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Research paper

Ancient terrane boundaries as probable seismic hazards: A case study from the northern boundary of the Eastern Ghats Belt, India

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A B S T R A C T

In the eastern part of the Indian shield, late Paleozoic–Mesozoic sedimentary rocks of the Talchir Basin lie precisely along a contact of Neoproterozoic age between granulites of the Eastern Ghats Mobile Belt (EGMB) and amphibolite facies rocks of the Rengali Province. At present, the northern part of the basin experiences periodic seismicity by reactivation of faults located both within the basin, and in the Rengali Province to the north. Detailed gravity data collected across the basin show that Bouguer anomalies decrease from the EGMB (∼+15 mGal), through the basin (∼−10 mGal), into the Rengali Province (∼−15 mGal). The data are consistent with the reportedly uncompensated nature of the EGMB, and indicate that the crust below the Rengali Province has a cratonic gravity signature. The contact between the two domains with distinct sub-surface structure, inferred from gravity data, coincides with the North Orissa Boundary Fault (NOBF) that defines the northern boundary of the Talchir Basin. Post-Gondwana faults are also localized along the northern margin of the basin, and present-day seismic tremors also have epicenters close to the NOBF. This indicates that the NOBF was formed by reactivation of a Neoproterozoic terrane boundary, and continues to be susceptible to seismic activity even at the present-day.

1. Introduction

Continental shield domains are generally regarded as stable segments of the Earth's surface, having experienced little internal strain since stabilization in the Precambrian time. This assumption is based on a central tenet of plate tectonic theory, that lithospheric plates are essentially rigid with deformation being confined to their boundaries (Wilson, 1965; McKenzie and Parker, 1967; Morgan, 1968). Global tectonic maps of lithospheric plates (e.g. Morgan, 1968) show that plate boundaries only rarely pass through continental interiors, such as the Alps and the Himalayas; these special domains represent the final stages of the convergence prior to the suturing of two erstwhile distinct plates. However, recent advances in satellite geodesy and the occurrence of intraplate earthquakes suggest that the assumption of plate rigidity may be an over-simplification (e.g. Gordon, 1998). Increasing evidence from various continental shield domains such as North America (e.g. Calais et al., 2006), Arabia (e.g. Al-Heety, 2007) and South Africa (e.g. Malservisi et al., 2013) indicates that stresses may accumulate in continental plate interiors and lead to seismic activity in zones that were generally assumed to be stable.

In India, recent seismic activity as evidenced by the Latur (1993), Jabalpur (1997) and Bhuj (2001) earthquakes has given rise to considerable uncertainty about the assumed stability of the Indian shield. All the above earthquakes occurred in an intraplate setting, and have generally been attributed to reactivation of basement faults (Krishna Brahmam and Negi, 1973; Rajendran et al., 1996). Interestingly, in most of these cases, the seismicity has been focused on previously stabilized continental lithosphere that is now capped either by volcanics or by sedimentary basins. Consequently, it has become increasingly important to detect the nature and geological affinity of the basement to the sedimentary successions within the shield, in order to fully understand the orientation of the faults that control seismicity in these intracratonic basins. The Talchir Basin, in the eastern part of the Indian shield, is one such intracratonic basin of Gondwana age that has till now been

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assumed to be located on stable continental crust. The basin is particularly important on account of its major coalfield, which covers an area of about 1800 km^2. The coalfield has the highest production (38.65 bt; GSI, 2004) in India, and caters to the need of the railways, besides being instrumental in power generation.

The Talchir Basin and bounding Precambrian shield domains lie within the state of Odisha (new name of Orissa) in eastern India. A magnified view of the Indian seismic zonation map (IS: 1893 (Part-I), 2002) reveals that a major part of this state lies in Zone II of the seismic zonation map of India (Fig. 1). However, a vital strip that includes the cities of Bhubaneswar, Cuttack, Angul, Talchir, Sambalpur, Dhenkanal and a part of Balasore district, is placed in Zone III (Fig. 1). This essentially means that the Talchir Basin is in the same seismic zone as Latur, Ahmedabad and Jabalpur, and that the basin with its thick sediment cover faces the threat of future earthquakes. Indeed, recent tremors within the basin (see the Seismotectonic Atlas of the Geological Survey of India, 2000; Mohanty et al., 2009; Walling et al., 2009) suggest that faults in the basement underlying the sediments are being periodically reactivated. There is, however, some ambiguity about the nature of the basement underlying the Talchir Basin, as it is located precisely on a geological contact of Proterozoic age between the Eastern Ghats Mobile Belt (EGMB) in the south and the Rengali Province in the north (Fig. 2). The EGMB is cross-cut by numerous shear zones (Mahalik, 1994; Sarkar et al., 2007; Chetty, 2010), while a number of faults of varying age (265–133 Ma, Lisker and Fachmann, 2001) have also been identified in the Rengali Province (Nash et al., 1996; Crowe et al., 2003). A precise estimate of the seismic hazard associated with the Talchir Basin can only be obtained by understanding the geological affinity of the basement that dictates its structural inheritance. Since the information required is necessarily in the sub-surface, geophysical techniques need to be employed and interpreted in conjunction with geological information. In this study, we examined the gravity data across the basin in conjunction with the available seismic information and the surface geology. Similar techniques have in the past been employed for interpreting the nature of the basement below the Narmada Basin (e.g. Verma and Banerjee, 1992).

2. Broad geological set-up

The Talchir Basin is of Gondwana age, and represents a sub-basin of the larger Mahanadi Basin. The basin has an E–W trend, and lies between the Singhbhum craton and the EGMB. The core zone of the Singhbum craton comprises a ca. 3.5 Ga supracrustal succession (Mukhopadhyay et al., 2008; Acharyya et al., 2010a, b) intruded by the multi-phase, 3.3–3.1 Ga Singhbum Granite (Tait et al., 2011; Mazumder et al., 2012 and references therein). The southern continuation of the Singhbum craton is the low-grade Malaygiri and Tikra Assemblage, and the amphibolite facies rocks of the Rengali Province (Mahalik, 1994; Crowe et al., 2003). The Rengali Province has been identified as a distinct terrane (Crowe et al., 2003), following earlier lithological and structural characterization (Mahalik, 1994, 1996; Dutta et al., 2010). The Eastern Ghats Mobile Belt (EGMB) represents a complex assemblage of polyphase deformed migmatitic gneisses that host a variety of granulite facies metasedimentary and meta-igneous lithologies (see a recent review by Gupta, 2012). The northern part of the EGMB comprises different tectonic domains separated by regional lineaments (Chetty and Murthy, 1994). The structural and lithological character of this region is well documented (Halden et al., 1982; Sarkar et al., 2007; Chetty, 2010). The WNW–ESE trending North Orissa Boundary Fault (NOBF, Fig. 2) reportedly marks the boundary between the Rengali Province in the north and the EGMB in the south (Mahalik, 1994). The Talchir Basin is located along this boundary zone; a segment of the NOBF, referred to as the Kerajang Fault, defines the northern boundary of the basin.

The Talchir Basin is oriented parallel to the structural trend of the northern EGMB, suggesting that its formation during the late Paleozoic may has been accompanied by reactivation of the NOBF and associated faults. Most workers visualize such a tectonic origin for the basin (Mukhopadhayay et al., 1984; Dasgupta, 2006). Nash et al. (1996) have proposed that the Mahanadi Basin was formed as a result of strike-slip motion during the evolution of the NOBF (Fig. 2). Available geochronological data (Lisker and Fachmann, 2001) support the rift-related formation of the basin, possibly within a half-graben structure (the Mahanadi Graben). At present, the basin structure is truncated by the Kerajang Fault in the north.

3. Seismicity of the region

Enhanced seismicity has recently been reported in some parts of the eastern Indian Precambrian shield. Fault plane solutions (Chandra, 1977) for three moderate size (ML: 5.3–5.5) earthquakes (Midnapur, 1964) revealed a strike-slip mechanism along a preferred ENE–WSW trending fault plane, and were interpreted to be associated with N–S directed tectonic stress. In the context of the present study, moderate size earthquakes have also been

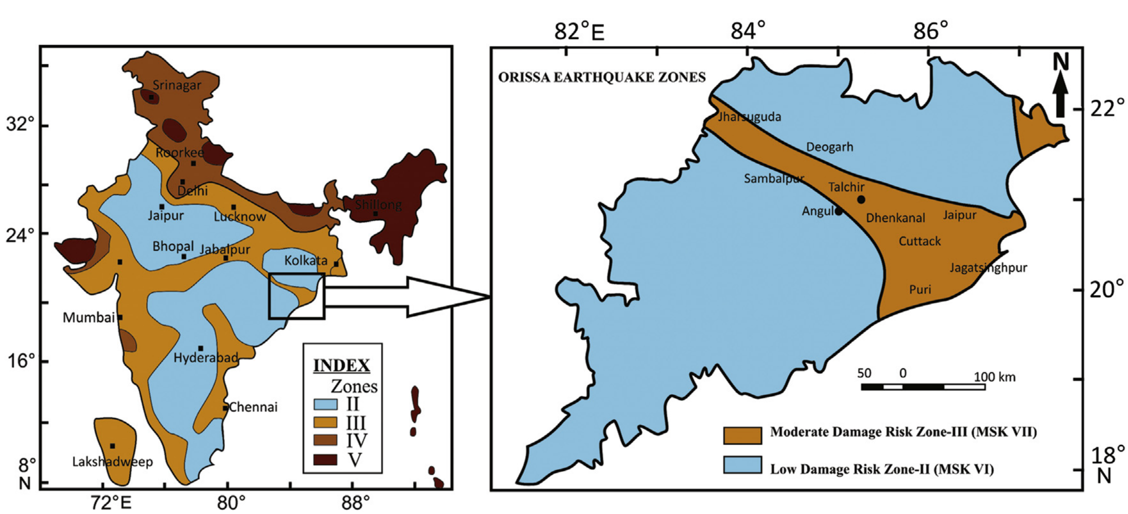

Figure 1. Map showing the seismic zones of Odisha (OSDMA, 2002).

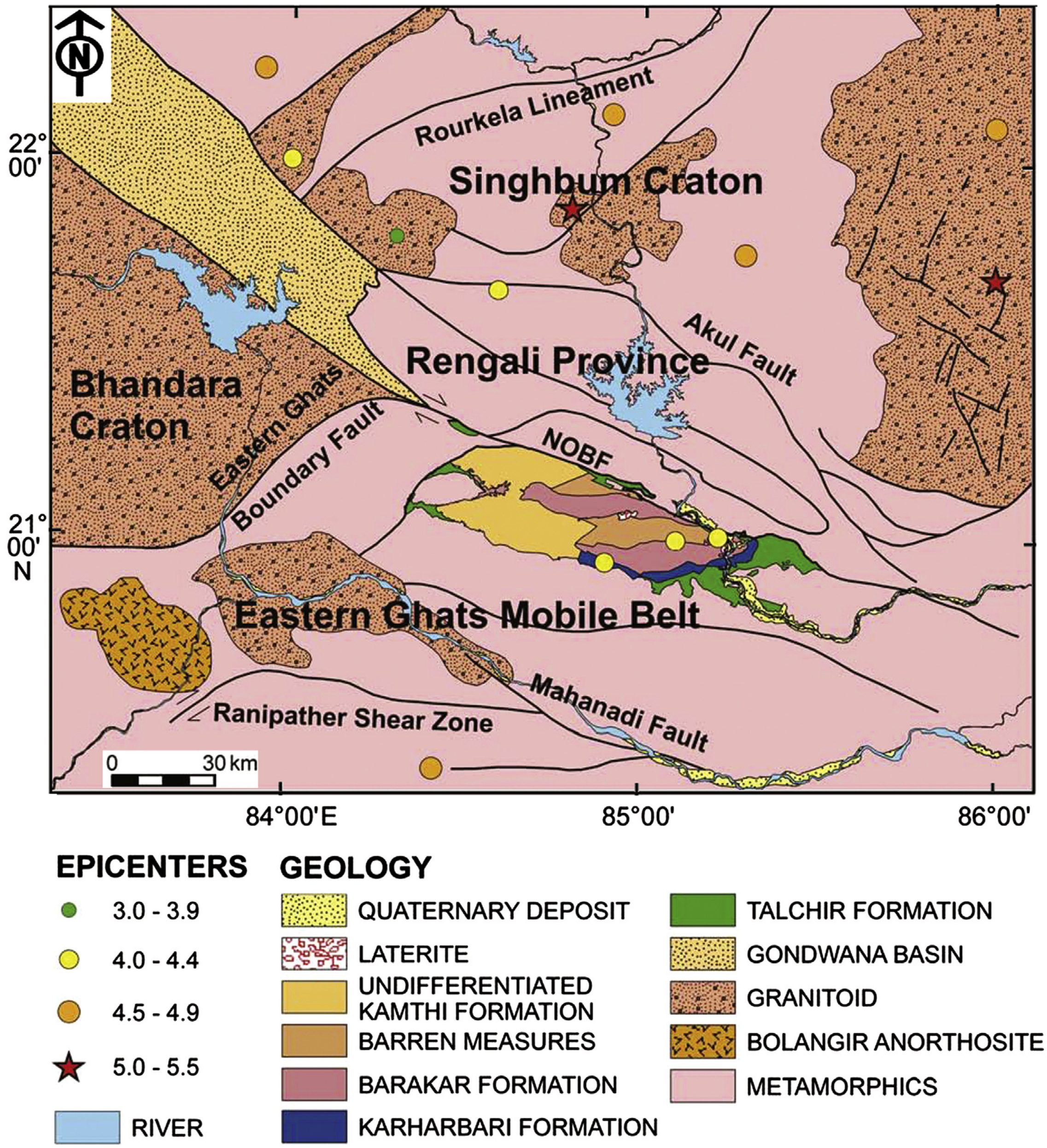

Figure 2. Geology of the Mahanadi Basin with the tectonic framework and the recorded earthquakes (BC: Bhandara Craton; NOBF: North Orissa Boundary Fault; EGMB: Eastern Ghats Mobile Belt; EGBF: Eastern Ghats Boundary Fault; RSZ: Ranipather Shear Zone; SC: Singhbhum Craton) (Modified after Lisker and Fachmann, 2001).

reported from the Bonaigarh–Talchir area, located along the EGMB – Singhbhum craton contact zone. An earthquake of magnitude ML 5.0 rocked Bonaigarh on Mar. 27, 1995 (Fig. 3a) causing moderate damage in the area. Another earthquake of magnitude ML 4.8 occurred in the same area after about three months, on June 22, 1995. The area has experienced two or more earthquakes of ML 5.2 in the past, in 1958 and 1962, respectively. These four earthquakes occurred within a 50 km radius and are located in the vicinity of the Rengali Province. The 71 m high Rengali Dam over the Brahmani River is located just north of the NOBF. Two earthquakes of magnitudes ML 4.4 and 4.1, occurred in January 1986, while one earthquake, of magnitude ML 4.3, occurred to the south of the NOBF in 1993, within the Talchir Basin. These two groups of earthquakes, one to the north and the other to the south of the Rengali Dam, originated from two different geological domains. Their spatial proximity makes the area, bound by latitudes N21°–22° and longitudes E84.5°–85.5°, vulnerable to earthquake-related hazard (De et al., 1998).

A temporary micro earthquake (MEQ) network of four stations was established by the Geological Survey of India (GSI) from January to mid-May, 1997, in the Bonaigarh–Talchir area (Fig. 3). During this period, 26 earthquakes were recorded with an S–P interval of about 20 s. Of these, 14 earthquakes are well located. The maximum seismic activity is observed to the south of the Rengali Dam, within the Talchir Basin. The epicenters are clustered at the junction of the ENE–WSW trending NOBF and the Brahmani River (Fig. 3b). The survey has thus delineated a seismically active zone 20 km south of the Rengali Dam (De et al., 1998). It may be noted that three earthquakes, of magnitudes ML 4.1–4.4, occurred in this zone within a span of 10 years. No focal mechanism solution could be obtained for these earthquakes due to meager data. However, a vertical cross section in a direction orthogonal to the trend of the

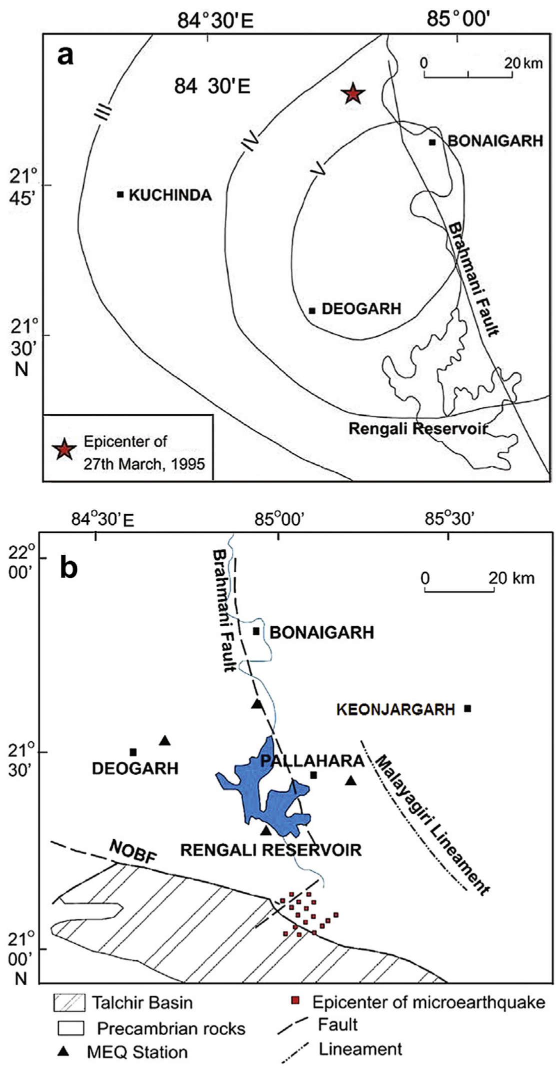

Figure 3. Map showing (a) the isoseismal map of Bonaigarh earthquake of 27th March, 1995 and (b) the micro earthquake (MEQ) network in and around Bonaigarh, Orissa (GSI, 2000).

NOBF shows that the hypocenters are clustered on either side of the NOBF, indicating that a segment of this fault is active at present. The junction of the NOBF and the Brahmani River possibly represents an asperity, with the earthquakes resulting from the accumulation of strain generated by present-day plate movements. Detection of such asperity zones within the shield is useful for microzonation and hazard mitigation (De et al., 1998). Fig. 2 shows the seismicity of the region, with earthquake magnitudes ranging from 3.0 to 5.2. The earthquake epicenters were obtained from the United States Geological Survey catalog (http://neic.usgs.gov/neis/epic/epic_rect/html). The list of earthquakes in the region is shown in Table 1.

4. Gravity studies

A preliminary idea of the nature of the gravity variations with geology across the region can be obtained from the regional Gravity Map of India (GSI-NGRI, 2006; Sundaram et al., 2006). It shows a regionally decreasing trend in the Bouguer gravity anomaly from the south (within the EGMB) to the north of the Talchir Basin (i.e., into the Singbhum craton) (Fig. 4).

Table 1
The earthquakes recorded in the Mahanadi Basin.

Year	Month	Day	Latitude (°)	Longitude (°)	M	Source
1963	5	8	21.70	86.00	*mb: 5.2*	GSI (2000)
1979	8	5	22.10	86.00	*mb: 4.7*	ISC
1982	10	14	20.39	84.42	*mb: 4.7*	ISC
1986	1	19	20.93	84.90	*mb: 4.4*	USGS
1986	3	17	22.87	85.16	*mb: 4.3*	GSI (2000)
1993	5	16	23.14	86.83	*mb: 4.5*	GSI (2000)
1993	11	1	21.00	85.10	*mb: 4.3*	GSI (2000)
1995	3	27	21.66	84.59	*mb: 5.0*	ISC
1995	6	21	21.76	85.29	*mb: 4.5*	ISC
1993	11	1	21.00	85.10	*mb: 4.3*	GSI (2000)
1996	9	25	22.00	84.00	*mb: 4.2*	ISC
1998	5	22	22.13	84.91	*mb: 4.8*	ISC
2001	6	12	22.24	83.92	mb: 4.7	ISC
2003	7	30	21.80	84.30	M_L: 3.4	ISC

(USGS: United States Geological Survey; ISC: International Seismological Centre; GSI: Geological Survey India).

For a better correlation of the variation of gravity values with geology across the Talchir Basin, gravity stations were established during the present study using a W. Sodin gravimeter. Three gravity field campaigns were conducted during December, 2006, December, 2007 and December, 2008, along transects oriented N–S across the Talchir Basin. The base station established by the National Geophysical Research Institute, Hyderabad (Qureshy et al., 1973), in the PWD Guest House within Angul town (20°49′49″ N, 85°06′05″ E) was used in the survey. Hand-held Global Positioning Systems (GPS) were used for locating stations that were subsequently plotted onto Survey of India topographic sheets. The observed Bouguer anomaly map of the area, based on about 270 gravity stations with a 5 mGal contour interval, is shown in Fig. 5. The map is characterized by the presence of many gravity highs and lows. The highs are prominent in the southern and western part, mostly over the EGMB, while the lows prevail over the northern part. This map was superposed on the lithological map of the region, and shows extremely interesting correlation with the surface geology (Fig. 5). It can be seen that the Bouguer anomaly ranges from +20 to 0 mGal in the southwestern part of the area, within the EGMB, through about −5 to −20 mGal over the Gondwana sediments, to even lower values of 0 to −30 mGal over the Rengali Province, in the extreme northeast of the surveyed area (Fig. 5). Importantly, the Bouguer gravity anomalies appear to decrease systematically and continuously through the Talchir Basin, although the exposed sedimentary rocks within the basin definitely have lower densities than the metamorphic rocks exposed in the Rengali Province. Unlike the drop in gravity across the EGMB–Talchir Basin contact, there is no corresponding increase across the northern flank of the basin, into the Rengali Province. Thus, the Kerajang Fault, the segment of the NOBF that defines the northern margin of the Talchir Basin, is not characterized by a change in gravity values. It can be concluded that the metamorphites of the Rengali Province and the EGMB are underlain by crust of fundamentally different density configurations.

5. Discussion

Assessing the geological affinity of the basement below the Talchir Basin requires knowledge of some geophysical characteristics of the terranes on either side of the basin, i.e., of the EGMB and/or the Rengali Province. Systematic geophysical characterization of the Rengali Province is as yet unavailable, but larger-scale studies on the gravity anomalies over the Indian shield (Verma and Subrahmanyam, 1984; Murthy and Raval, 2000) suggest predominantly negative Bouguer gravity anomalies over the cratonic

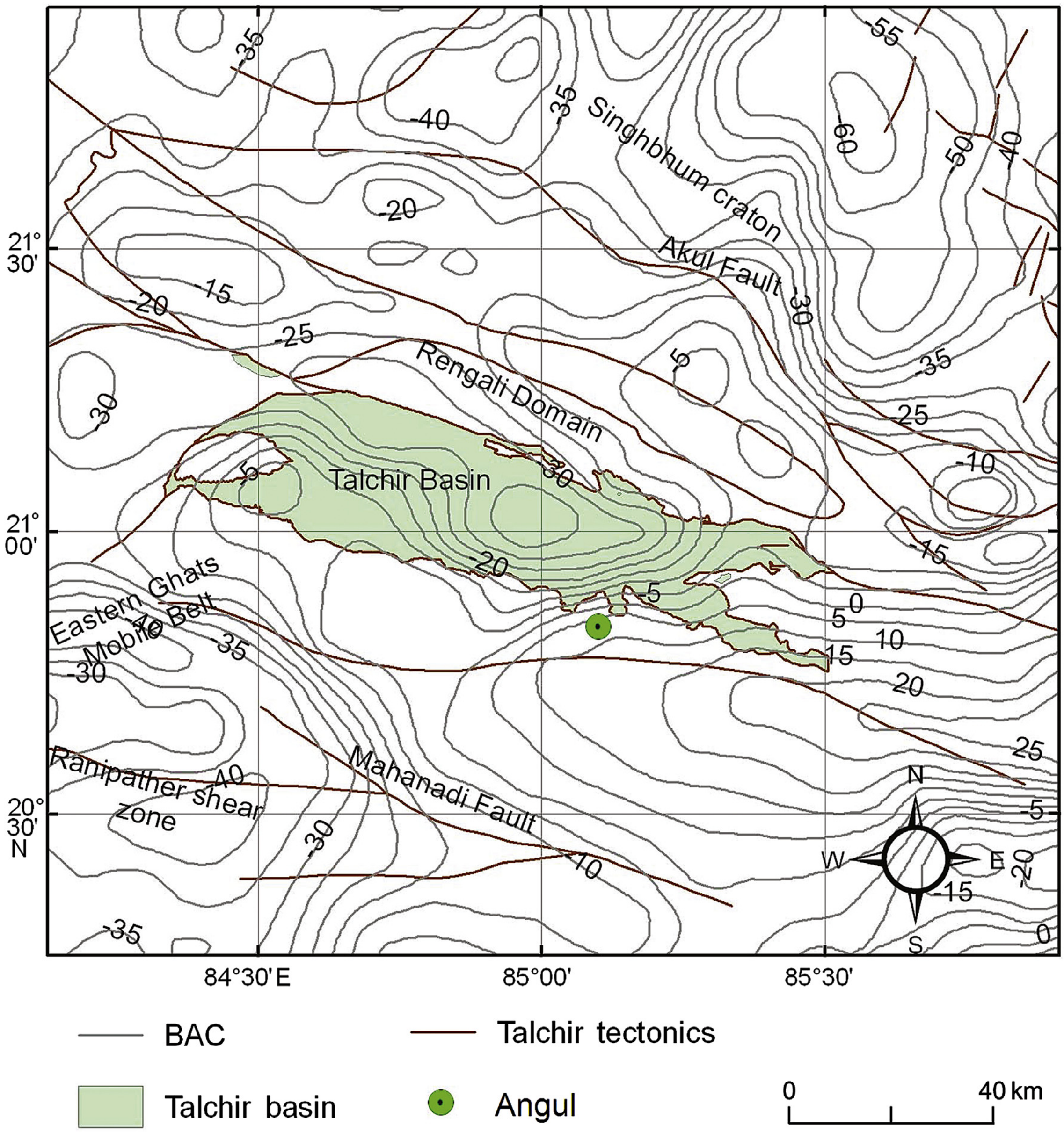

Figure 4. Bouguer Gravity Anomaly contour map as extracted from the regional Gravity Map of India (GSI-NGRI, 2006; Sundaram et al., 2006). The extent of the Talchir Basin and the regional tectonic set up is superimposed in the contour map.

domains. In contrast, the granulite terrane of the EGMB is characterized by positive Bouguer gravity anomalies, with sharp jumps in gravity values across the geological boundaries with the craton (Verma and Subrahmanyam, 1984; Subrahmanyam and Verma, 1986; Murthy and Raval, 2000; Singh and Mishra, 2002). This has generally been ascribed to the presence of higher density crust below the EGMB compared to the craton, which is also correlatable with the higher density granulitic lithologies presently exposed at the EGMB surface. The sudden change in gravity from high to low coincides with the geological contact between the mobile belt and the craton, and has been used in the past to interpret the existence of fossil plate boundaries (Gibb and Thomas, 1976). In an insightful review encompassing gravity data, seismicity and geology, Krishna Brahmam (1993) suggested that several geological terrane boundaries in southern India could represent paleo-suture zones. Subsequently, paired gravity anomalies (i.e. high and low) across Proterozoic terrane boundaries in other parts of the Indian shield have also been interpreted as signatures of Proterozoic collision zones (Mishra et al., 2002; Mishra and Vijaya Kumar, 2005).

In the Talchir Basin, the presence of low density Gondwana sedimentary rocks (e.g. shales and sandstones) explains the decrease in the gravity anomalies over the basin. Interestingly, these values become increasingly negative into the crystalline basement of the Rengali Province north of the basin. Indeed, the systematic decrease in the gravity anomalies from south to north within the Talchir Basin, into even more negative values over the Rengali Province, indicates that a higher density basement underlies the Talchir sediments. This basement is unlikely to represent the Rengali Province, and is more likely to be constituted of the higher density granulitic crust of the EGMB. The northern boundary of the Talchir Basin, represented by the Kerajang Fault, must therefore also be coincident with the Proterozoic contact between the EGMB and the Rengali Province (Sarkar et al., 2007).

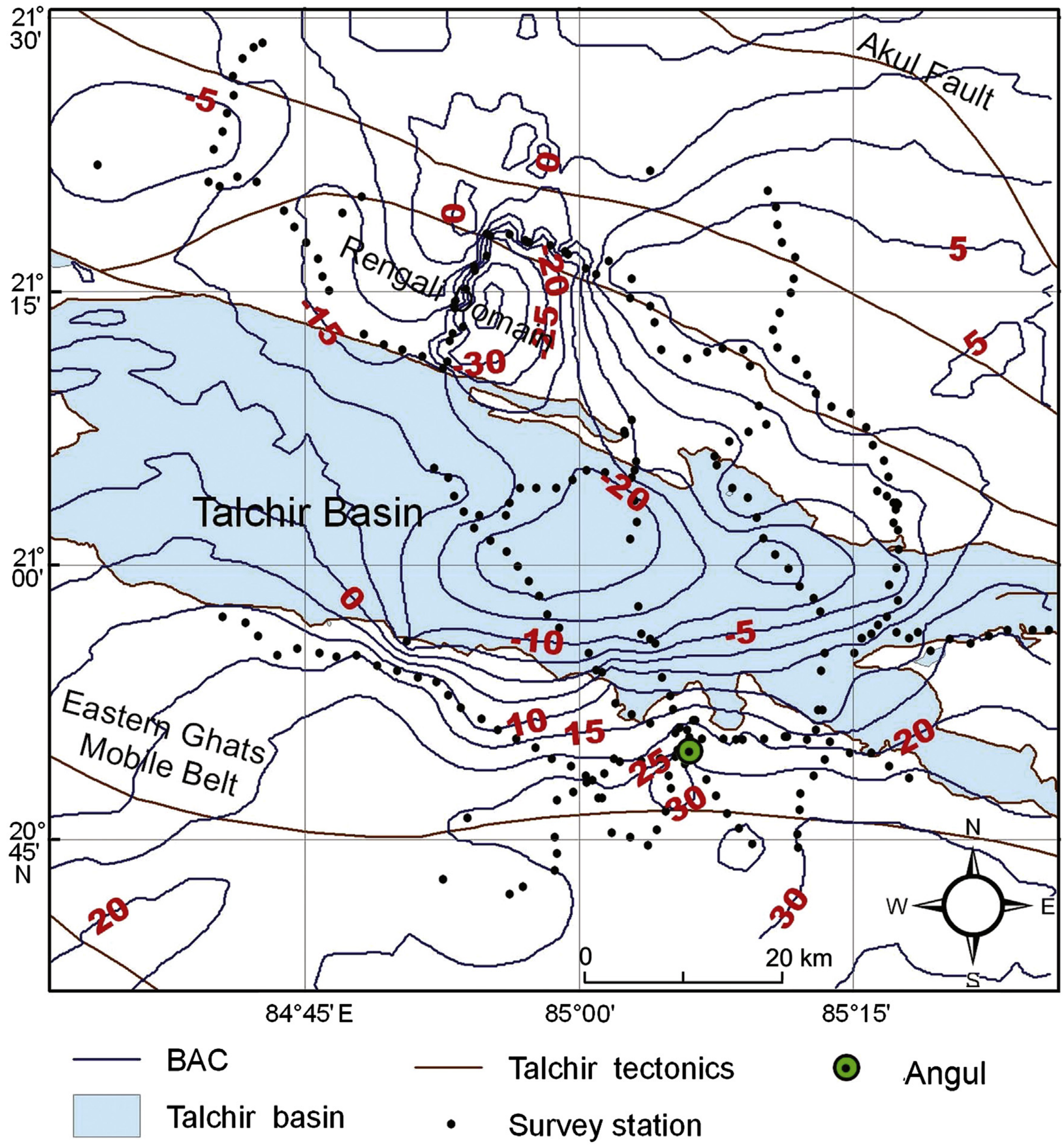

Figure 5. Bouguer Gravity Anomaly contour map based on the present gravity observations. The extent of the Talchir Basin and the regional tectonic set-up are superimposed on the contour map.

The implications of this interpretation are significant in the light of the tectonics of this region. The original contact between the Rengali Province and the EGMB was clearly reactivated during the late Paleozoic (formation of the Gondwana graben), and then again in the Mesozoic (Lisker and Fachmann, 2001), when the present-day Kerajang Fault truncated the Gondwana sediments. Indeed, brittle faults are seen to have localized close to the boundary domain, within the basin; these faults trend WNW–ESE and contain fragments of sandstone clasts (Fig. 6) testifying to post-Gondwana reactivation of the northern boundary domain. These geological inferences indicate that this old terrane boundary has been periodically reactivated throughout its history. Ominously, parts of the area are clearly also susceptible to seismic activity at present (Mohanty et al., 2009; Walling and Mohanty, 2009), indicating that this highly industrialized and populated area remains vulnerable to renewed seismicity. This activity is likely to occur by reactivation of basement faults below the Talchir Basin, which shows the highest present-day seismicity. The results of this study suggest that WNW–ESE, and E–W oriented structures in the EGMB basement (Sarkar et al., 2007) below the Talchir Basin are possible sites of reactivation. In view of the havoc resulting from the Latur and Jabalpur earthquakes, it is clear that more robust monitoring of seismicity in the area is warranted in view of the findings in this study.

A final point of discussion relates to the locations along which intraplate seismicity appears to be focused. The Indian shield is now accepted as being composed of several fragments (blocks) amalgamated along what may be regarded as Precambrian suture zones (e.g. Meert et al., 2010); these sutures have sometimes been related to past supercontinent formation (e.g. Rogers and Santosh, 2002, 2003). Not all these sutures have been reactivated; for instance, while this study demonstrates present-day seismicity along the northern margin of the EGMB, the western contact of this belt with the Bastar and Dharwar cratons is not known to be

Figure 6. Field photograph of a fault rock containing clasts of Gondwana sandstone, from WNW–ESE trending fault close to the northern margin of the Talchir Basin. The coin diameter is 2.2 cm.

seismically active. We suggest that present-day seismicity is essentially driven by far-field stresses related to the northward movement of the Indian plate towards Eurasia, such that pre-existing planes of weakness that are sympathetic to the orientation of this plate boundary are prone to reactivation. The WNW–ESE orientation of the NOBF is fortuitously aligned sub-parallel to the Himalayan trend; indeed, the Narmada-rift (Krishna Brahmam and Negi, 1973) shows a similar E–W alignment. The most devastating intraplate earthquake zone in India is in Kutch, Gujarat, where seismicity on E–W trending faults (Biswas, 2005; Karanth and Gadhavi, 2007) has been tentatively linked to the Himalayan orogeny (Thatcher, 2001). In contrast, the western terrane boundary of the EGMB (Bhadra et al., 2004) is oriented almost perpendicular to this trend, and is not remobilized. Thus, while pre-existing crustal or lithospheric discontinuities can always act as potential zones of reactivation, triggering of movement along these faults depends critically on the orientation of these discontinuities with respect to the driving stresses. Integration of plate vector movements with the orientation of basement faults, therefore, may provide a first order estimate of the seismic potential of intracontinental terrane boundaries.

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References

Acharyya, S.K., Gupta, A., Orihashi, Y., 2010a. New U–Pb zircon ages from Palaeo-Mesoarchaean TTG gneisses of the Singhbhum craton, eastern India. Geochemical Journal 44, 81–88.

Acharyya, S.K., Gupta, A., Orihashi, Y., 2010b. Neoarchaean–Palaeoproterozoic stratigraphy of the Dhanjori basin, Singhbhum craton, Eastern India: and recording of a few U–Pb zircon dates from its basal part. Journal of Asian Earth Science 39, 527–536. http://dx.doi.org/10.1016/j.jseaes.2010.04.023.

Al-Heety, E.A.M., 2007. Historical seismicity of the stable Continental regions (scrs) in the arabian plate (preliminary study). Journal of Al-Anbar university for pure science 1 (1), 1–10.

Bhadra, S., Gupta, S., Banerjee, M., 2004. Structural evolution across the Eastern Ghats Mobile Belt – Bastar craton boundary: hot over cold thrusting in an ancient collision zone. Journal of Structural Geology 26, 233–245.

Biswas, S.K., 2005. A review of structure and tectonics of Kutch basin, western India, with special reference to earthquakes. Current Science 88 (10), 1592–1600.

Calais, E., Han, J.Y., DeMets, C., Nocquet, J.M., 2006. Deformation of the North American plate interior from a decade of continuous GPS measurements. Journal of Geophysical Research 111, B06402. http://dx.doi.org/10.1029/2005JB004253.

Chandra, U., 1977. Earthquakes of Peninsular India – a seismotectonic study. Bulletin of the Seismological Society of America 67 (5), 1387–1413.

Chetty, T.R.K., 2010. Structural architecture of the northern composite terrane, the Eastern Ghats Mobile Belt, India: Implications for Gondwana tectonics. Gondwana Research 18, 565–582.

Chetty, T.R.K., Murthy, D.S.N., 1994. Collision tectonics in the late Precambrian Eastern Ghats Mobile Belt: mesoscopic to satellite-scale structural observations. Terra Nova 6, 72–8113.

Crowe, W.A., Nash, C.R., Harris, L.B., Leeming, P.M., Rankin, L.R., 2003. The geology of the Rengali Province: implications for the tectonic development of northern Orissa, India. Journal of Asian Earth Sciences 21, 697–710.

Dasgupta, P., 2006. Facies characteristics of Talchir Formation, Jharia Basin, India: implications for initiation of Gondwana sedimentation. Sedimentary Geology 185, 59–78.

De, Reena, Chowdhury, S.N., Rao, P.R., 1998. A Micro Earthquake Survey in the Bonaigarh- Talcher area of Orissa, Peninsular Shield Area. Abstract Volume of Chapman Conferences of American Geophysical Union on Stable Continental Region (SCR) Earthquakes, January 25–29, Hyderabad.

Dutta, A., Gupta, S., Panigrahi, M.K., 2010. The southern Rengali Province – a reworked or exotic terrane? Indian Journal of Geology 80 (1–4), 81–96.

Geological Survey of India (GSI), 2000. Seismotectonic Atlas of India and its Environs.

Geological Survey of India (GSI), 2004. Coal Resources of India (accessed on 07.02.2013). http://www.portal.gsi.gov.in/gsiDoc/pub/IndiaCoalResources2004.pdf.

Geological Survey of India – National Geophysical Research Institute (GSI-NGRI), 2006. Bouguer Anomaly Map of India. Published by Geological Survey of India and National Geophysical research Institute, Hyderabad, India.

Gibb, R.A., Thomas, M.D., 1976. Gravity signature of fossil plate boundaries in the Canadian Shield. Nature 262 (5365), 199–200.

Gordon, R.G., 1998. The plate tectonic approximation: plate nonrigidity, diffuse plate boundaries, and global plate reconstructions. Annual Review of Earth and Planetary Sciences 26, 614–642.

Gupta, S., 2012. Strain localization, granulite formation and geodynamic setting of 'hot orogens': case study from the Eastern Ghats Province, India. Geological Journal 47, 334–351.

Halden, N.M., Bowes, D.R., Dash, B., 1982. Structural evolution of migmatites in granulite facies terrane: the Precambrian crystalline complex of Angul, Orissa, India. Philosophical Transactions of the Royal Society of Edinburgh (Earth Sciences) 73, 109–118.

IS: 1893 (Part 1), 2002. Indian Standard Criteria for Earthquake Resistant Design of Structures, Part 1 – General Provisions and Buildings, Fifth ed. Bureau of Indian Standards, New Delhi, p. 42.

Karanth, R.V., Gadhavi, M.S., 2007. Structural intricacies: emergent thrusts and blind thrusts of central Kachchh, western India. Current Science 93, 1271–1280.

Krishna Brahmam, N., 1993. Gravity in relation to crustal structure, paleo-sutures and seismicity of southern India (south of 16 parallel). Memoir Geological Society of India 25, 165–201.

Krishna Brahmam, N., Negi, J.G., 1973. Rift valleys beneath Deccan Trap, India. Geophysical Research Bulletin (Hyderabad) 11, 207–237.

Lisker, F., Fachmann, S., 2001. Phanerozoic history of the Mahanadi region, India. Journal of Geophysical Research, B: Solid Earth 106 (B10), 22027–22050.

Mahalik, N.K., 1994. Geology of the contact between the Eastern Ghats Belt and North Orissa craton, India. Journal of the Geological Society of India 44, 41–51.

Mahalik, N.K., 1996. Lithology and tectonothermal history of the precambrian rocks of Orissa along the eastern coast of India. Journal of Southeast Asian Earth Sciences 14, 209–219.

Malservisi, R., Hugentobler, U., Wonnacott, R., Hackl, M., 2013. How rigid is a rigid plate? Geodetic constraint from the TrigNet CGPS network, South Africa. Geophysical Journal International 192 (3), 918–928. http://dx.doi.org/10.1093/gji/ggs081.

Mazumder, R., Van Loon, A.J., Mallik, L., Reddy, S.M., Arima, M., Altermann, W., Eriksson, P.G., De, S., 2012. Mesoarchaean–Palaeoproterozoic stratigraphic record of the Singhbhum crustal province, eastern India: a synthesis. In: Mazumder, R., Saha, D. (Eds.), Palaeoproterozoic of India, vol. 365. Geological Society, London, pp. 31–49. Special Publications.

McKenzie, D., Parker, R.L., 1967. The North Pacific: an example of tectonics on a sphere. Nature 216, 1276–1280.

Meert, J.G., Pandit, M.K., Pradhan, V.R., Banks, J., Sirianni, R., Stroud, M., Newstead, B., Gifford, J., 2010. Precambrian crustal evolution of Peninsular India: a 3.0 billion year odyssey. Journal of Asian Earth Sciences 39, 483–515.

Mishra, D.C., Singh, B., Gupta, S.B., 2002. gravity modeling across satpura and godavari belts: signatures of Proterozoic plate tectonics. Current Science 83 (8), 1025–1031.

Mishra, D.C., Vijaya Kumar, V., 2005. Evidence for Proterozoic collision from airborne magnetic and gravity studies in Southern Granulite Terrain, India and signatures of recent tectonic activity in the Palghat Gap. Gondwana Research 8 (1), 43–54.
Mohanty, W.K., Walling, M.Y., Franco, Vaccari, Tripathy, T., Panza, G.F., 2009. Modelling of SH- and P-SV-wave fields and seismic microzonation based on response spectra for Talchir Basin, India. Engineering Geology 104, 84–97.
Morgan, W.J., 1968. Rises, trenches, great faults, and crustal blocks. Journal of Geophysical Research 73, 1959–1982.
Mukhopadhayay, A., Chaudhuri, P.N., Banerji, A.L., 1984. Contemporaneous intra-basinal faulting in Gondwana Basin — the Jurabaga fault of lb River Coalfield, a type example. Journal of the Geological Society of India 25, 557–563.
Mukhopadhyay, J., Beukes, N.J., Armstrong, R.A., Zimmermann, U., Ghosh, G., Medda, R.A., 2008. Dating the oldest Greenstone in India: a 3.51 Ga precise U–Pb SHRIMP Zircon Age for Dacitic Lava of the Southern Iron Ore Group, Singhbhum Craton. Journal of Geology 116, 449–461.
Murthy, Y.S., Raval, U., 2000. Bouguer gravity image of India and the neighbouring ESCAP region: a study of tectonics and natural resources. Journal of Geophysics 21, 59–70.
Nash, C.R., Rankin, L.R., Leeming, P.M., Harris, L.B., 1996. Delineation of lithostructural domains in northern Orissa (India) from Landsat Thematic Mapper imagery. Tectonophysics 260, 245–257.
OSDMA, 2002. Map showing the seismic zones of Odisha (after IS 1893 (Part 1)), 2002; Orissa State Disaster Mitigation Authority.
Qureshy, M.N., Subba Rao, D.V., Bhatia, S.C., Aravamadhu, P.S., Subrahmanyam, C., 1973. Gravity bases established in India by N.G.R.I. – Part IV. Geophysical Research Bulletin 11 (2), 136–152.
Rajendran, C.P., Rajendran, K., John, B., 1996. The 1993 Killari (Latur) central India earthquake: an example of fault reactivation in Precambrian crust. Geology 24 (7), 651–654.
Rogers, J.J.W., Santosh, M., 2002. Configuration of Columbia, a Mesoproterozoic supercontinent. Gondwana Research 5, 5–22.
Rogers, J.J.W., Santosh, M., 2003. Supercontinents in Earth history. Gondwana Research 6, 357–368.
Sarkar, M., Gupta, S., Panigrahi, M.K., 2007. Disentangling tectonic cycles along a multiply deformed terrane margin: structural and metamorphic evidence for mid-crustal reworking of the Angul granulite complex, Eastern Ghats Belt, India. Journal of Structural Geology 29, 802–818.
Singh, A.P., Mishra, D.C., 2002. Tectonosedimentary evolution of Cuddapah basin and Eastern Ghats Mobile Belt (India) as Proterozoic collision: gravity, seismic and geodynamic constraints. Journal of Geodynamics 33, 249–267.
Subrahmanyam, C., Verma, R.K., 1986. Gravity fields, structure and tectonics of the Eastern Ghats. Tectonophysics 126, 195–212.
Sundaram, R.M., Surendranath, M., Reddy, U.S.N., 2006. Revised Gravity Maps of India (2006 series) – A Cartographic Perspective. Conference Proceedings of Map World Forum, January 22–25, 2007, Hyderabad, India. http://www.gisdevelopment.net/proceedings/mapworldforum/sem1/MWF_sem1_Cartography_53.pdf.
Tait, J., Zimmermann, U., Miyazaki, T., Presnyakov, S., Chang, Q., Mukhopadhyay, J., Sergeev, S., 2011. Possible juvenile Palaeoarchaean TTG magmatism in eastern India and its constraints for the evolution of the Singhbhum craton. Geological Magazine 148, 340–347.
Thatcher, W., 2001. Pop-up disaster. Nature 410, 757–758.
Verma, R.K., Banerjee, P., 1992. Nature of continental crust along the Narmada-Son lineament inferred from gravity and deep seismic sounding data. Tectonophysics 202, 375–397.
Verma, R.K., Subrahmanyam, C., 1984. Gravity anomalies and the Indian lithosphere: review and analysis of existing gravity data. Tectonophysics 105, 141–161.
Walling, M.Y., Mohanty, W.K., 2009. An overview on the seismic zonation and microzonation studies in India. Earth Science Reviews 96, 67–91.
Walling, M.Y., Mohanty, W.K., Nath, S.K., Mitra, S., Jhon, A., 2009. Microtremor survey in Talchir, India to ascertain its basin characteristics in terms of predominant frequency by Nakamura's ratio technique. Engineering Geology 106, 123–132.
Wilson, J.T., 1965. A new class of faults and their bearing on continental drift. Nature 207, 343–347.