Analysis of gravity and magnetic anomalies of Kachchh rift basin, India and its comparison with the New Madrid seismic zone, USA

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The M_w 7.6 Bhuj earthquake of 26 January 2001 is in many ways considered similar to New Madrid earthquakes of 1811–12 in the central United States. Analysis of gravity and magnetic anomalies constraining with the seismic and magneto-telluric studies suggests faulted basement and a zone of high magnetic and denser material (Deccan Trap affinity) in the Bhuj epicentral region and found analogous to the Gabbroic intrusion along Commerce Geophysical lineament of New Madrid seismic zone. Isostatic regional gravity anomaly map of Kachchh presents two gravity lows within the Kachchh rift basin, indicating mass deficiency due to crustal thickening up to 8 km, similar to one in Mississippi embayment by Missouri batholith, intersecting the Reelfoot rift and the two might be intimately related to seismicity in respective regions. Seismicity in Kachchh, though, might be due to stress concentration due to coupled force system, i.e. the horizontal tectonic stresses due to movement of the Indian plate and intraplate stresses induced by crustal heterogeneities; however, the source of gravity lows could intimately be related to earthquake activity in Kachchh, as widely inferred for Missouri gravity low in case of New Madrid seismic zone.

THE Bhuj earthquake of 26 January 2001 of magnitude 7.8 with epicenter[1] around 23.4°N and 70.3°E and focal depth of 23 km is considered to be one of the largest intraplate earthquakes, which has caused considerable damage both to human beings (dead > 20,000, injured > 150,000) and property (> $ 10 billion) and has been considered as analog to New Madrid earthquakes[2] of 1811–1812. New Madrid seismic zone is considered to be one of the most active seismic zones in the United States east of Rocky Mountains, where earthquake of 6.3 or greater magnitude can be expected once every 100 years. The New Madrid and the Bhuj earthquakes occurred in the ancient failed-rift zones (see Figure 1) and both these zones represent the present-day compressive regime formed under very different geologic circumstances, they are zones of relatively weaker crustal rocks where earthquake processes may cause faulting to occur more easily than in surrounding regions. The relationship of the New Madrid and Bhuj earthquakes to plate-tectonic motions remains unresolved. Kachchh is a well-known seismic zone and felt earthquakes on regular basis[3], notable among them being the Kachchh earthquake[4,5] of almost similar magnitude in 1819 and Anjar earthquake[6] of magnitude 6.0 in 1956 (Figure 2). At least three pre-historic earthquakes affecting the Indus Valley Civilization at Dholavira in Khadir uplift (D, Figure 2) during 2900–1800 BC have been reported[7]. Kachchh is an E–W trending Mesozoic rift basin formed due to breakup of Africa, from the Indian plate during middle Jurassic and related activities[8,9]. Geological and tectonic elements of Kachchh consist of several fault-controlled uplifted blocks. Island Belt Fault[10] (IBF) in the north is associated with several small uplifts where Mesozoic sediments are exposed while the adjoining region between the IBF and the Kachchh Mainland Fault (KMF, F1) is covered by sand and salt flats known as the Banni plains and the Rann of Kachchh. The elevated land south of the KMF (F1) is Kachchh Mainland uplift (KMU), which is occupied by Mesozoic sediments. In the southern part, the Mesozoic sediments are overlain by Deccan trap of late Cretaceous and Cenozoic sediments. They are separated from Mesozoic sediments by faults F2 and F3 (ref. 8). The Deccan trap in NW India occupies a vast area in Saurashtra and Kachchh[11] (Inset, Figure 2) and represents the volcanic basaltic flows formed due to eruption from Reunion plume during late Cretaceous when the Indian plate moved over it[12]. The NW–SE trending KMF (F1) converging to E–W towards the east, resembles the southern coastline (Figure 2) indicating its evolutionary relationship. Similarly boundaries of geological formations south of the KMF varying in age from Jurassic to Recent also follow the same trends. The faults F4 and F5 towards south and north of Wagad uplift respectively are E–W oriented faults known as south and north Wagad faults (SWF and NWF), which control the Wagad uplift[13]. In this paper we attempt to explore the similarities of geologic structures expressed as prominent potential field anomalies in the two most seismogenic zones namely Kachchh and New Madrid seismic zone in an old rift system.

Bouguer anomaly map of Kachchh

Utility of potential field data in siesmotectonic studies has been emphasized from time to time (see refs 34, 35)

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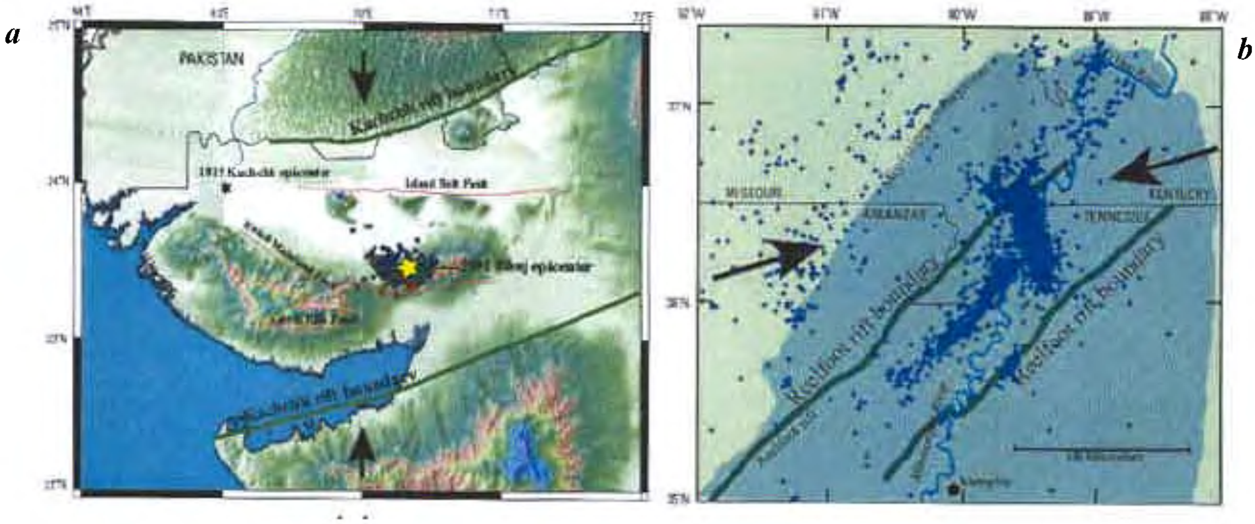

Figure 1. *a*, Tectonic map of Kachchh Rift basin showing the epicenters of two earthquakes (stars) in Kachchh region, viz. 2001 Bhuj earthquake and 1819 Kachchh earthquake. Dots show aftershock locations and colour indicate their depths; red = deep, green = intermediate and blue = shallow. *b*, Tectonic map of New Madrid seismic zones with a pattern of epicenters indicating major faults that broke during 1811–1812 earthquakes. The present day compression is shown by black arrows.

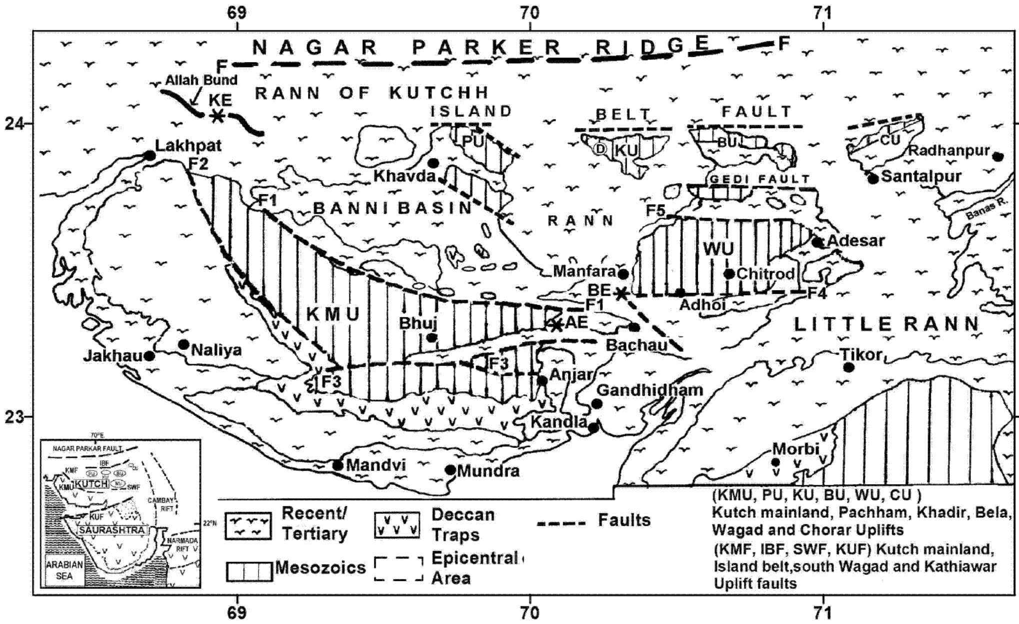

Figure 2. Geology of Kachchh showing various formations and faults referred to as F1–F5. KE, AE and BE are the epicenters of Kachchh, Anjar and Bhuj earthquakes of 1819, 1956 and 2001. Inset shows Deccan trap coverage in Kachchh and Saurashtra region.

and to great extent helped in demarcating the weak zones, viz. fractures, faults and crustal heterogeneities (potential stress concentrators) that are intimately related to seismicity and are widely used in providing insights on the geologic framework of any seismogenic region. Bouguer anomaly map of Kachchh (Figure 3) is prepared incorporating some additional gravity data (250 stations) acquired in the gap area with the existing gravity data (about 1000 stations[14]). The gravity data are acquired using Lacoste–Romberg gravimeter with an accuracy of 0.01 mGal (10^{-5} m/s^2). The elevation of gravity stations are measured using geodetic leveling and in some cases electronic altimeter with an overall accuracy of better than ± 1 m causing an error of about ± 0.2 mGal in the computed Bouguer anomaly. The gravity data is processed using IGSN, 1971 for a standard density of 2670 kg/m^3 for the Bouguer slab[15]. The overall accuracy of Bouguer anomaly map prepared from this data is about ± 0.5 mGal and is good enough for the present study. A large portion of Rann of Kachchh could not be covered due to its inaccessibility; however Banni could be covered

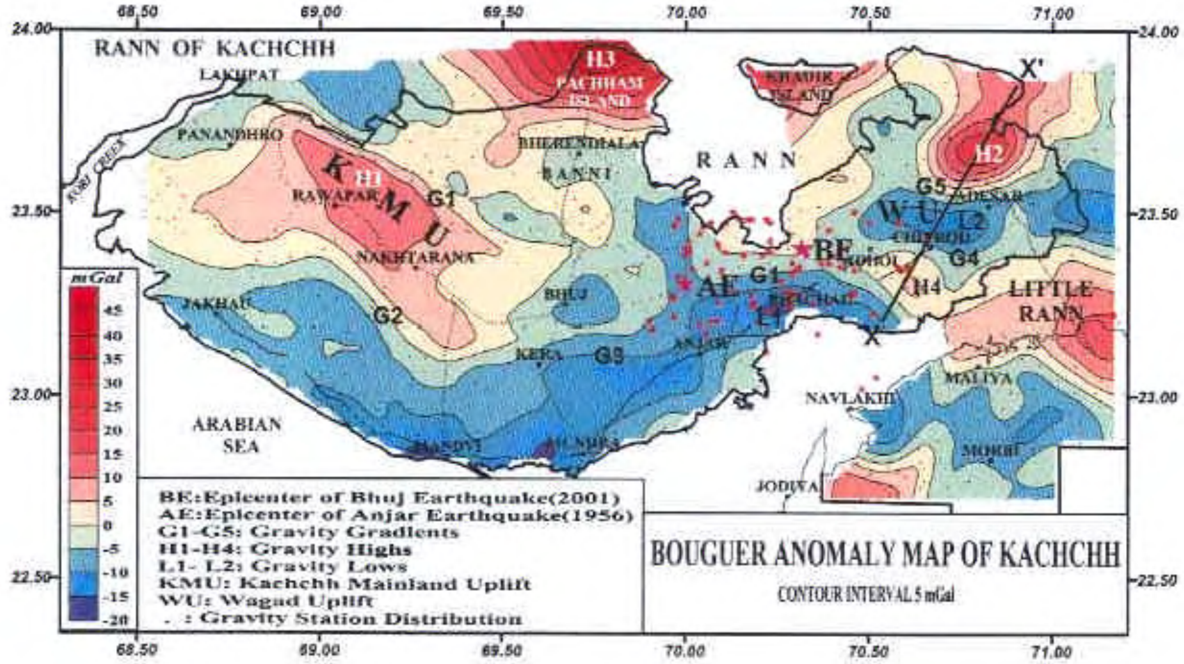

Figure 3. Bouguer anomaly map of Kachchh, G1–G4 are gravity gradients corresponding to faults F1–F4, H1 represents the Kachchh Mainland Uplift (KMU) and H2 and H3 constitute parts of Wagad and the Pachamm uplift.

due to availability of tracks. The Bouguer anomaly map of the Kachchh (Figure 3) shows pronounced gravity highs and lows, representing the structural trends of this region, it remarkably shows the gravity gradients expressed by the known faults of Kachchh rift basin such as Kachchh mainland, Vigodi, Katrol hill, south Wagad and Gedi faults. The anomaly map depicts a central gravity high (H1) coinciding with KMU with gravity gradients G1 and G2 towards its northern and southern margins representing the thrust faults F1 (KMF) and F2 (Vigodi fault) (Figure 2), respectively. F1 clearly extends up to Bhuj and beyond, further east gets diffused under the influence of gravity lows around Bhachau (L1). Similarly G3 representing F3 (Katrol hill fault) at the southern margin of the KMU extends up to Anjar along the southern coast of Kachchh. The circular gravity high (H2) and (H3) with a relief of around 30–40 mGal indicates the presence of intrusives in this area, similar to volcanic plugs of Saurashtra and coincidentally both these highs are located near the epicenters of the two most destructive earthquakes of this region, viz. Kachchh earthquake of 1819 and Bhuj earthquake of 2001.

Total intensity map of epicentral area

Total intensity magnetic field was recorded along roads and tracks at about 1 km interval in the epicentral area of Bhuj earthquake and its aftershocks. The total intensity data is acquired using a proton precision magnetometer with 1 gamma accuracy. This area being located in low geomagnetic latitude of 25° in northern hemisphere, a basement uplift will be characterized by a large magnetic low over it and a small high shifted towards the south for normal induced magnetization. On the other hand, a basement depression provides a magnetic high over it with a small low shifted towards the south. In sedimentary basins, there are several basement uplifts and depressions and therefore, the magnetic fields due to them interfere with each other and we get a combined effect due to individual sources. However, one can attempt to separate them based on similarity of positive and negative centers of adjoining magnetic anomalies and in comparison to the gravity anomalies, which are located exactly over the causative sources. The gravity and magnetic highs and lows are therefore shifted slightly with respect to each other due to bipolar nature of magnetic field. Hence, it may be noted that the gravity high (H4) corresponding to basement high is reflected as magnetic low (ML1) in this map. Similarly, the gravity low and high, L2 and H4 (Figure 3) are reflected as part of MH1 and ML2 (Figure 4) representing a basement depression and uplift. The gravity gradients are also reflected as magnetic gradients in the magnetic anomaly map and may represent basement faults.

Regional isostatic anomaly map

The state of isostasy can provide vital information about the nature of vertical forces operating in any region. Such as, if the excess mass by topographic load is over compensated at depth, then due to buoyant forces the region tends to rise to attain the isostatic balance. Similarly, the

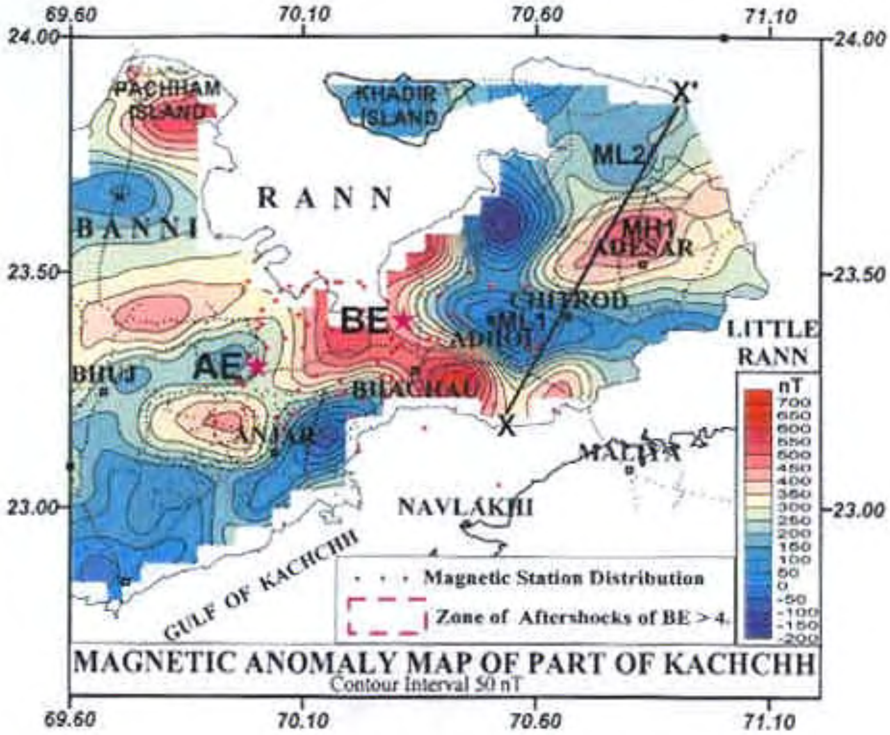

Figure 4. Total intensity magnetic map of epicentral zone showing some important magnetic anomalies. ML1 and MH1 indicate magnetic lows and highs corresponding to Wagad uplift.

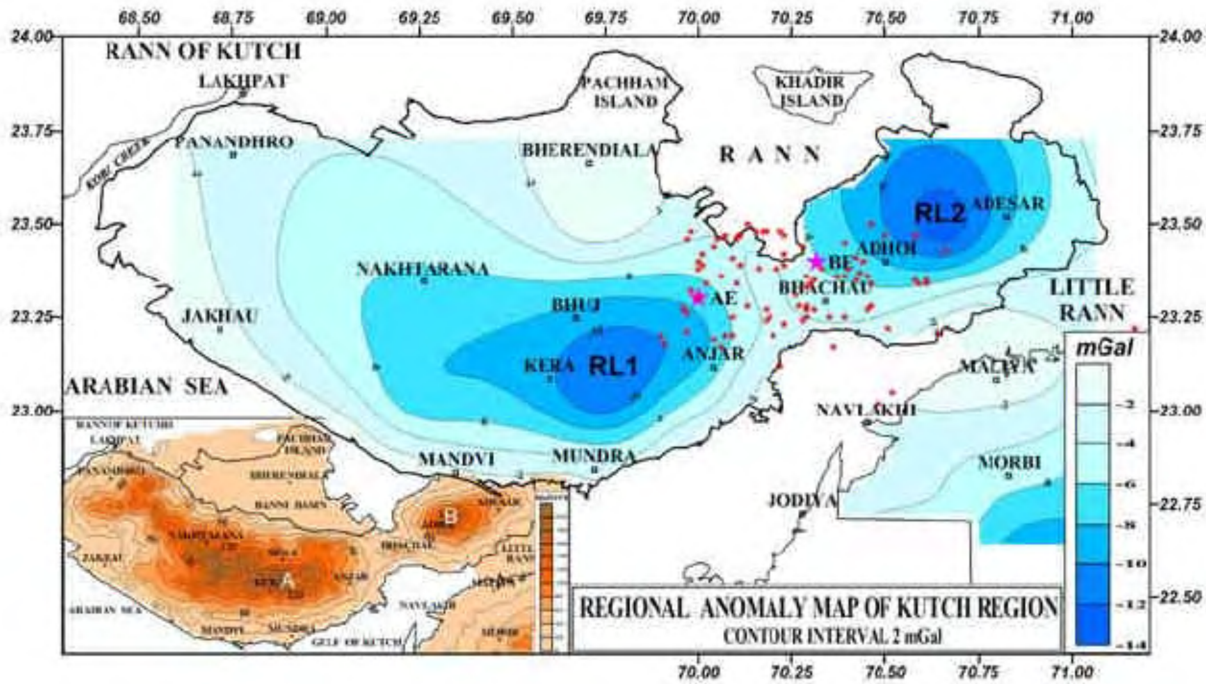

Figure 5. Regional isostatic map derived from Figure 3 based on zero free air anomaly, RL1 and RL2 denote isostatic gravity lows corresponding to elevated zones of the KMU and WU (A and B, Inset).

under-compensation would result in subsidence. Free air and Bouguer anomaly with respect to elevation have been widely studied to assess the state of isostasy in a region[16]. Free air anomaly can be an indicator for the state of compensation and for a fully compensated case; its value is zero on a regional scale as the effect of topographic load is balanced by the effect of the compensating mass. Consequently, the Bouguer anomaly corresponding to regional elevation where free air anomaly is zero represents the effect of the compensating mass in any area and is known as isostatic regional[16,17]. Both the free air and the Bouguer anomaly however, will have the effects of local sources, which are localized and can be differentiated from the regional isostasy based on regional elevation in an area and nature of anomalies. An unbiased estimate of isostatic regional field can therefore be obtained from the Bouguer anomaly for the regional elevation in an area where free-air anomaly is zero[17]. Isostatic regional obtained in this manner (Figure 5) provides two circular gravity lows, RL1 and RL2, of amplitude –11 and –13 mGal. They coincide with the elevated topography of the SE part of KMU and the Wagad uplift (A and B, Inset, Figure 5). The isostatic regional lows RL1 and RL2 represent large wavelength gravity lows and centers of mass deficiency at the Moho.

Modeling of basement faults and crustal thickness

Profile: X–X′

To map the faults controlling the Wagad uplift in the epicentral area of Bhuj earthquake and its aftershocks, residual gravity and magnetic data along a profile XX′ across this zone are modeled using constraints based on previous studies[18]. This profile (Figures 3 and 4) shows conspicuous gravity and magnetic anomalies towards south and north of the Wagad uplift. The basement model computed by simultaneous inversion[19] of gravity and the magnetic data and corresponding density and magnetization of different layers and the basement is given in Figure 6. In this model Mesozoic sediments are treated as one single unit of bulk density 2350 kg/m^3 due to predominance of upper Mesozoic in this region. The sediments being non-magnetic in nature, magnetic field originates from susceptibility distribution of the basement, which is used to compute the magnetic field. The basement model along this profile shows that the northern part of the Wagad uplift is controlled by the thrust fault, which is dipping southwards by 40–50°. This infact is the most conspicuous contact in the basement whose projection on surface coincides with the northern margin of the Wagad uplift. It shows basement uplift by about 1.5 km along this contact. The mafic body at a depth of 1.5 km north of it under Bela uplift (H2) shows a remnant magnetization with bulk direction of magnetization as $D = 350°$ and $I = -50°$, which is almost similar to normal magnetization of Deccan Trap[20] exposed in the southern part of Kachchh and Saurashtra, this high density (2800 kg/m^3) and high susceptibility (0.115 SI units) body under Bela uplift (H5) may, therefore, represent a mafic intrusive of Deccan volcanism similar to plugs of Saurashtra[21].

Isostatic compensation normally takes place at Moho depth and regional isostatic gravity anomaly represents its effect. The regional gravity anomaly along profile XX′ (Figure 5) is therefore, modeled for Moho variations using standard density of 2900 and 3300 kg/m^3 for the lower crust and the upper mantle respectively (Figure 6). The computed model shows a crustal thickening from 35 km along the coast to 43 km under Wagad uplift. A thick crust of 44 km in Kachchh is also indicated by receiver function analysis of teleseismic data[22]. Results of seismic survey also indicate crustal thickening along a profile from Mundra to Adesar, which show Moho depth varying from 35 km along the coast to 44 km under the Wagad uplift[23]. In order to deduce the crustal thickness indicated by seismic results around 44 km under the Wagad uplift, the density contrast between the lower crust and the upper mantle is required to be 400 kg/m^3, implying that either the density of lower crust is higher than its normal average value as incase of under plated crust or the density of the upper mantle is less compared to its universal value of 3300 kg/m^3. Possibilities of both exist in this case as indicated by high velocity lower crust and low velocity upper mantle in seismic tomography studies towards west and SE[24] of this area.

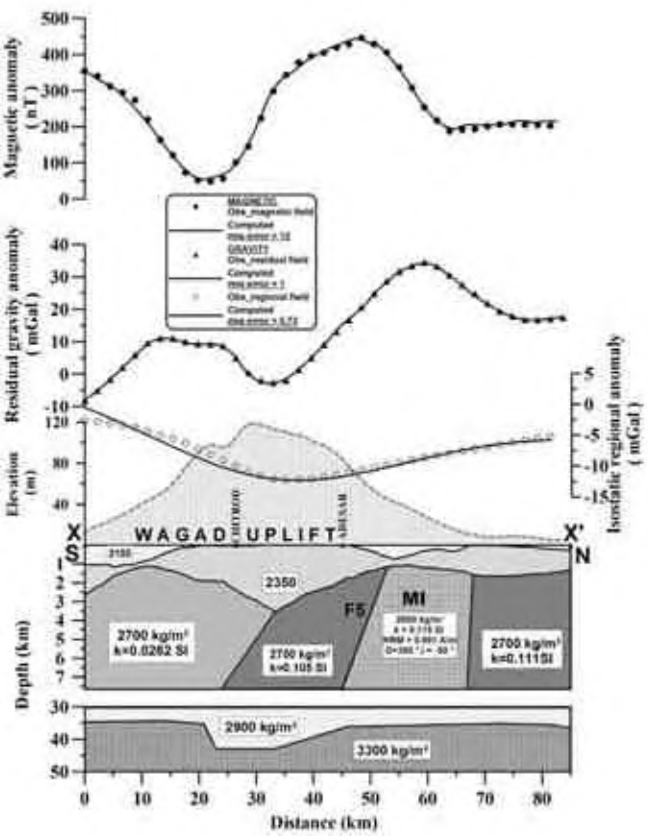

Figure 6. Shallow and deep cross section derived from 2-D modeling of residual gravity and isostatic regional anomaly along a profile XX′.

Bouguer anomaly map of new Madrid region

The New Madrid seismic zone is the site of three devastating earthquakes that occurred in 1811–1812 and commerce geophysical lineament may reflect the seismically hazardous feature parallel to Reelfoot Rift and suggest its close affiliation with the Reelfoot Rift. Bouguer anomaly map of New Madrid region[25–27] shows a belt of linear, but discontinuous positive gravity (highs) representing the commerce geophysical lineament with positive aeromagnetic anomalies. On closer inspection it does not consist of single magnetic high, but of several anomalies with amplitude of around 150 nT and a zone of gravity low (see Figure 7). Positive gravity anomalies in the upper Mississippi embayment are interpreted to be caused by high density rocks beneath the embayment that were emplaced during the late Pre-Cambrian to early Paleozoic rifting event or during Mesozoic reactivation of the rift. Another feature that may be intimately linked to earthquake activity in the region is the source of the Missouri gravity low (MGL), which extends to the Mississipi embayment. Hildenbrand[28] investigated and indicated a low density, shallow source called the Missouri batholith for the Missouri gravity low. The intersection of Reelfoot graben and the Missouri batholith represents a weak zone that contrasts with more competent, flanking metamorphic terranes. The seismic activity mostly confines within the intersection[29] of this weak zone in the Mississipi embayment (see Figure 7).

Crustal model along profile A–B

Profile AB crosses the commerce geophysical lineament where it is best expressed in the gravity and magnetic field (Figure 8). The commerce geophysical lineament anomalies are superimposed on a fairly flat regional magnetic field. Modeling of gravity[30] and magnetic anomalies[26] indicate that the commerce geophysical lineament is a zone of magnetic, slightly denser material (0.018 SI; 2680 kg/m^3) ~35 km wide that has a high magnetic (0.023 SI) and dense (2740 kg/m^3) core dipping steeply to the southeast (Figure 8). The Precambrian upper crustal rocks are heavily intruded by dense igneous plugs which are strongly correlated with the hypocenters. The prominent gravity and magnetic anomalies of the junction segment of the commerce geophysical lineament may be caused by gabbroic intrusion analogous to the gabbro intrusive bodies along the Saudi Arabian dike swarms[31]. Stresses sufficient to generate earthquakes in New Madrid is possibly due to combination and superposition of far field stresses by tectonic plate forces and local stress concentration due to crustal heterogeneity (igneous intrusions) and slips on the detachment fault near the domal rift cushion.

Discussion and conclusions

Shallow and deep crustal structures play significant and important role in understanding the earthquake processes. Potential field data are primarily used in the detection and delineation of geologic structures and crustal heterogeneities that are mostly associated with the earthquake processes.

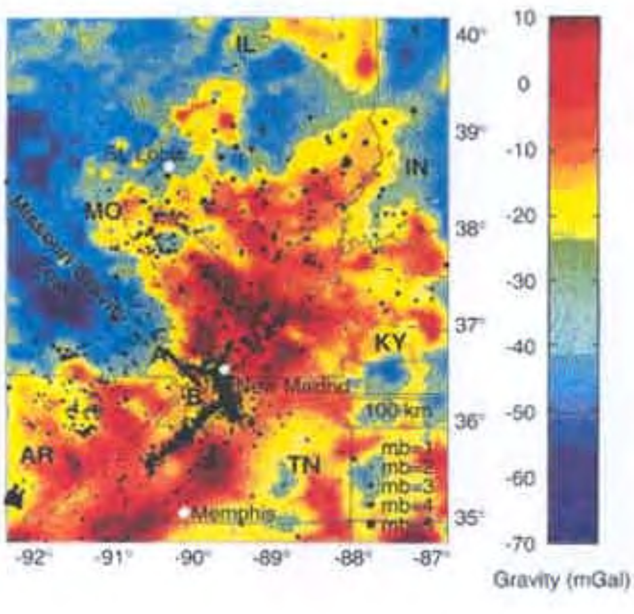

Figure 7. Bouguer anomaly map of New Madrid seismic zone showing discontinuous gravity highs due to commerce geophysical lineament and a broad Missouri gravity low.

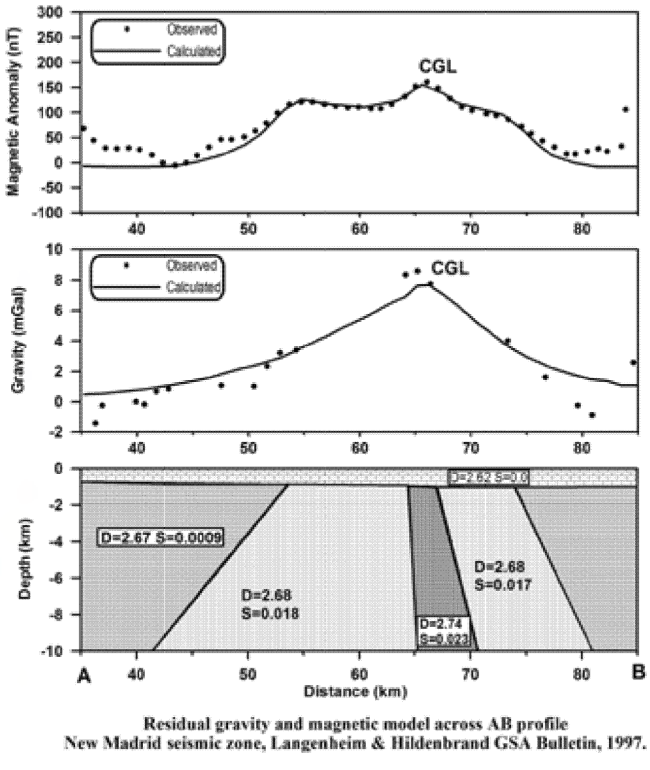

Figure 8. Shallow cross section derived from 2-D modeling of residual gravity anomaly along a profile AB. It shows a commerce geophysical lineament and its core having high magnetic and denser material.

Analyses and inversion of gravity and magnetic data of Kachchh region are carried out using constraints from seismic, magneto-telluric and other geological inputs to provide vital information about the overall crustal architecture of this region. Modeling of gravity and magnetic anomalies constraining with the seismic and magneto-telluric studies suggest faulted basement[18] in the epicentral region and the simultaneous inversion of gravity and magnetic data along a profile across the epicentral region suggest a 15 km wide zone of high magnetic and dense material. This central zone of high-density/magnetic is analogous to the Gabbroic intrusion about 35 km wide along Commerce Geophysical lineament of New Madrid, USA, wherein similar increased magnetization and density have been demonstrated by integrated geophysical study. This high density and magnetic body (intrusive) in the Bhuj epicentral area can be related to the episode of volcanic activity (Deccan volcanism) that has been documented in abundance in the immediate neighborhood, viz. southern part of Kachchh and entire Saurashtra. However, the source age of gravity and magnetic anomalies of commerce geophysical lineament is not well established, as several episodes of intrusive activity spanning Phanerozoic to Cretaceous, even extending into Eocene, have been documented for the region surrounding the commerce geophysical lineament. The regional gravity lows over the Kachchh rift basin indicate deficit mass at Moho level, in the form of crustal root of 8 km thickness, Similarly, the regional gravity low of New Madrid region represents mass deficiency by shallow Missouri batholith in the seismic zone and its intersection with the Reelfoot rift, appears to be intimately related to the seismicity in New Madrid seismic zone. Pronounced gravity anomalies expressing mass deficiency at deeper level (Moho) in the Bhuj epicentral region underline the role of anomalous crustal root, together with the tectonic forces due to movement of Indian plate and stressed volumes (igneous intrusions) at shallower depth in triggering the earthquakes (mostly thrust) in Kachchh rift basin, as fault plane solutions from teleseismic studies consistently suggest a reverse-slip mechanism for the Anjar[6] and Bhuj[32,33] earthquakes. Similar large regional gravity low is also observed in Saurashtra over Jasdan plateau and frequent occurrence of small magnitude earthquakes in Bhavnagar at the peripheral margin of large gravity low is reported[21,34]. In our study the analyses of gravity and magnetic anomalies of Kachchh region not only delineate the crustal heterogeneity in the epicentral region of Bhuj earthquake, but also underline the significance of source of gravity low embedded within the Kachchh rift basin. The occurrence of strong earthquakes in the Kachchh might be due to anomalous concentration of stresses by coupled force system, i.e. the horizontal tectonic stresses by the continual movement of the Indian plate, intraplate stresses induced by crustal heterogeneities[35,36] and to some extent stress contribution from the source of gravity low, i.e. deep-seated mass anomaly (deficiency) in the Bhuj epicentral area. These stresses collectively might be responsible for the large thrust events in Kachchh rift basin and bring out similarities with new Madrid events in the intraplate regions.

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