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2024 Mulugu Earthquake: Reactivation of a deep-seated crustal fault in Godavari Graben (India)

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ABSTRACT

Indian subcontinent has been experiencing intraplate seismicity since historical times having witnessed a number of damaging earthquakes. Recently, on December 4, 2024, Godavari graben was rocked by a moderate earthquake (M=5.0) close to Mulugu town in Telangana state of India. It has a focal depth of around 10 km. Earlier too, this graben has experienced a number of moderate-magnitude destructive earthquakes. We have analyzed high-resolution satellite gravity data over this region in order to identify the active faults and genesis of this intraplate earthquake. The residual gravity anomaly, deduced using Finite Element Method, brought-out a clear expression over different geologic and tectonic features. Eastern flank of Godavari graben is seen to be characterized by extremely high-gradient gravity anomalies corresponding to a deep-seated crustal-level fault, over which the hypocenter of the Mulugu earthquake lies. Similarly, western flank is also associated with high gravity gradients, corresponding to a fault structure which also reaches to mid-crustal depth. These seismogenic faults are getting reactivated due to neo-tectonic activities caused possibly by underlying thermal anomaly. It appears that all the major intra-plate earthquakes of Indian shield have occurred along the prominent rift structures, which are associated with high heat flow and thin lithosphere, and have undergone quaternary uplifting and crust-mantle thermal interaction.

Key Words: Intraplate seismicity, Deep-seated crustal fault, Godavari graben, Mulugu earthquake; Gravity field; FEM (Finite Element Method); Heat flow.

INTRODUCTION

Some of the Stable Continental Regions (SCR) have been experiencing moderate to large intraplate seismic activity since historical times. Indian subcontinent is one of the finest examples. It has a dynamic past of active rifting, and has undergone multiple plume interaction and continuous uplifting. During the last 50 years, it has witnessed more than 20 events of magnitude five and above, many of which have been destructive and led to the loss of human life and property. This includes, 1819 Kachchh (M=7.7), 1927 Son-valley (M=6.4), 1967 Koyna (M=6.3), 1969 Bhadrachalam (M=5.7), 1970 Broach (M=5.4), 1993 Killari (M=6.2), 1997 Jabalpur (M=5.8) and 2001 Bhuj (M=7.7) earthquake (Gupta et al. 2001; Pandey, 2020; Vasanthi, 2022). In general, intraplate earthquakes are caused by sudden movement along pre-existing weak zones or faults in response to the perturbation of the local stress regime due to plate boundary forces, surface and sub-surface loading, localized strength weakening of the crustal rocks as well as reservoir loading (Kuang et al., 1989; Gupta, 1992; Mandal, 1999; Ramalingeswara Rao, 2000). Despite several extensive geoscientific studies (Mandal et al., 1997; Singh et al. 1999; Rajendran et al., 2008; Kayal, 2008; Mandal and Pandey, 2011; Vasanthi and Sathish Kumar 2016), the genesis of these intraplate earthquakes is yet to be clearly understood.

Usually, major intraplate earthquakes, are known to have intimate relationships with rift valleys, like New Madrid (USA), Baikal (Siberia), East African region, Shanxi rift zone in China and Koyna, Jabalpur, Bhuj and Broach in India to name a few (Krishnabrahmam and Negi, 1973; Liu and Zoback, 1997; Mandal and Pandey, 2010; Catchings et al., 2015; Mukherjee et al., 2017; Oliva et al., 2019; Xu et al., 2020). The rift-valleys are often characterised by elongated narrow extensional features with a central depression and shoulder uplifts, which are commonly bordered by normal faults. Apart from this, the continental rifts are also typically associated with magmatic activity (particularly at the early stages of rifting), alkali basalts, bimodal volcanism, crustal thinning, magmatic underplating across the Moho and relatively high heat flow (McKenzie and Bickle 1988; Dixit et al., 2010; Pandey, 2020). In the present study, high-resolution satellite gravity data over Godavari graben has been analyzed to understand the genesis of Mulugu earthquake, which occurred recently in this graben. It has a focal depth of 10 km and epicenter, 18.45° N and 80.33° E.

GEOLOGY AND TECTONIC FRAMEWORK

Godavari graben is a NNW-SSE trending intra-cratonic rift basin, flanked by Bhopalpatnam high-grade granulitic belt in the east, and Karimnagar granulites to the west (Figure 1). The graben is roughly 400 km in length, and 50 km in width, and separates the Dharwar and Bastar cratons. This graben having a thick sedimentary succession with several cycles of deposition that began in Late Carboniferous period, was formed after the closure of Proterozoic period. The Gondwana outcrops occur primarily as a linear belt along the axial part, that separate the Proterozoic outcrops. Both Proterozoic and Gondwana formations maintain similar depositional and structural trends (Chaudhuri et al., 2012). These sediments are underlain by Archean crystalline basement. Tectonically, it is known to contain various NW-SE deep-seated fault structures that include, Godavari Valley Fault (GVF) on the eastern flank, and the Kaddam (KF) and Kinnerasani Godavari Faults (KGF) on its west. This graben is bifurcated by Bhadrachalam ridge into two major parts, Pranhita-Godavari basin in the north and Chintalpudi sub-basin in the south. Deccan volcanics are spread over the north-western part, while the south-eastern part is covered by Paleoproterozoic Eastern Ghats Belt (EGB).

REGIONAL GRAVITY FIELD

The satellite-derived gravity data for the entire Godavari graben and the surrounding region is derived from the XGM2019e Model (Zingerle et al., 2020). This is a combined global gravity field model with lesser artifacts that uses the spheroidal harmonics up to degree and order 5399, corresponding to a spatial resolution of 2′ (~4 km). It is composed of three data sources, the satellite-only model GOCO06s, the 15′ ground gravity anomaly dataset, and the 1′ min augmentation dataset consisting of gravity anomalies derived from altimetry over the oceans and topography over the continents. The Bouguer gravity map of the present studied region is shown in Figure 2**.** It can be seen from this figure that the Gondwana sediments in the axial part are characterized by high-order gravity low of -100 mGal. Similarly, the peripheral Proterozoic sediments are associated with moderate gravity low of around -60 to -80 mGal. In comparison, the prominent gravity high on the eastern flank corresponds to Bhopalpatnam granulitic belt.

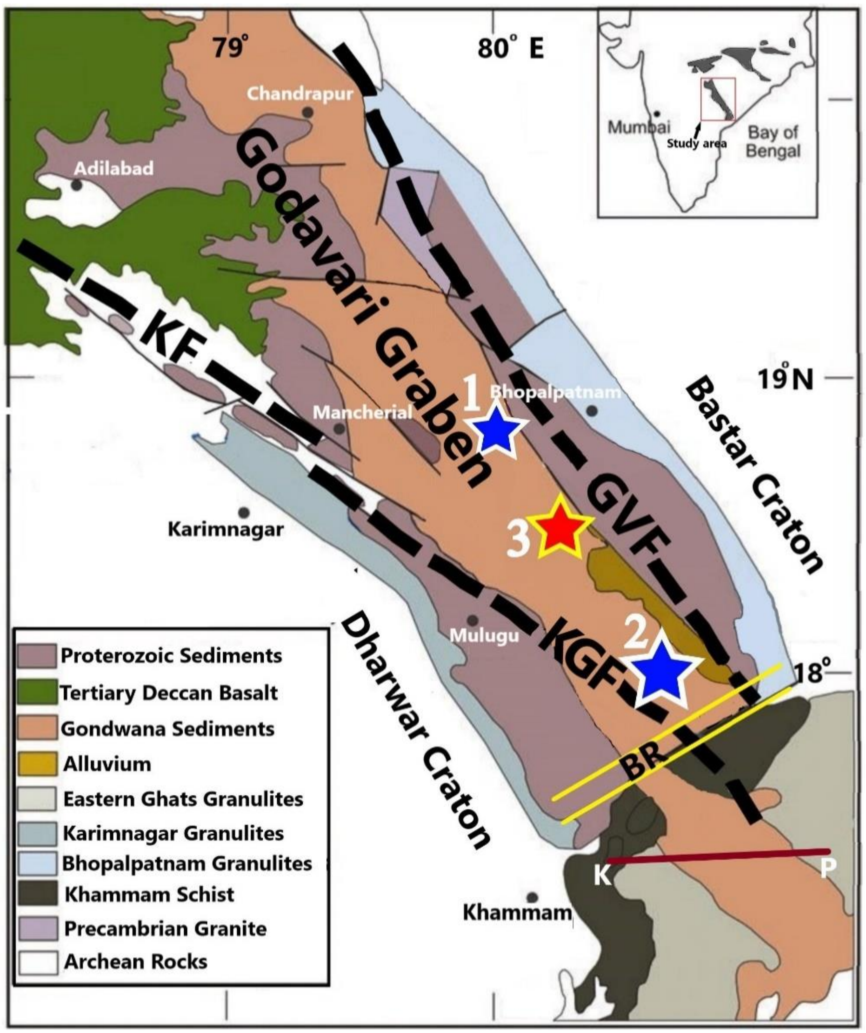

Figure 1. Generalized geotectonic map of the Godavari graben (modified after Chaudhuri et al., 2012). Location of the present study area is marked by red box in the Inset map. Location of DSS profile along Kallur-Polavaram (K-P) that cuts across the basin is shown by maroon solid line. KF: Kaddam fault, KGF: Kinnerasani-Godavari fault, GVF: Godavari valley fault, BR: Bhadrachalam ridge. Epicenters of 1872 Sironcha (M=5.0), 1969 Bhadrachalam (M=5.7) and 2024 Mulugu (M=5.0) earthquakes which occurred in this graben, are also shown and numbered as 1, 2 and 3 respectively.

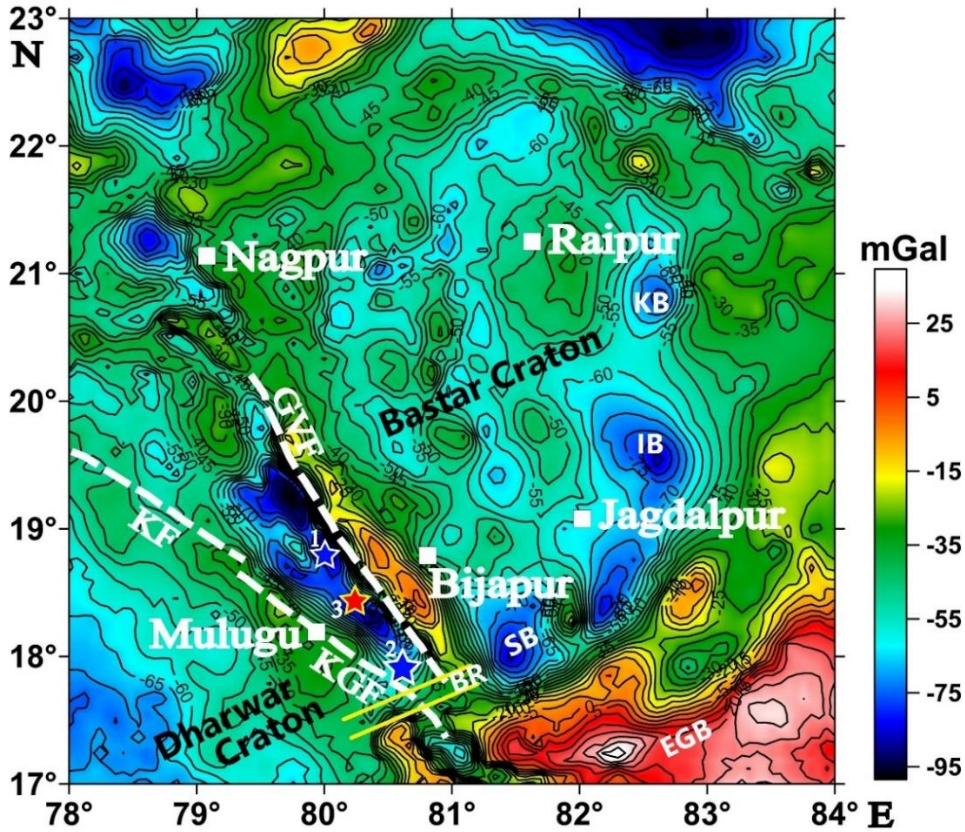

Figure 2. Bouguer gravity anomaly map of the Godavari graben and adjacent region, as prepared using the recent and advanced Model: XGM2019e_2159 (Zingerle et al., 2020). KF: Kaddam fault, KGF: Kinnerasani-Godavari fault, GVF: Godavari valley fault, BR: Bhadrachalam ridge, EGB: Eastern Ghats Belt, KB: Khariar sub-basin, IB: Indravati sub-basin, SB: Sabari sub-basin. Epicenters of 1872 Sironcha, 1969 Bhadrachalam and 2024 Mulugu earthquakes are shown and numbered as 1, 2 and 3 respectively.

Similarly, Eastern Ghats Belt is well reflected by conspicuous E-W and NE-SW gravity high trends. In the southeastern part of Bastar craton, the major sub-basins, like Khariar, Indravati and Sabari, are in good correspondence with low-gravity zones (Figure 2).

As the observed Bouguer gravity data represent the combined response from deeper (regional) as well as shallower (residual) geological structures. However, in practice, the terminology of a regional gravity anomaly varies according to the target of the investigation, and therefore does not necessarily refer to the fields generated at lower crustal depths. If the target is a mineral deposit located at the depths of 100 to 200 m, the basement rocks will form the regional structure. In case of hydrocarbon accumulation, the target sources are a few kilometers deep, and the regional field is generated by the rocks at the base of the sedimentary columns. In the studies involving large-scale structures like subduction zones, large sedimentary basins etc. the regional field originates at lower crustal depths or still greater depths at Moho (Mallick et al., 2012). The regional and residual, therefore, are relative terms. These vary from problem to problem, and from place to place. The separation of these two components is thus crucial in further interpretation of the gravity data. For this purpose, we have used the Finite Element Method (FEM), developed by us, to compute the regional gravity anomaly (Mallick et al., 2012; Vasanthi and Santosh, 2021a, b), which is subsequently subtracted from the observed gravity field to obtain the residual gravity anomaly, as shown in Figure 3. This figure clearly brings out Gondwana and Proterozoic sediments having NW-SE trending high-order gravity low. This low is sandwiched between a conspicuous gravity high (+60 mGal) on the east, which corresponds to Bhopalpatnam granulitic belt, and a relatively moderate gravity high zone (+35 mGal) on the west that is associated with the Karimnagar granulites. It is interesting to observe a bifurcation in this NW-SE trending gravity low anomaly at around 81° E, that may have been caused due to Bhadrachalam ridge dividing Pranahita-Godavari basin in the north, and Chintalpudi sub-basin on the south. In correspondence with Bouguer anomaly, residual gravity anomalies also bring out different gravity low zones in the Bastar craton, corresponding to various sub-basins, like Khariar, Indravati and Sabari. The SE part of the study area is associated with a significant gravity high anomaly zone, which can be correlated with the Eastern Ghats Belt rocks.

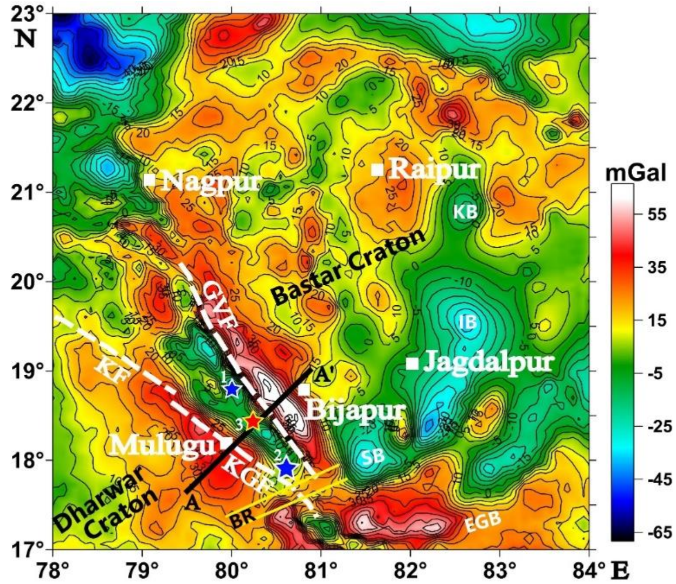

Figure 3. FEM deduced residual gravity anomaly map of Godavari graben and the adjacent region. KF: Kaddam fault, KGF: Kinnerasani-Godavari fault, GVF: Godavari valley fault, BR: Bhadrachalam ridge, EGB: Eastern Ghats Belt, KB: Khariar sub-basin, IB: Indravati sub-basin, SB: Sabari sub-basin. Epicenters of 1872 Sironcha, 1969 Bhadrachalam and 2024 Mulugu earthquakes are shown and numbered as 1, 2 and 3 respectively. Location of the profile, AA', is also shown, along which 2.5D modeling is carried out.

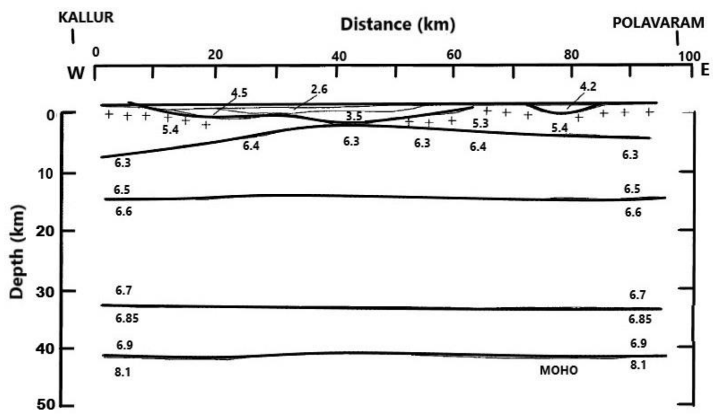

Figure 4. Velocity model along Kallur-Polavaram DSS profile. P-wave velocities are in km/s. ++ denotes crystalline basement (modified after Kaila et al., 1990).

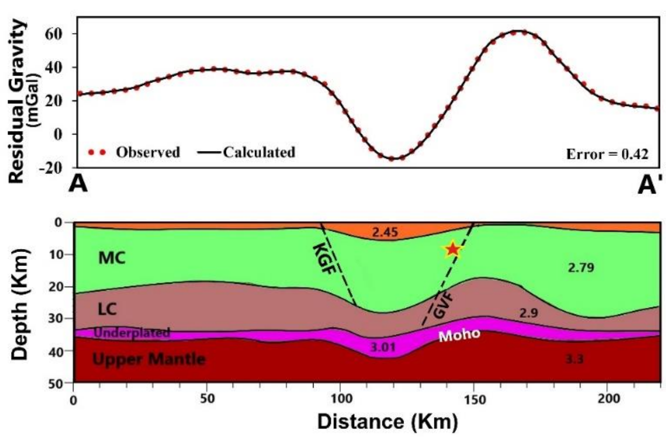

Figure 5. Density model along Profile AA' using residual gravity field. 2024 Mulugu earthquake is shown by red star. KGF: Kinnerasani-Godavari fault, GVF: Godavari valley fault. The numbers in the depth section refer to density in g/cm^3. MC – Mid crust and LC – Lower crust.

2.5D GRAVITY MODELING

In order to understand the crustal architecture of any region, it is essential to image the density variations up to Moho depths (Lachenbruch and Morgan, 1990). As the precise interpretation of gravity anomalies is non-unique, and often depends on direct inputs like the nature of the underlying rocks and their in-situ densities, we have used the available geophysical constraints in this region for different crustal layers in terms of their thicknesses and densities based on DSS profile along Kallur-Polavaram (Kaila et al., 1990) and studies of Pandey and Rao (2006) and Kindangi and Subramanyam (2025) in order to model the NE-SW profile AA' (location shown in Fig. 3), which cuts across the graben structure.

2-D velocity model and crustal configuration along Kallur-Polavaram deep seismic sounding (DSS) profile (Kaila et al., 1990), is shown in (Figure 4). It can be seen from this figure that all the earthquakes that occurred in this graben (Figure 1), fall in the mafic middle crust (Vp: 6.3-6.4 km/s) which has upwarped to an extremely shallow depth below the graben axis. It appears that it is a common feature of almost all the recent damaging earthquakes in India. Further, the second lower crustal high velocity layer (6.85-6.9 km/s) (which is underlain by first lower crustal layer having velocity 6.6-6.7 km/s), may be magmatically infected, similar to underplated magmatic layer that is found in almost all young grabens).

For the modelling purpose, we use the GM-SYS Profile Modeling Software, in which the number of iterations with less RMS error provides the best-fit model. Initially, the layers and their *insitu* densities are fixed following initial constraints. In further iterations, the densities and layer thicknesses are changed in such a way that the calculated anomaly matches well with the observed gravity field. The best fit between the observed and calculated gravity fields is obtained by minimizing the difference in a least-square sense.-The resultant best-fit density model (with an error of 0.42) along the profile AA*'* is shown in Figure 5. The top layer, corresponding to sediments, is assigned a density 2.45 g/cm^3. This layer is directly followed by mid-crustal layer (2.79 g/cm^3) which is further underlain by a relatively high density lower-crustal layer (2.9 g/cm^3). This layer is underplated by a thick magmatic layer above the Moho (Pandey and Rao, 2006) having density 3.01 g/cm^3. Lithospheric mantle is assigned a density of 3.3 g/cm^3. Moho along this profile varies from 41 km in the central part corresponding the graben structure, to 37 km on its either sides. A high gravity gradient on the eastern flank categorically indicates presence of a deep-seated crustal fault that possibly reaches till Moho. This fault coincides with the Godavari Valley fault. It is important to note that the epicenter of recently occurred Mulugu earthquake falls on this fault. Earlier, it is reported that this fault may have been responsible for the destructive 1969 Bhadrachalam earthquake as well. Location of 1872 Sironcha also falls in the vicinity of this fault, indicating the reactivation of this deep-seated crustal fault time and again due to neo-tectonic activities. Similarly, the mid-crustal level delineated fault on the western flank (KGF) (Figure 5), is also apparently active, as indicated by Sangode et al. (2013).

DISCUSSION AND CONCLUSIONS

Entire Indian peninsular shield is tectonically active majorly due to its ongoing collision with the Eurasian Plate, that causes frequent earthquakes, particularly in regions like the Indo-Gangetic Plain and the northeastern states. Additionally, India is also affected by intraplate seismicity, especially in areas like the Narmada-Son lineament and the Kutch rift, where tectonic forces are creating weak zones in the crust. Intraplate seismicity is often associated with intra-plate stresses, which are typically the result of rifting, or the process where the Earth's lithosphere is stretched and pulled apart. This stretching of the lithosphere can lead to faulting and the release of accumulated stress in the form of earthquakes. Such seismic events in the interior region of the plate are although less frequent, but can cause significant damage, for example, 1819 Kachchh, 1927 Son-valley, 1967 Koyna, 1969 Bhadrachalam, 1970 Broach, 1993 Killari, 1997 Jabalpur and 2001 Bhuj (Gupta et al., 2001; Vasanthi, 2022).

Recently on December 4, 2024, an earthquake of magnitude 5.0 had occurred, close to Mulugu in the Telangana state, which is located in the Godavari graben. It has a focal depth of around 10 km. Earlier too, this graben has experienced a number of moderate-magnitude destructive earthquakes, like 1969 Bhadrachalam (M=5.7) and 1872 Sironcha (M=5.0). We analyzed high-resolution satellite gravity data over this region in order to identify the active faults and genesis of these intraplate earthquakes. The residual gravity anomaly computed in this study not only brought out the major tectonic units of this region very clearly, but delineated a deep-seated crustal-level fault on the eastern flank of Godavari graben. It is important to note that the epicenter of the Mulugu earthquake falls on this fault. Earlier, it is reported that this fault may have also been responsible for the destructive 1969 Bhadrachalam earthquake (focal depth ~11 km) as well. Further, the location of 1872 Sironcha also falls in the vicinity of this fault, indicating the reactivation of this deep-seated crustal fault time and again due to neo-tectonic activities. Earlier studies too have confirmed the neo-tectonism by identifying siesmites, a sedimentary bed deformed by seismic shakings developed in the Quaternary sediments of this region (Sangode et al., 2013).

It is well known that the small to large magnitude deep crustal earthquakes keep on occurring in many Indian rift zones, like Narmada-Son and Kachchh rift regions. In view of the occurrence of a deep crustal fault on its eastern flank of

Godavari graben that reaches Moho and where all the three earthquakes apparently fall (Fig. 3), it is likely that in future, this graben may experience lower crustal earthquakes as well. In Figure 6, we have shown the epicentral locations of the major intraplate destructive earthquakes (M>5, shown by blue stars) occurring in Peninsular India (Ramalingeswara Rao, 2000), along with the topography, heat flow values (red solid circles) (Gupta and Rao, 1970; Rao and Rao, 1983; Sunder et al., 1990; Pandey and Rao, 2006; Pandey, 2020) and the major rift valleys. It can be seen from this figure that almost all the major earthquakes fall on the rift axes. Major intraplate earthquakes, do have intimate relationships with rift valleys (Vasanthi, 2022), as mentioned before. Besides, most continental rifts are characterized by thick magmatic underplating (Edel et al., 1975; Maguire et al., 1994; Dixit et al., 2010). Our 2.5D density model across Godavari graben also delineated around 5 km thick underplated layer beneath the graben. Similarly, mafic crustal exhumation, substantial removal of the crystalline upper crust and thin lithosphere are also common in such areas (Pandey, 2020).

It is also felt that the mantle metasomatism could be one of the plausible reasons for the occurrence of intraplate earthquakes. In this process, a fluid-aided mass transfer occurs in the uppermost mantle and overlying lower crust, due to the hydrothermal fluids and halogens generated by sub-crustal erosion, magmatic underplating and delamination (Vasanthi and Sathish Kumar, 2016; Pandey et al., 2016; Liu et al., 2020; Vasanthi, 2022). This causes widespread chemical alteration, partial replacement and further additions of elements under high stress and strain conditions. Such a zone is likely to enhance stress concentration in the upper crust, which in turn results in a mechanical failure resulting in to the initiation of the earthquakes. There are now reports that emphasize the role of entrapped CO_2 fluids emanated from the mantle during magmatic infusion, in triggering the earthquakes (Miller et al., 2004; Mandal and Pandey, 2010). Several studies in different seismic prone areas, like, Koyna (Vasanthi and Sathish Kumar, 2016), Killari (Tripathi et al., 2012a, b), Bhuj (Karmalkar and Rege, 2002; Sen et al., 2009), the Son-Narmada rift zone (Desai et al., 2004) and India's western margin (Desai et al., 2004), support pervasive mantle metasomatic activity in these regions. In view of the substantial mafic crustal exhumation, magmatic underplating and Deccan volcanism, it would appear that the Mulugu earthquake may not be any different.

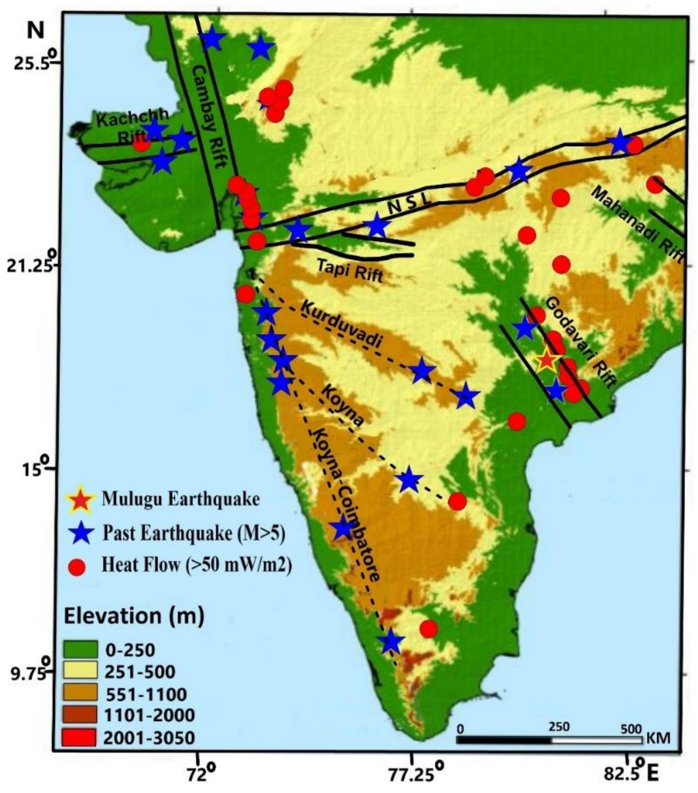

Figure 6. Relationship of intra-plate earthquakes (M>5) (Ramalingeswara Rao, 2000), which occurred in Indian Peninsula since historical times, with the topography (Radhakrishna et al., 2019), major rift valleys and measured heat flow (red solid circles ; >50 mW/m^2) (Gupta and Rao, 1970; Rao and Rao, 1983; Sunder et al., 1990; Pandey and Rao, 2006; Pandey, 2020). Kurduvadi, Koyna and Koyna-Coimbatore rift axes are shown by black dashed lines.

Further, it can also be observed from the (Figure 6) that the majority of the earthquakes, often occur in the continental rift zones where the heat flow values are higher. In the Godavari graben, measured surface heat flow varies from 46 to 104.1 mW/m^2 with a mean of 66.3 ± 19.1 mW/m^2 (Pandey, 2020). Negi et al. (1987) earlier indicated presence of a hotspot below the Godavari graben. In general, the high heat flow within the Earth's crust causes thermal expansion and weakening of the lithosphere. Actually, the areas associated with mantle plumes, young rifted zones, have increased subsurface temperatures in the crust that causes the crust to become more ductile, reducing its ability to withstand tectonic stresses. As a result, the existing faults in the crust may get reactivated allowing for the release of accumulated stress in the form of earthquakes (Molnar, 2020). It is observed that high heat flow plays a significant role in triggering intraplate seismicity by facilitating fault movements within the interior of tectonic plates. Higher heat flow in and around this graben is supported by thermal manifestations in the form of thermal springs. Thus, it is felt that the intraplate seismicity is related to the reactivation of faults, mantle metasomatism, Quaternary uplift, crust-mantle thermal interaction, high heat flow, lower-crustal magma underplating, thin lithosphere and regional geodynamics associated with these rift structures.

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Data Availability: The satellite gravity data is available in http:// icgem.gfz-potsdam.de/calcgrid (Zingerle et al., 2020).

Compliance with ethical standards: The author does not have any competing interest and adhere to copyright norms.

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