Anomalous mass distribution in the epicentral area of Latur earthquake, India

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A detailed gravity survey in the epicentral area of Latur earthquake of 30 September 1993 has delineated NW–SE and NE–SW trends similar to the regional ones, besides some additional trends which intersect in the epicentral area of this earthquake and its aftershocks. It has also delineated several low amplitude small wavelength gravity 'lows' and 'highs' which are caused by local shallow sources. The epicentre of main shock coincides with a NW–SE gravity gradient, suggesting its association with a local tectonics related to similar oriented regional tectonics and reactivated under suitable conditions.

The observed gravity field is separated into regional and residual components, and the latter is modelled due to a low-density layer in the upper crust (10–12 km) warping up to a depth of 3.5 km along the axis of gravity 'lows' and some high-density bodies in the basement. The low-density bodies coincide with the conductive bodies delineated from magneto-telluric measurements and may represent fluid filled fractured zones in the basement at a depth of approximately 3.5 km in the epicentral area. High-density source mass may indicate basic intrusions or lithological changes due to inclusion of high-density metasediments and metavolcanics in the basement. The high-density and low-density bodies in basement make the area very heterogeneous and can cause local stress concentration at their contact with host rocks. They can also provide path for seepage of meteoric water to greater depth and can enhance the fluid pressure by reducing porosity and permeability which may trigger seismic activities.

THE Latur earthquake of magnitude 6.1, which occurred in the peninsular shield of India on 30 September 1993, is one of the deadliest earthquakes razing several villages and killing about 10,000 people[1]. There have been several earthquakes in the peninsular shield of India in the past which were mainly attributed to some known features such as older rifts like Godavari rift and Narmada–Son lineament or reservoir-induced seismicity as in the case of Koyna earthquake of 1967 and subsequent tremors. The Latur earthquake could not be explained in the first instance due to absence of known specific tectonic features. However, now it is considered owing to the accumulation of stress in the upper crust due to erosion and presence of fluid[2] and reactivation of an old fault[3].

The Latur area is covered by Deccan Traps which erupted during Late Cretaceous (66 my)[4] when India passed over Reunion hot spot during its drifts from Gondwana land to its present position. There are several lineaments in this region which are largely oriented NW–SE and NE–SW, some of which may be faults[5]. The epicentre of this earthquake is located almost at the eastern fringe of the exposed Deccan Trap (Figure 1). The focal depth of this earthquake is estimated to be 2.5 km (ref. 6). The fault plane solution indicates NW–SE oriented reverse faulting. The study of after-shocks yields focal depth starting almost from 0.5 km up to 10 km but majority of them are confined to upper 5 km (ref. 7).

As this area is covered by the Deccan Trap, the subsurface geology/tectonics is unknown and has been a matter of speculation. Therefore, detailed geophysical surveys are essential to delineate subsurface structures and tectonics. Gravity surveys are extremely useful as they provide two-dimensional maps capable of delineating structures in a plane and provide information on their third dimension, namely depth extent.

Various geoscientific experiments conducted in Latur region after this earthquake have provided several information about structure/tectonics of this region relevant to this earthquake[8]. The Bouguer anomaly map of the epicentral area shows several linear structural trends and blocks which are at different levels indicating movement along their boundaries. The epicentre of this earthquake coincides with the junction of these trends[9]. Magneto-telluric (MT) studies revealed a conductive zone at a shallow depth of 10–12 km in the entire area which warped up to a depth 5–6 km in the epicentral area[10]. The Latur earthquake has caused a rupture at the surface. A borehole located at this rupture has provided mainly tholeiitic basaltic flows up to a depth of 338 m and encountered a gneissic basement at a depth of 346 m, with 8 m of intratrappean section of oxidized shale and conglomerate between them[11].

The regional Bouguer anomaly map of Deccan Trap (Figure 1)[12], prepared from data recorded along roads at 6–7 km spacing, shows large wavelength gravity anomalies oriented mainly NW–SE which are basically of crustal origin[13]. However, there are some short wave-length anomalies of small amplitude oriented NE–SW along the eastern fringe of the trap south of Killari (Figure 1), suggesting the intersection of these two prominent trends in the epicentral region of this earth-quake.

The Bouguer 'low', centered at Kuruduvadi extending NW–SE, does not coincide with Balaghat range, suggesting that it is not related to isostatic compensation. The Balaghat range, whose average elevation is approximately 600 m, shows the positive isostatic anomaly, suggesting it to be under compensation which may cause

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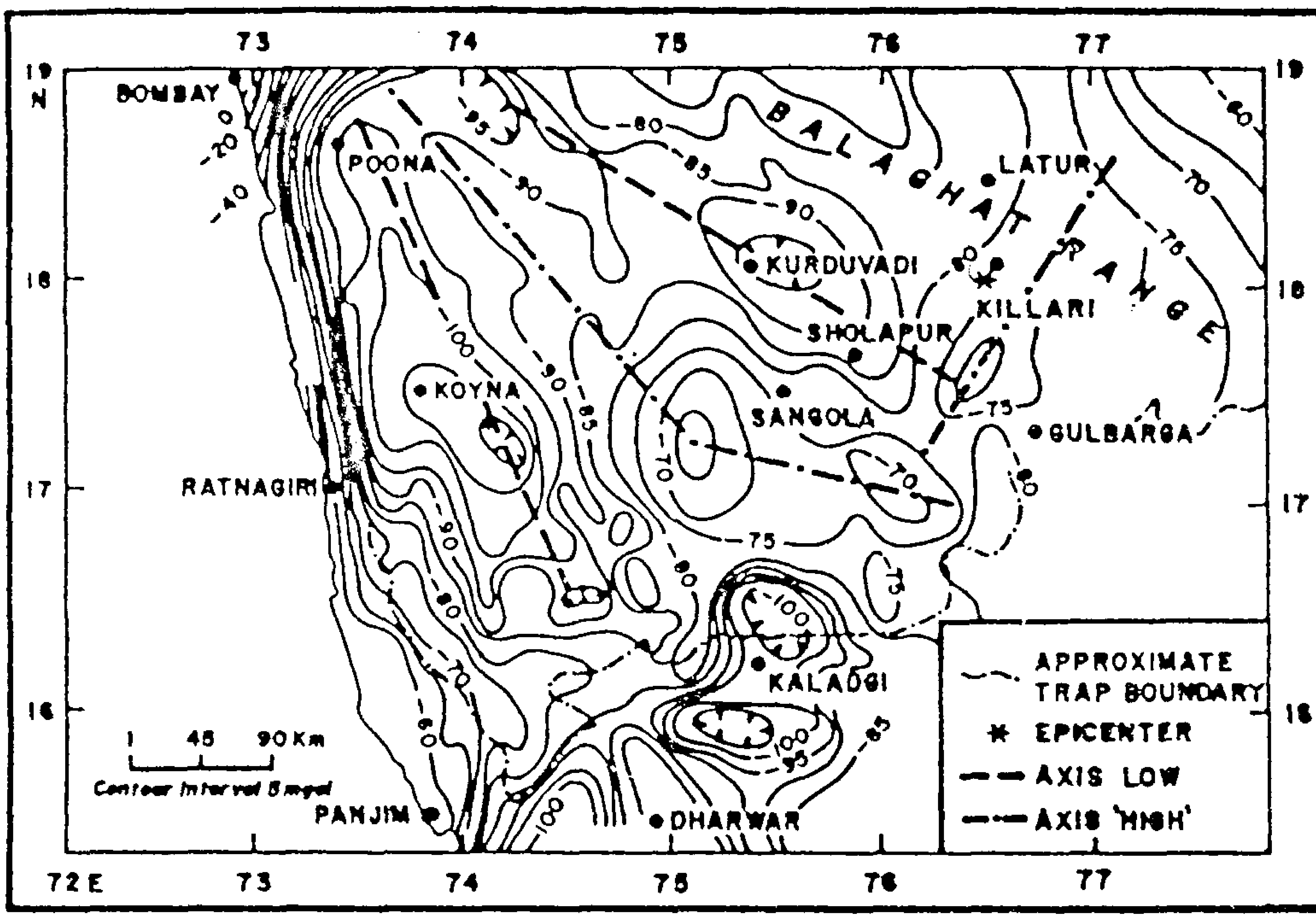

Figure 1. Regional Bouguer anomaly map of Deccan volcanic province showing major structural trends and the epicenter of the Latur earthquake.

changes in the stress conditions at shallow depth. However, in order to delineate shallow/basement tectonics relevant to the present earthquake, a detailed gravity survey of the epicentral area at a closer station-spacing of approximately 1 km was undertaken, which revealed several shallow structures .

Figure 2 presents the Bouguer anomaly map of the epicentral area based on the data recorded along roads/tracks at a station-spacing of approximately 1 km using a Lacoste–Romberg gravimeter. The overall accuracy of the present survey may be of the order of 1 mgal (ref. 9). Another gravity survey conducted by Geological Survey of India in this region[14] also presents a similar Bouguer anomaly map, confirming its accuracy. The Bouguer anomaly map shows several 'lows' (L_1–L_5) and 'highs' (H_1–H_3) of 4–5 mgal amplitude oriented mainly NW–SE, NNW–SSE, NE–SW and E–W. This suggests that though the two regional trends, namely NW–SE and NE–SW are common, there are some additional trends which intersect in the epicentral area. A close examination of the Bouguer anomaly map (Figure 2) indicates that there are more than one sources of these anomalies. As is evident from Figure 2, there are at least two specific kinds of anomalies: (1) Relatively small amplitude, elongated 'highs' of short wavelength (H_1, H_2 and H_3). Sources of these anomalies may be shallow high-density bodies. (2) Relatively small amplitude elongated 'lows' of short wavelength (L_1 to L_5) which may represent shallow sources of low-density.

It may be noted that the epicentre of the Latur earthquake coincides with the gravity gradient between gravity 'high' (H_1) and 'low' (L_1) and the epicenters of the aftershocks are mainly confined to the gravity 'low' (L_1), suggesting its significance. These observations are important as they are associated with the epicentral area. To model these gravity anomalies, we selected two profiles A–A′ and C–C′. The profile A–A′ is chosen to pass through the maximum gravity anomalies while profile C–C′ approximately coincides with the MT profile discussed by Sarma *et al.*[10]. The gravity anomalies along these profiles are modelled using the inversion scheme by Webring[15].

The profile C–C′ which coincides with the MT profile presents two gravity 'lows' (L_1 and L_3) and two 'highs' (H_1 and H_2) (Figure 2). We have selected regional from our recent study in this area using a method proposed by Subbarao[16]. It is based on zero free air anomaly value in the surrounding region which corresponds to isostatic compensated level. This regional component is removed from observed field (Figure 3). The residual field is modelled constrained with available information. The trap thickness along the profile which varies between 200 and 400 m, is adopted from the MT results. The resulting model is shown in Figure 4.

The second profile A–A′ passes through the maximum observed anomalies (H_1, H_2 and H_3 and L_1, L_2 and L_5) in this area. The observed Bouguer anomaly is likewise separated into regional and residual components and modelled using similar approach (Figure 5).

Both the models show a low-density body at a depth of approximately 8–12 km warped up in the epicentral region to a depth of 3–4 km to explain observed low.

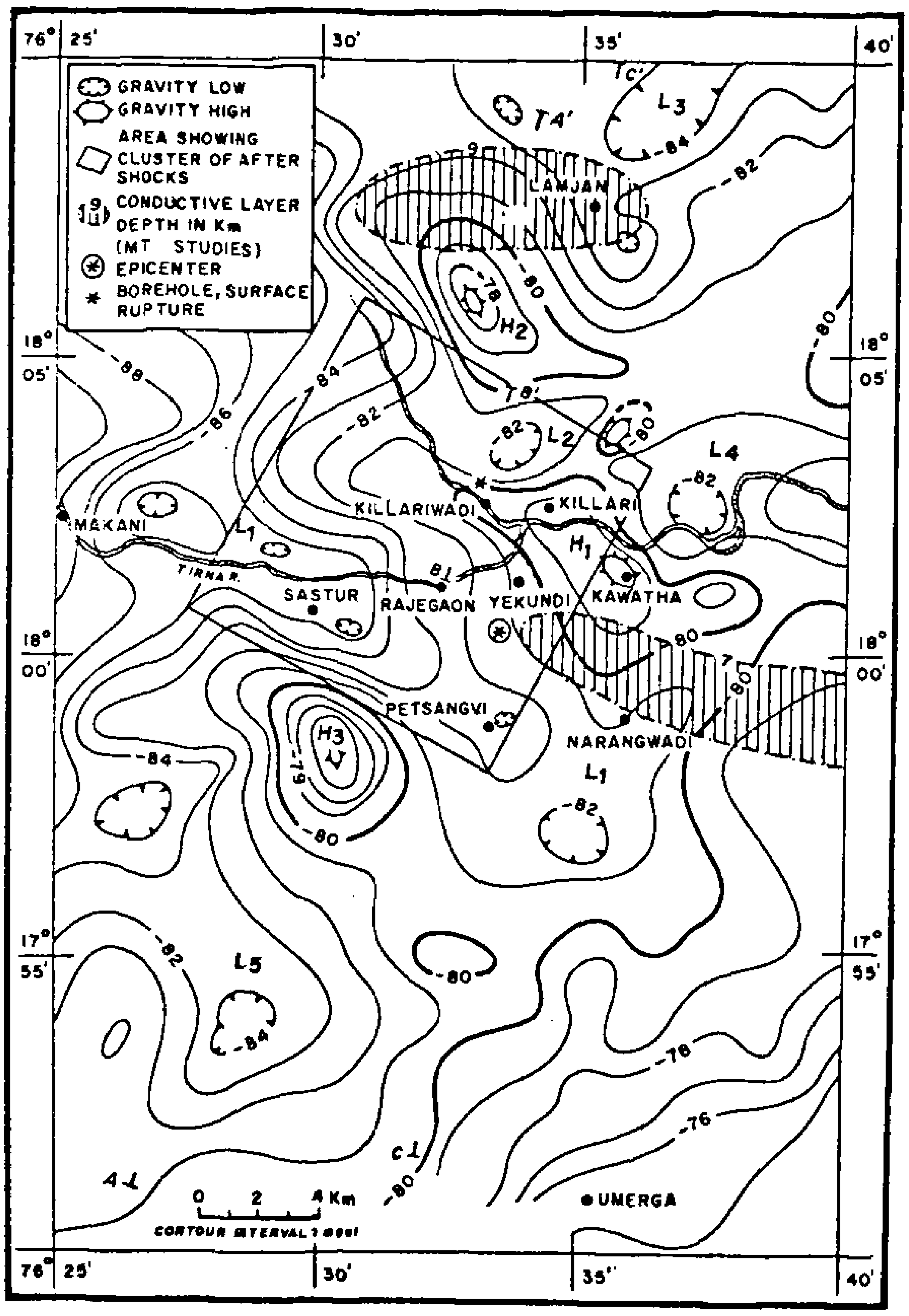

Figure 2. Bouguer anomaly map of the epicentral area showing the central block of aftershocks coinciding with a pair of gravity 'low' and 'high'. The profiles used for modelling are also shown here.

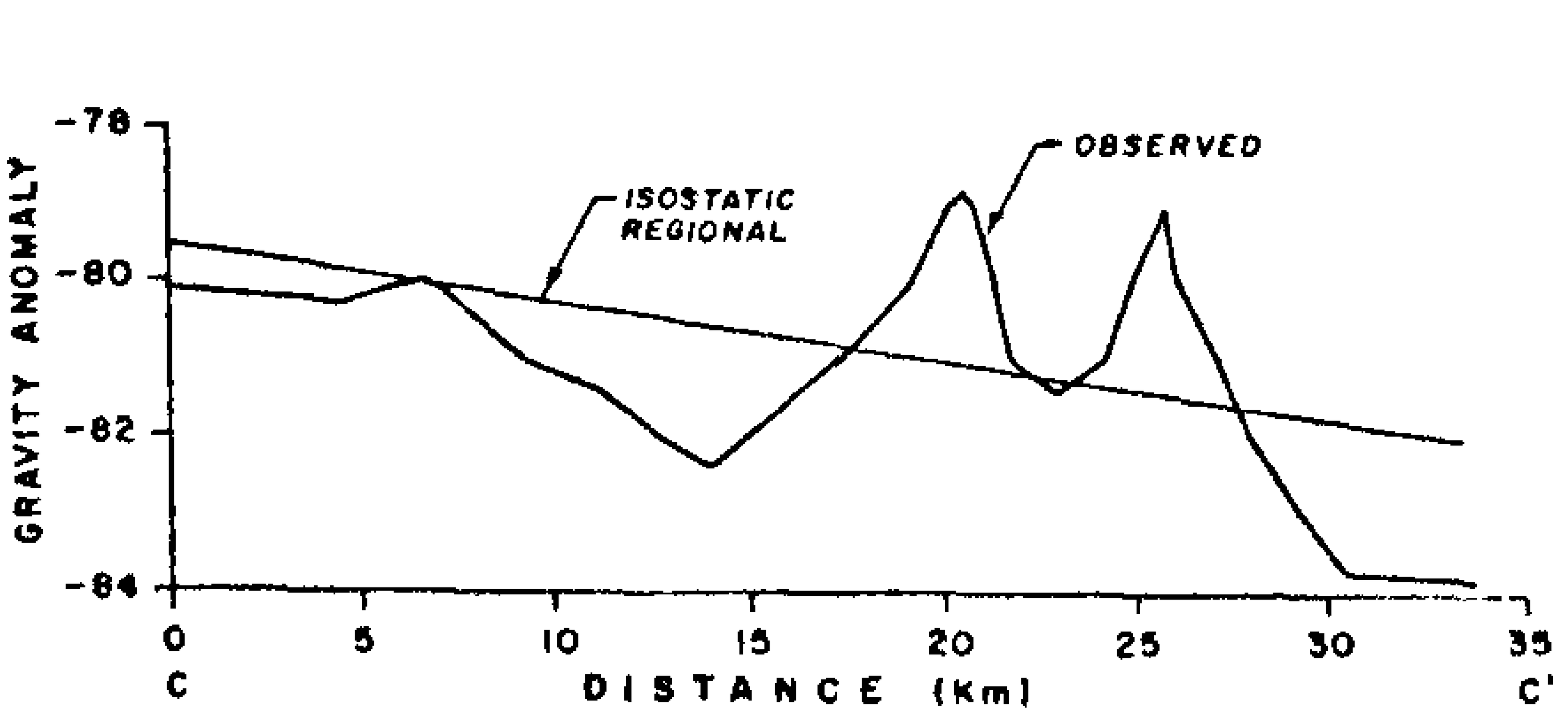

Figure 3. Gravity profile C′–C with observed and isostatic region.

It approximately coincides with the conductive layer reported from MT measurements referred above. However, the observed low can also be explained with proterozoic sediments below trap but it requires sedimentary thickness more than 1 km, which seems to be unlikely, although few tens of meter thick sediment cannot be ruled out. The gravity highs are caused by high-density bodies in the basement.

The continental shields, which form the old parts of the continents, are supposed to have mature tectonics which do not get affected in the present times. However the occurrence of several earthquakes in the shield regions of the world indicates that they were not as

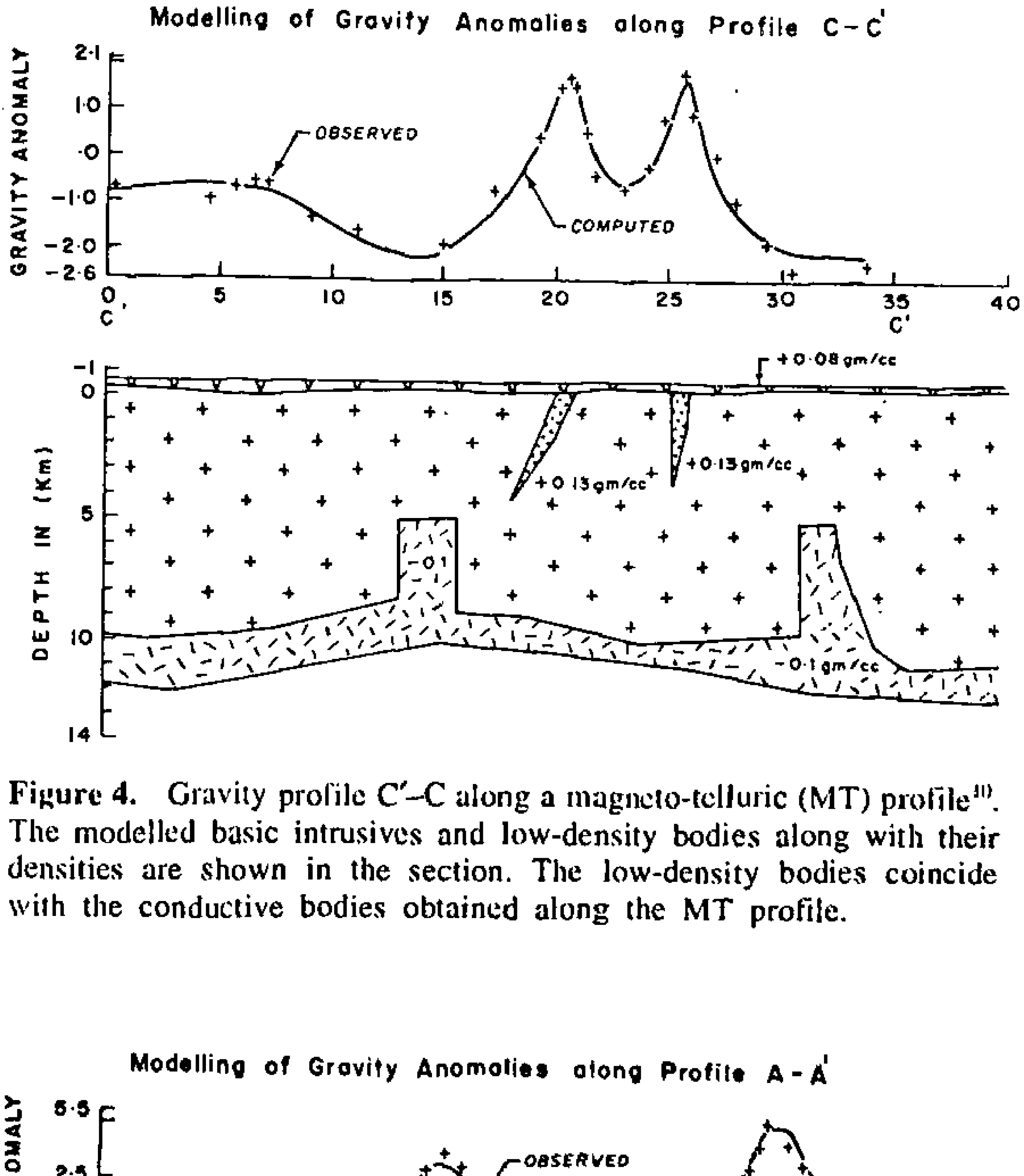

Figure 4. Gravity profile C′–C along a magneto-telluric (MT) profile[10]. The modelled basic intrusives and low-density bodies along with their densities are shown in the section. The low-density bodies coincide with the conductive bodies obtained along the MT profile.

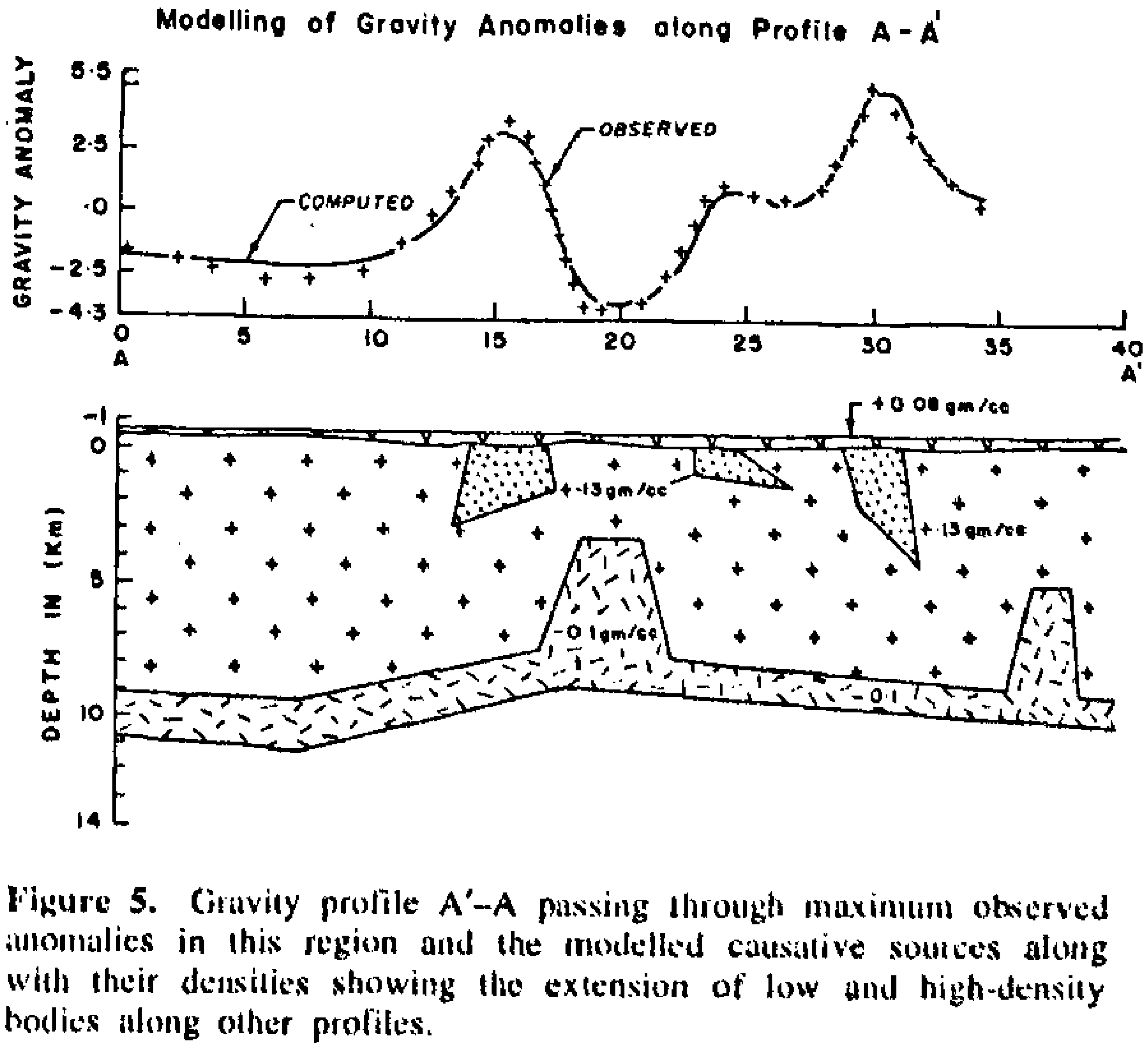

Figure 5. Gravity profile A′–A passing through maximum observed anomalies in this region and the modelled causative sources along with their densities showing the extension of low and high-density bodies along other profiles.

stable as thought of and are prone to seismic activities though to a much lesser extent compared to plate boundaries[17]. Continental shields largely consist of two parts, namely mobile belts and cratons. Mobile belts consisting of rifts, thrusts, etc. have been active in the geological past, and are therefore more prone to seismic activities compared to the cratons which show very little tectonic activity during geological past. However, it has been found that in several cases intraplate earthquakes occur on secondary faults instead of first order faults like thrust and rifts[18]. Association of intraplate earthquakes with gradient of gravity anomaly and intrusions as in the present case has also been reported by McGinnis and Ervin[19] which may be caused by inhomogeneities in rigidity[20]. McKeon[21] has suggested that local high stress concentration could occur within the intrusions and at their contacts with host rock.

The Bouguer anomaly map of the epicentral area of Latur earthquake has delineated several low-amplitude small wavelength anomalies of shallow origin. Their modelling along two profiles has delineated some high- and low-density bodies in the basement at different depths. The low-density bodies which almost coincide with conductive body, delineated from MT measurements may be fluid-filled fractured zones. The low-velocity layer is also reported in this area at almost similar depth[2]. The high-density bodies may represent lithological changes due to high-density metasediments and metavolcanics rocks which are exposed south of Deccan volcanic province or basic intrusions in the basement. The presence of rocks of different densities suggests the area to be very heterogeneous, which is also indicated by the presence of high frequency content and longer signal duration of aftershocks[22]. Intrusive bodies can provide path for seepage of meteoric water and can reduce the permeability and porosity and increase the fluid pressure. The lower value of the heat flow[23] suggests fluid to be water which might have percolated through fractures and faults from surface or been trapped there, being released from various geological processes. Fractures filled with high pressure fluid provide an ideal environment for slippage of rocks due to even small accumulation of stresses leading to an earthquake[24,25]. It is, therefore, likely that the interaction of changes in regional stress regime, local stress and fluids in fractured basement in epicentral area may be responsible for these seismic activities.

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ACKNOWLEDGEMENTS. We thank Dr Harsh K. Gupta for permission to publish this work. V.M.T. thanks CSIR, New Delhi for providing a research fellowship.

Received 8 July 1997; revised accepted 18 December 1997

Tectonic reorganization in the Indian Ocean: Evidences from seafloor crenulations

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Multibeam bathymetric data from seafloor area of 24,568 km^2 constrained between magnetic anomaly 18 and anomaly 25 in the Central Indian Ocean Basin (CIOB) reveal presence of three types of seafloor lineaments. Deformation of seafloor across these lineaments, oriented in N–S, NW–SE and E–W directions, vary in time and space. A sharp change in nature and orientation of these seafloor lineaments, as well as of magnetic anomalies, occurs along 73°E long., which appears to act as contact between older crust