519–534.
20. Mavrogenes, J. A. and Bodna, R. J., *ibid*, 1994, **58**, 141–148.
21. Bakker, R. and Mamtani, M. A., *Contrib. Mineral. Petrol.*, 2000, **139**, 163–179.
22. Sisson, V. B. and Holtister, L. S., *Am. Mineral.*, 1990, **75**, 59–70.
23. Ugarkar, A. G., *Gondwana Res.*, 1998, **1**, 215–219.
24. Phillips, G. N. and Powell, R., *Econ. Geol.*, 1993, **88**, 1084–1098.
25. McDonald, R. S., *J. Phys. Chem.*, 1968, **62**, 1168–1178.
26. Kronenberg, A. K. and George, H. W., *Tectonophysics*, 1990, **172**, 255–271.
27. White, S. H., Burrows, S. E., Carreras, J., Shaw, N. D. and Humphreys, F. J., *J. Struct. Geol.*, 1980, **2**, 175–188.
28. Nakashima, S. *et al.*, *Tectonophysics*, 1995, **245**, 263–276.
29. Nyfeler, D. and Armbruster, T., *Am. Mineral.*, 1998, **83**, 119–125.

ACKNOWLEDGEMENTS. We are grateful to Dr V. P. Dimri, Director, National Geophysical Research Institute, Hyderabad for permitting us to publish this work. Dr S. M. Naqvi is acknowledged for his support to carry out this work. Field work and geological mapping were carried out as a part of CSIR Young Scientist Project awarded to Dr C. Manikyamba under the guidance of Dr S. M. Naqvi. Discussions and suggestions from Dr Biswajit Mishra have greatly helped in improving the manuscript.

Received 19 April 2002; revised accepted 24 July 2002

On the correlation of seismicity with geophysical lineaments over the Indian subcontinent

Y. Sreedhar Murthy

Centre of Exploration Geophysics, Osmania University, Hyderabad 500 007, India

A large number of earthquakes of different magnitudes are recorded over the years in the Indian subcontinent, including Southern Peninsular shield. Geophysical images enable one to understand the tectonic and structural fabric of the region. The spatial distribution of earthquakes and their correlation with geophysical mega lineaments are demonstrated.

EARTHQUAKES of magnitude 7 and above are generally confined to the Himalayan region, the northeast and parts of western India. However, historical data suggest that the subcontinent has witnessed several hundreds of earthquakes of varied magnitude[1–5]. Several workers have prepared catalogues and maps giving epicentre, magnitude and other relevant parameters of these earthquakes. The National Seismic Information Centre, World Data Centre for Seismology of the United States Geological Survey (USGS) Denver, USA also maintains a popular site (www.usgs.gov), which includes information on earthquakes over the Indian subcontinent.

The long recurrence interval of moderate earthquakes in the amplitude range of 4 to 6 in peninsular India gives an impression that this region is relatively stable. The 1967 Koyna and 1993 Latur earthquakes have demonstrated that earthquakes can occur in parts of peninsular India but due to their scarcity, there have been fewer opportunities to study them. Clearly, there are many gaps in our knowledge about the earthquake sources and processes in the southern peninsular shield. As is well known, distribution of the seismic stations over the country is not uniform and different stations have varying recording sensitivities. Although there are difficulties due to these inherent problems, the preponderance of seismic activity over the subcontinent calls for a relook into the spatial distribution of earthquakes and their correlation with tectonics and structural fabric of the subcontinent in general and the southern shield in particular. Geophysical data, particularly the gravity and magnetics, provide a window to understand the tectonic and structural fabric of the region. The spatial distribution of earthquakes and their correlation with geophysical mega lineaments form the subject of this communication.

The recent development of an 'Auto trace and Digitize Methodology'[6] provided an opportunity to transform large volume of available gravity and magnetic data from

e-mail: aegindia@hd1.vsnl.net.in

analogue to digital format, and present them in a user-friendly image mode. The geophysical images are intrinsically better suited to bring out the structural lineaments, regional fault-fractures and tectonic fabric in comparison to the conventional contour maps[7,8]. The gravity map series of India on 1 : 5,000.000 scale[9], when presented in image mode, brought out many mega lineaments, which were not seen or recognized on the contour maps[10] published earlier.

It would have been ideal to plot all the recorded earthquakes in India to study their spatial pattern. The earthquake epicentral data of India published by earlier workers are seen to be incomplete and suffer from several limitations. During our study it was noticed that the data compiled by individual workers are incomplete and many of the events reported by USGS are missing in these works. For example, the widely-used catalogue of Bapat *et al.*[4] does not give the earthquakes listed by USGS, as shown in Table 1. Similarly, USGS data do not contain some of the earthquakes reported by Bapat *et al.*[4], as shown in Table 2. It was also noticed that the map prepared by Surendra Kumar[2] does not include some of the well-known earthquakes in central India. The uneven distribution of seismic stations precludes the use of 2 and 3 magnitude events, as their reliable recording is dependent on the local observatories. To overcome this problem, the epicentral data of earthquakes with magnitudes 4 and above only are plotted from the USGS source, to which the data shown in Table 2 are added. In view of the fact that none of the data sets are complete and since the purpose of the present work is not to prepare an earthquake epicentral map of India, the USGS data are adopted for this study. The earthquakes discussed in this communication are plotted by selecting symbol size and colour to denote earthquakes of different magnitudes. It is beyond the scope of this communication to examine the accuracy of magnitude estimates of each of the events, and the data as given by USGS are adopted. It is to be recognized here, that there is an urgent need for compiling a comprehensive catalogue of the earthquake data and their dissemination.

Major structural and tectonic features of the subcontinent, as collated from the published literature[11,12], are shown in Figure 1. A study of the geophysical images generated by us earlier[7,8,10], clearly shows that all the major structures and tectonic elements in the subcontinent are reflected well on these images. The shaded relief image of free-air gravity map of India is shown in Figure 2. A comparison of Figures 1 and 2 clearly shows that all the well-known and reported tectonic features are well

Table 1. List of earthquake events reported by USGS but not included in the catalogue of Bapat *et al.*[4]

Year	Month	Date	Latitude	Longitude	Magnitude
1950	11	18	27.7	94.6	6.7
1950	12	24	24.4	91.7	6.3
1952	11	14	30	92	6
1953	7	26	9.9	76.3	5
1955	2	14	7.8	94	6.25
1955	6	17	32.5	78.6	6
1956	9	7	7.1	94.1	6
1957	12	12	24.5	93	6
1957	12	13	17.3	73.7	5.5
1958	1	4	27	92	6
1958	1	6	25.6	96.8	5.75
1958	2	13	27.6	92.5	5.5
1958	3	22	23.5	93.8	6.5
1959	6	7	24	94	5.5
1959	6	10	30	91	5.75
1959	11	2	28	93	5
1960	8	21	26.4	88.6	5.5
1961	11	6	26.7	91.9	6
1962	9	1	24	73	5
1962	9	15	31.9	76.2	5.5
1962	10	30	26.6	93.3	6
1963	1	30	29.5	80.9	6
1963	2	22	27.2	87.1	5.25
1963	10	22	10.4	94	5.1
1963	11	27	30.8	79.1	5.1
1965	11	18	29.9	80.3	5.2
1967	3	27	15.6	80	5.8
1968	5	3	23	86.6	5.6
1969	2	26	26.6	92.4	5
1969	4	13	17.9	80.6	5.7
1970	5	9	24	94.1	5
1972	7	29	11	77	5

Table 2. List of earthquake events not reported by USGS but included in the catalogue of Bapat *et al.*[4]

Year	Month	Date	Latitude	Longitude	Magnitude
1954	3	31	12.4	57.9	7.2
1954	4	11	10.8	57.1	6.2
1954	4	11	36.4	70.8	6.5
1954	7	10	36.6	71.1	6
1955	6	27	32.5	78.6	6
1955	7	14	7.8	94	6.1
1956	1	11	7.7	94	6.3
1956	1	21	23.5	93.5	6.1
1956	3	18	5.4	93.8	5.9
1956	10	13	36.3	71.3	6.1
1956	11	14	36.7	71.1	6.4
1956	11	14	36.5	71	6.5
1957	3	11	0.2	97.1	6.4
1957	5	28	25.4	95	6
1957	9	2	36.5	71.2	6.4
1958	2	17	36.5	70.7	6.6
1958	3	28	36.4	71	6.8
1959	3	4	12.2	92.7	6.1
1960	1	3	44	84.5	6.6
1961	6	27	28	99.4	6.2
1962	3	6	14	93	5.8
1964	6	13	10	93	6
1964	11	30	6.8	94.8	6.5
1965	2	18	25	94.3	6
1972	9	3	35.9	73.3	5.6
1973	4	7	7	91.4	5.9
1975	1	19	32.5	78.4	6.2

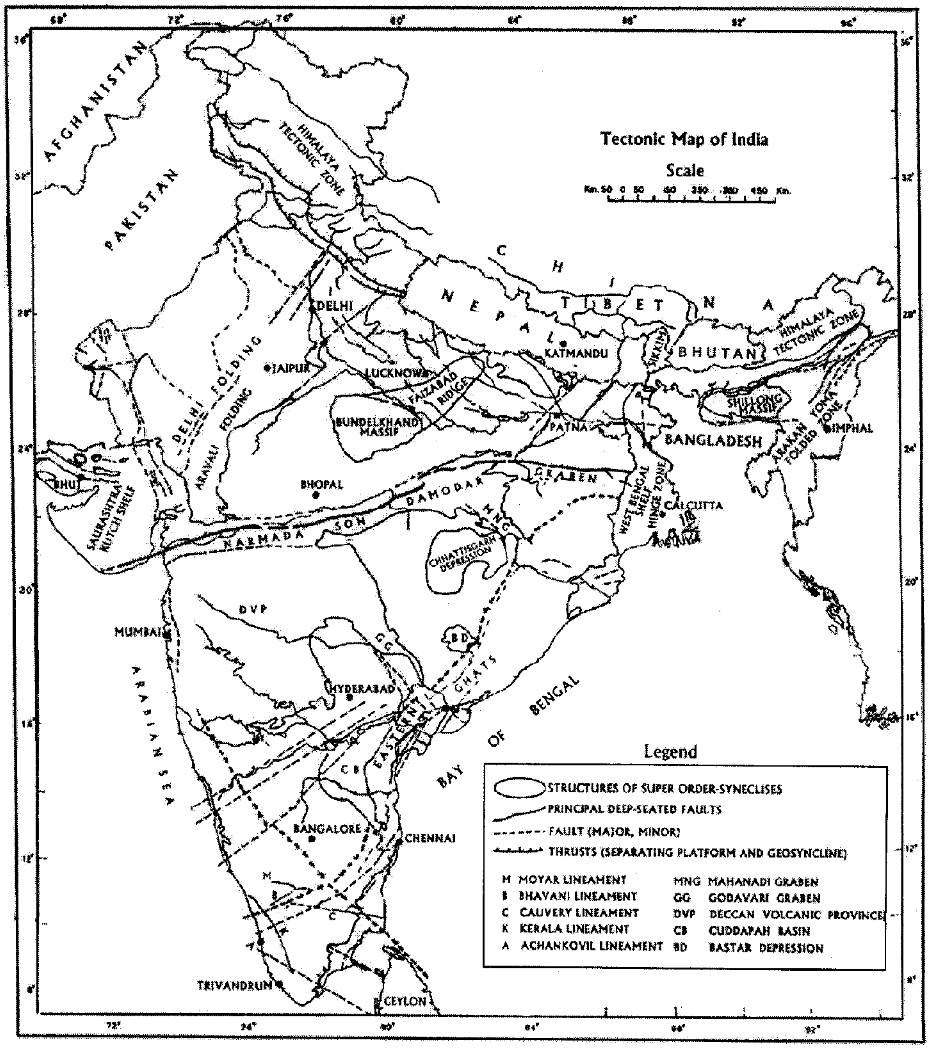

Figure 1. Tectonic map of India (modified from refs 11 and 12).

reflected on the gravity image. For example, the different cratons (Dharwar, Bastar, Bhandara, Singhbhum and Aravalli), the shear zones in south India (Moyar, Bhavani, Cauvery and Kerala lineaments), the proterozoic Cuddapah basin, the Gondwana grabens (Godavari, Mahanadi, Satpura and Damodar), the Western Ghats, the Eastern Ghats and Aravalli fold belt and the Narmada–Son Lineament are unmistakably evident in the image. In addition, some of the new features, which are either unknown or not well reflected in earlier maps, are also seen in the gravity image. These include:

(1) A NW–SE trending mega lineament from Chennai on the east coast to north of Mumbai and close to Surat on the west coast, and extending further towards NW into Saurashtra Peninsula.
(2) A near N–S trending lineament (Raval line)[8] starting from Karakorum and passing through Ahmedabad and extending further south into offshore region through Laccadive and Maldives.
(3) A NE–SW lineament starting east of Jaipur and its extension into the Himalayas in an ENE–WSW direction.
(4) ENE–WSW trending Narmada–Tapti–Son Lineament (NTSL) and similar parallel trends within the Vindhyan and Indo-Gangetic plains.
(5) The West Bengal shelf bounded by two prominent arcuate N–S trends.

The earthquake epicenters with magnitudes greater than 4 are superposed on the free-air gravity image (Figure 3). From the distribution of earthquakes, the Indian subcontinent can broadly be divided into three zones, viz. Western, Central and Southern. To be specific, the western region includes the entire area to the north and west of Surat. Similarly, central India is to the east and north

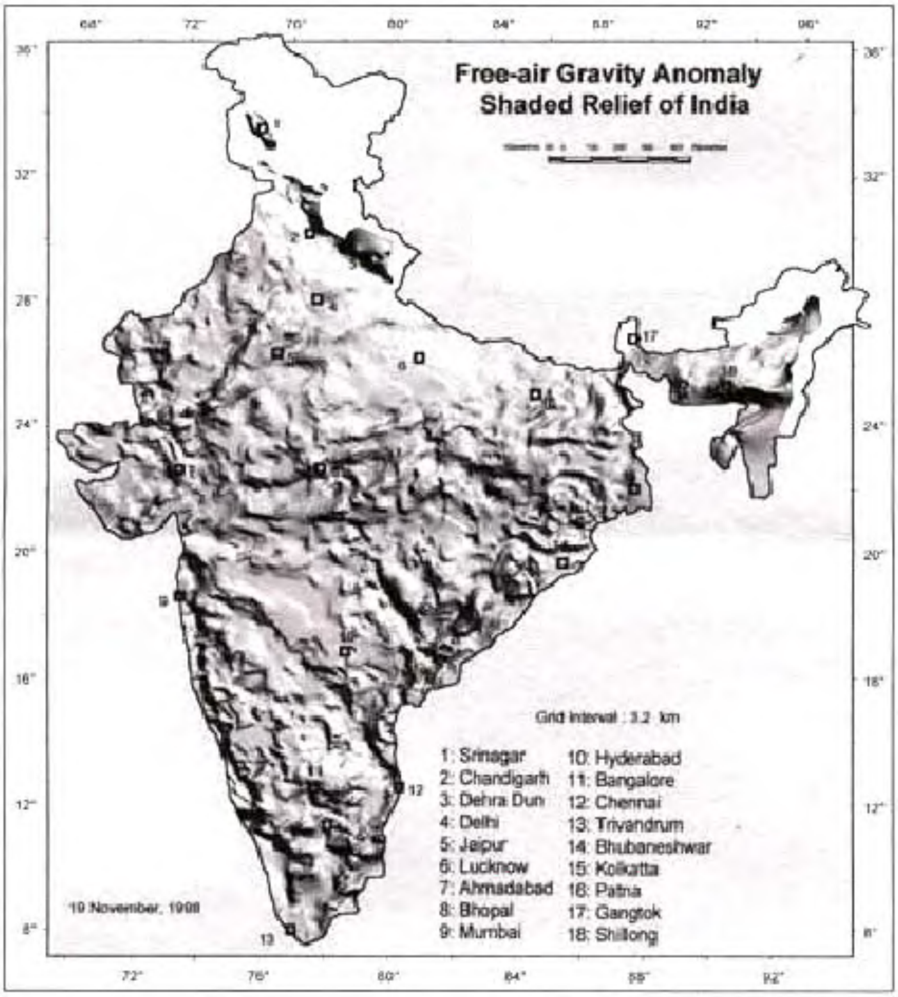

Figure 2. Free-air gravity shaded relief image of India.

Table 3. Distribution of earthquakes of different magnitudes in Western, Central and Southern regions of India for the period 1063–1997

Earthquake magnitude	Western region	Central region	Southern region
4–6	26	38	108
> 6	7	16	9

of NTSL zone. South of Surat and NTSL zone is delineated as the southern zone for convenience of discussion. The distribution of earthquakes of different magnitudes in these regions is shown in Table 3. The earthquake epicentres of all magnitudes in the Himalayas, from NE India and Burmese Arc are excluded from the discussion, as they are well studied and also do not form a part of the Indian peninsular region, and reflect the earthquakes outside the SCR of India.

The earthquake epicenters with magnitudes between 4 and 6 are superposed on the free-air gravity image (Figure 4*a*) and earthquake epicenters with magnitudes greater than 6 are shown in Figure 4*b*. Distribution of the earthquake epicenters with magnitudes between 4 and 6 are mainly along (1) the west coast, (2) the Eastern Ghats, (3) Narmada–Son Lineament and (4) the entire western region comprising Saurashtra and Kutch peninsula. It is interesting to note that in south India, barring a few, majority of earthquake epicenters are confined to the high-grade granulite terrain. The few events in the granite-gneiss–greenstone terrain are distributed on either side of the NW–SE Chennai–Mumbai line. It is interesting to note that the large area confined between north of Chennai line and south of Tapti fault comprising Deccan trap and gneisses is devoid of any seismic activity. It is also interesting to observe that Latur event is seen to be in close proximity to the NW–SE Chennai–Mumbai line, while the Koyna events are mostly along the west coast lineament. Further, the other earthquake epicenters are seen all along the Eastern Ghats.

In central India, the earthquake epicenters are mainly distributed along NTSL. In the western zone, majority

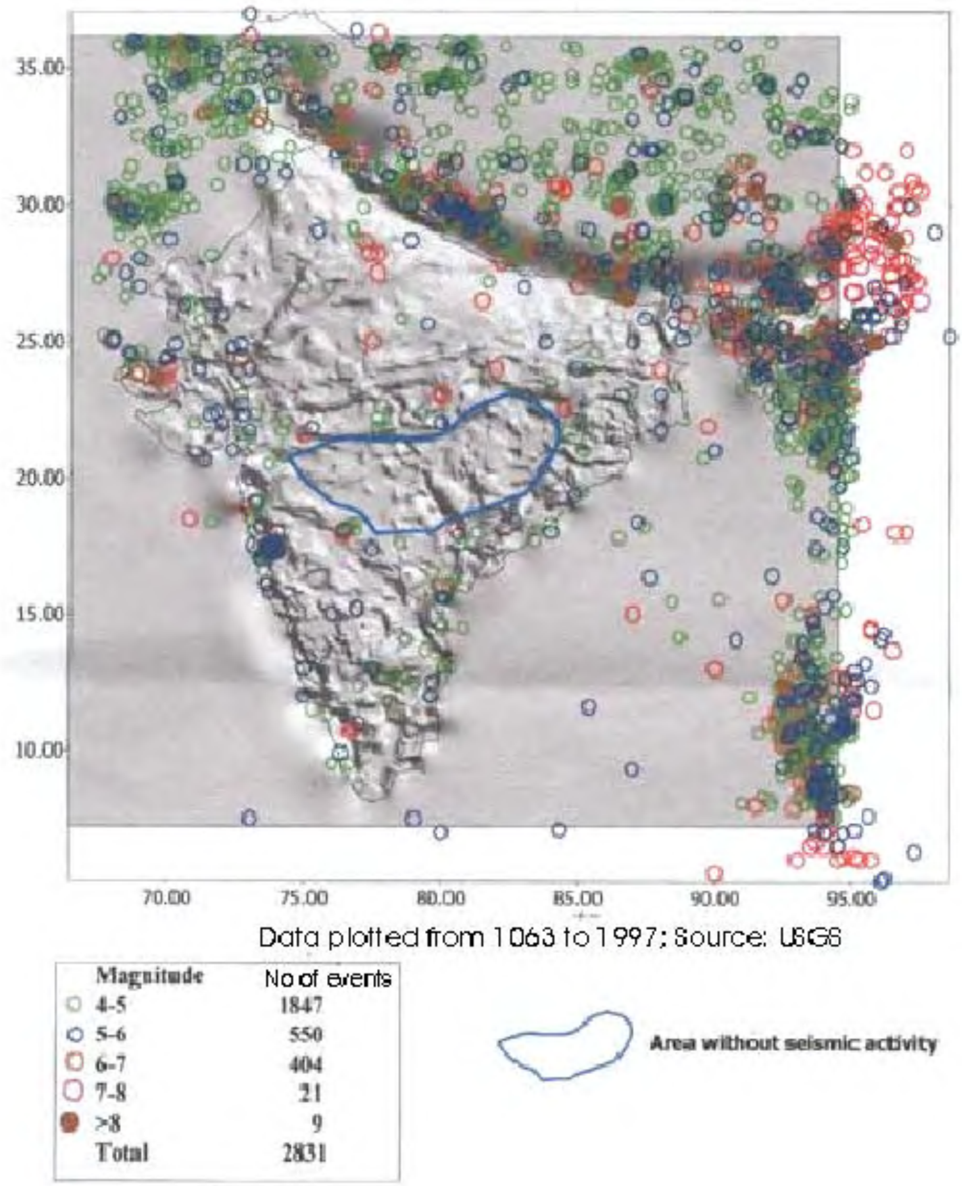

Figure 3. Earthquake epicentral data of magnitude > 4 superposed on free-air gravity shaded relief image of India.

are in south Kutch region which is believed to be an ancient rift system and quite different from the rest of the peninsular shield[5]. It is also noticed that earthquakes are aligned mostly along the so-called Raval line[8] and a few events are located along the Aravalli zone. The vast Indo-Gangetic plains have less number of events compared to western and southern parts of the country.

The earthquake epicenters with magnitudes greater than 6 superposed on the free-air gravity image (Figure 4*b*) do not show any specific cluster or pattern for their distribution. They are spread all over the country, with specific clusters in the Kutch and north of Delhi. Earthquakes of magnitude greater than 7 are absent in southern India and are confined to Gujarat and northeast India.

The Indian subcontinent is seismically active, with different regions showing varying levels of seismic activity, and no part of the country can be said to be seismically inactive or stable. However, a large part of the region confined between Tapti fault in the north, Chennai–Mumbai line in the south and the Eastern Ghats in the east, as shown in Figure 3, is devoid of any seismic activity. As can be seen from Figure 1, the Godavari graben, Mahanadi graben, contact of Deccan trap and granitic terrain are seen to be passing through this region. In addition, this area is in close proximity to Chennai–Mumbai lineament, Tapti fault, Satpura folding and is obviously an area of tectonic interest and concern. In view of the above, this region needs a closer look for *a*

b

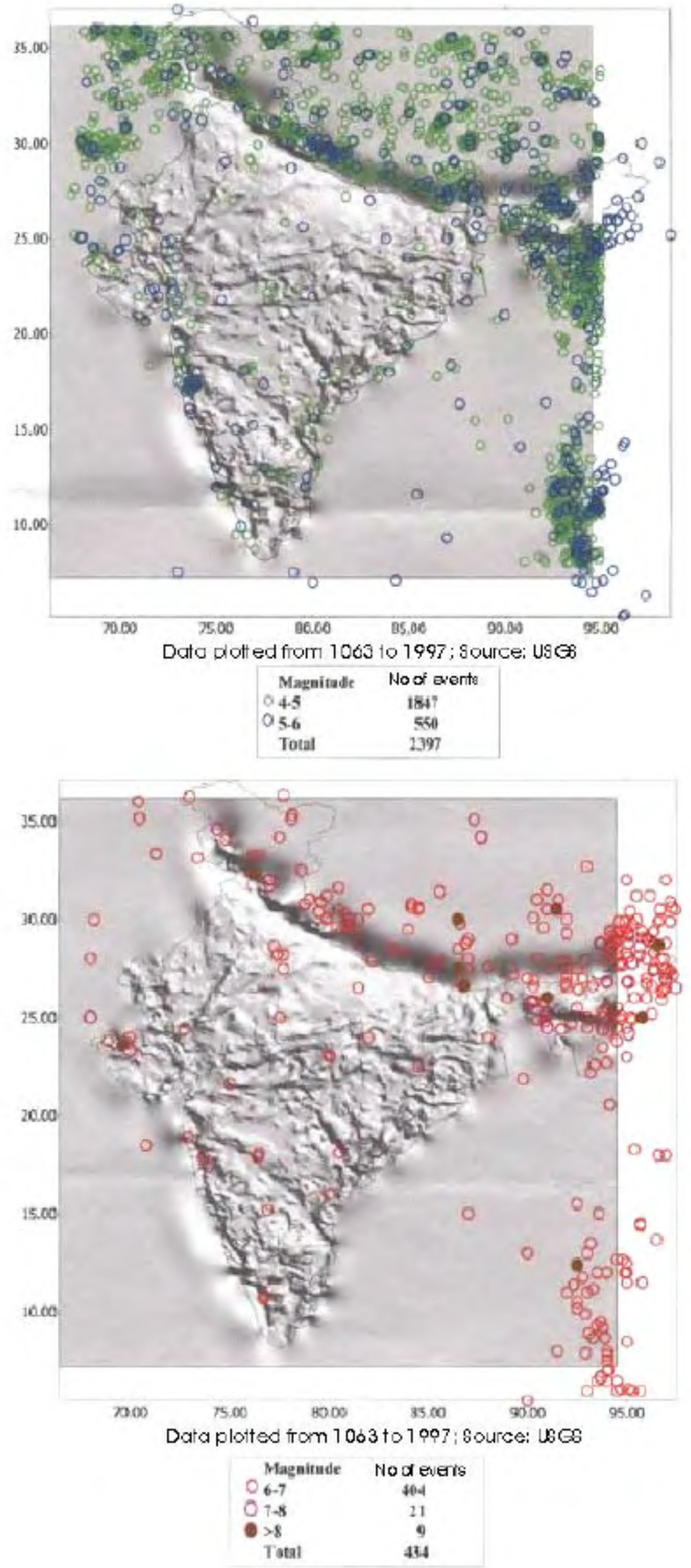

Figure 4. Rangewise distribution of earthquake epicentral data for events ***a***, $4 \leq M \leq 6$; and ***b***, $M > 6$ superposed on free-air gravity shaded relief image of India.

understanding the seismic processes responsible for lack of energy release or otherwise, over a large area of more than 250,000 km^2 since historical times.

1. Oldham, T., *Mem. Geol. Surv. India*, 1883, **19**, 163–215.
2. Surendra Kumar, *J. Geodyn.*, 1998, **25**, 109–128.
3. Rao, B. R. and Rao, P. S., *Bull. Seismol. Soc. Am.*, 1984, **74**, 2519–2533.
4. Arun Bapat, Kulkarni, R. C. and Guha, S. K., *Catalogue of Earthquakes in India and Neighbourhood*, ISET, Roorkee, 1983.
5. Rajendran, K. and Rajendran, C. P., *Curr. Sci.*, 2000, **79**, Seismology Spl. Sect.
6. Sreedhar Murthy, Y., Govindarajan, K. and Babu Rao, V., *J. Geophys.*, 1998, **19**, 141–148.
7. Babu Rao, V., Sreedhar Murthy, Y. and Govindarajan, K., *ibid*, 1998, **19**, 195–203.
8. Sreedhar Murthy, Y. and Raval, U., *ibid*, 2000, **21**, 59–70.
9. Hari Narain, *Gravity Map Series of India*, NGRI, 1978.
10. Sreedhar Murthy, Y., *J. Geol. Soc. India*, 1999, **54**, 221–235.
11. *Tectonic Map of India*, ONGC, 1968.
12. Reddi, A. G. B., Mathew, M. P., Singh, Baldau and Naidu, P. S., *J. Geol. Soc. India*, 1988, **32**, 368–381.

ACKNOWLEDGEMENTS. Sincere thanks are due to Prof. A. B. Roy, Mohanlal Sukhadia University, Udaipur and to Dr U. Raval, NGRI, Hyderabad for suggesting the problem and to Dr V. Babu Rao for constant encouragement and stimulating discussions. Critical and constructive review of the manuscript by anonymous reviewers is greatly appreciated. Thanks are due to Ms Nyni Renu and Mr Y. Sridhar for technical support. This work is carried out as an extension of a DST project.

Received 29 August 2001; revised accepted 18 June 2002