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Fluids below the hypocentral region of Latur earthquake, India: Geophysical indicators

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Abstract. A set of geophysical measurements and observations was undertaken to investigate the nature of the crust beneath the epicentral region of the deadly Mw 6.1 Latur earthquake of September 30, 1993. With an estimated focal depth of 2.6 km and the associated well defined but subtle surface ruptures, it is a rare stable continental region (SCR) earthquake with surface rupture. The focal depth of 69 out of 73 well located aftershocks is less than 5.5 km. Broad band (10^3 - 10^{-3} Hz) magnetotelluric (MT) soundings reveal the presence of an anomalously high conductivity zone at a shallow depth range of 6-10 km. Consistent with this result is the observation of a Pc phase, lagging behind the Pg phase by about 0.6 to 0.8 sec in the aftershock seismograms indicating a low velocity layer (LVL) at 7 to 10 km depth. A Bouguer gravity low of 5 m.gal, nearly coincident with this feature, is also observed. Above evidences indicate that the focal zone of the Latur earthquake sequence is limited to depths of about 5 to 6 km in the upper crust by an underlying low-velocity and high conductivity layer. We interpret this high conductive, low velocity layer as a fluid filled fractured rock matrix. The inferred stress regime, including due to uplift of the Deccan Plateau, triggered by erosion of basalt cover is likely to be confined mostly in the upper part of the crust. Existence of a low velocity, high conductivity fluid filled layer will enhance stress concentration in the uppermost brittle part of the crust causing mechanical failure.

Introduction

The Mw 6.1 Latur earthquake of September 29, 1993 (early morning of September 30, 1993 according to the Indian Standard Time) is a rare stable continental region (SCR) earthquake. It claimed an estimated 11,000 human lives becoming globally the deadliest SCR earthquake (Gupta, 1993). This earthquake also generated distinct surface ruptures: An addition to a select group of ten SCR earthquakes causing surface faulting (Johnston, 1994a). According to Johnston (1994a and 1994b) and Johnston and Kanter (1990) SCR earthquakes account for only 0.5% of global seismicity and most of these are associated with crust that underwent extension in the recent past and with passive margins. Johnston (1994c) has prepared a list of about 800 stable continental region earthquakes with a magnitude of 4.5 and above. Out of these there are only about 100 earthquakes exceeding magnitude 6. He has divided these earthquakes into two categories - those occurring in the regions of extended crust i.e. the failed rifts and the others associated with the non-extended crust i.e. cratons and platforms. Latur earthquake belongs to the second category. In this category earthquakes exceeding magnitude 6 occur approximately once in 17 years (Johnston, 1994b).

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The Latur area lies on the south eastern margin of a vast basalt covered Deccan Volcanic Province (DVP) of peninsular India (inset in Figure 1), popularly known as the Deccan Traps. A majority of these tholeiitic basalts belonging to the upper Cretaceous age, are known to be mainly fissure type eruptions. They are comprised of several layers, the thickness of each one amounting to a few tens of meters. In basalt covered areas, probing of subtrappean lithology through conventional geophysical methods like seismics, gravity and magnetics is

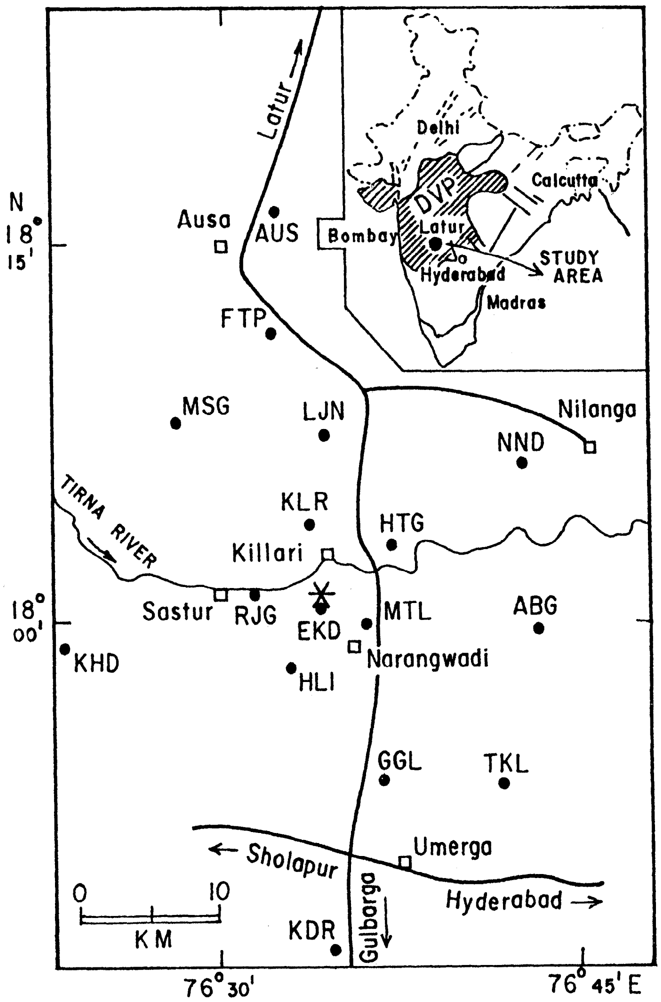

Figure 1. Location map of MT soundings in the Latur earthquake (*) area. Inset shows the location of the study area on the south eastern margin of Deccan Volcanic Province (DVP). Major grabens and thrust zones of the Indian shield are indicated.

beset with several problems. Efforts using a combination of the magnetotellurics (MT) with conventional geophysical methods have been found to be very effective (Prieto et al 1985). Hence, to understand the nature of the crust underneath the basalt covered area of the devastating Latur earthquake, a set of geophysical measurements and observations have been carried out by the National Geophysical Research Institute (NGRI), Hyderabad. In this communication, the results of a magnetotelluric study in the epicentral area, along with the complementary inferences drawn from seismic, gravity and other observations are presented.

Focal Depths

Since no seismic station was operating in the near vicinity of the Latur earthquake epicenter, the closest station being at a distance of about 220 km at NGRI, Hyderabad, there were no accurate estimates of the depth of the main shock immediately available and it was debated to be between 5 and 15 km (Gupta, 1993). In a recent work, Seeber et al (1995) have obtained a moment tensor solution for the Latur main shock and estimated its focal depth to be 2.6 km. Soon after the occurrence of the earthquake a network of seismic stations was set up by the NGRI in collaboration with GeoforschungsZentrum, Potsdam, Germany (Baumbach et al, 1994) to record the aftershocks. These included 3 three-component digital data acquisition systems; 14 analog data acquisition systems and 4 strong motion recording instruments. A majority of the aftershocks occurred within a 10 km radius of the main shock. The operation of digital data acquisition system made it possible to generate transverse and radial component seismograms. This enabled better identification of the S phase and considerably improved estimation of hypocentral parameters. 73 of the aftershocks could be located using high precision data and the focal depth distribution was found to be as follows:

Magnetotelluric Investigations

The Magnetotelluric (MT) study covered an area of approximately 40 km x 40 km in and around the epicentral region (Fig.1, Sarma et al, 1994) with a total of 16 broad band (10^3 Hz - 10^{-3} Hz) MT soundings. Figure 2 presents examples of magnetotelluric sounding curves obtained at two stations, Hulli (HLI) in the epicentral zone and Rohilgad, a station along the Aurangabad (AUR) - Wadgaon (WDG) profile, about 80 km north of the study area. An interesting feature is a distinct signature of a crustal conductor that shows up in the form of a depression in the apparent resistivity in the 1 - 10 sec period range and can be seen in the magnetotelluric sounding curve at Hulli.

Table 1. Focal Depths of the Aftershocks, Latur Earthquake

Focal depths (Km)	No. of Aftershocks	Focal depths (Km)	No. of Aftershocks
0.5 - 1.4	7	4.5 - 5.4	6
1.5 - 2.4	28	5.5 - 6.4	2
2.5 - 3.4	20	6.5 - 7.4	1
3.5 - 4.4	8	7.5 - 8.4	1

The above table shows that the focal depths of most of these shocks were confined within 5.4 km or less. Only 4 aftershocks were deeper than 5.5 km.

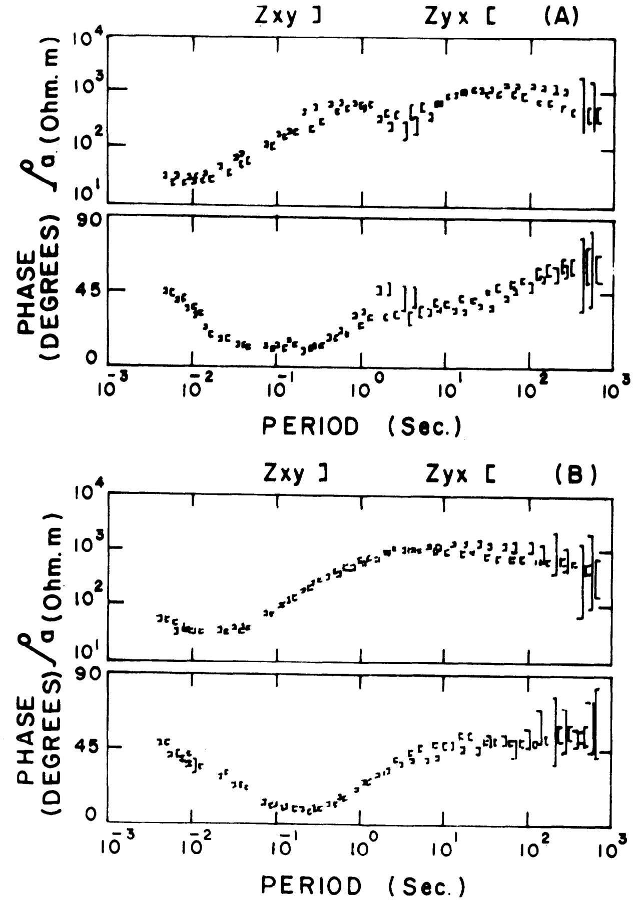

Figure 2. Magnetotelluric sounding curves: (A) At Hulli (HLI) in Figure 1, a station in the epicentral region showing a depression in the apparent resistivity in 1 to 10 sec range indicative of a conductor and (B) at Rohilgad, a station outside the epicentral region which does not show any conductor. Both stations are located in the basalt covered area of the DVP.

A qualitative assessment of subsurface geoelectric section of the Latur area is deduced through the ρ* - Z* representation of Schmucker (1987) for the MT data (Figure 3a) along a 50 km along N-S profile from Ausa (AUS) in the north to Khandher (KDR) in the south (Figure 1) passing through the epicentral zone. The presence of a shallow upper crustal conductor located underneath the epicentral region is clearly brought out. For comparison a similar ρ* - Z* pseudo-section obtained along the Aurangabad-Wadgaon profile, located far away from the epicentral region, is also shown (Figure 3b). This profile also lies in the same DVP and is characterized by similar surface geological conditions but does not show any shallow crustal conductor, thus pointing out to a distinct difference in the character of subsurface section between the Latur earthquake region and the one away from the earthquake region.

A quantitative evaluation of the subsurface geoelectric section of the Latur region has been carried out by modeling of MT sounding data using the 1D inversion scheme of Jupp and Vozoff (1975). The results show that the top basalt cover has a resistivity of about 40-60 Ohm.m. The thickness of basalt cover ranges from 300 m to 400 m indicating that the variation of trap thickness across the epicentral area is not significant. The results also point out that basalts in the epicentral zone lie

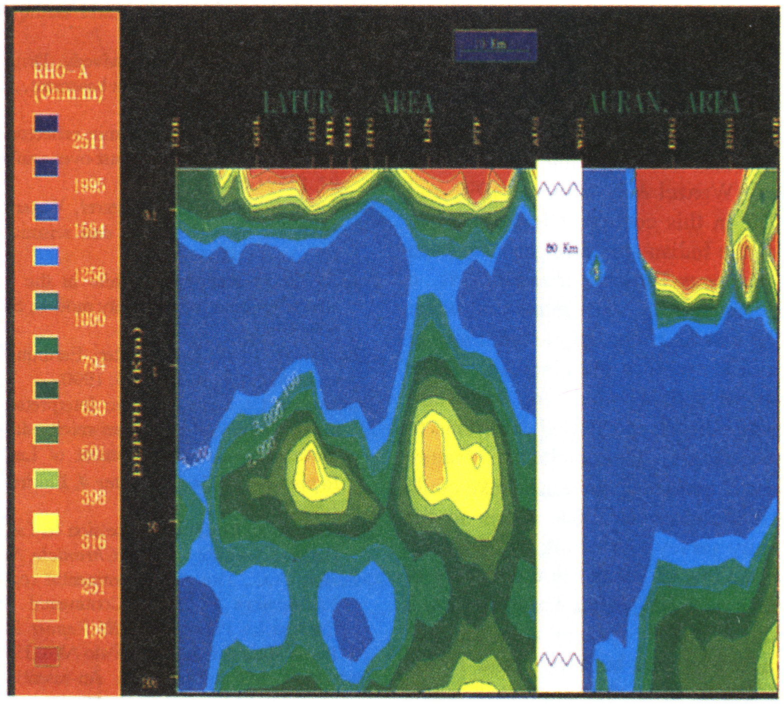

Figure 3. Magnetotelluric transformed resistivity versus depth sections (ρ^*-Z^*) bringing out (A) the presence of conductors at shallow depths in the hypocentral region of the Latur earthquake along a north-south profile in the Latur area from AUS to KDR passing through the epicentre and (B) absence of a conductor along a profile from Aurangabad to Wadgaon, outside the epicentral region but within DVP.

directly over the high resistive granite basement. The recent drilling results confirmed the thickness of the lava flow sequence near Killari, as inferred from MT soundings (Gupta and Dwivedy, 1996). The high resistive (3-5 x 10^{3} Ohm.m) upper crust underlying the basalt cover contains a distinct conductive feature (15-25 Ohm.m). The 1D modeling results of the invariant impedance of the data show that the depth to the conductor ranges from about 6-10 km with lower values underneath the epicentre near Killari (Sarma et al, 1994).

The Pc phase

Another feature of interest is the observation of a phase inferred as a reflection from the base of a velocity inversion (denoted Pc) that is consistently present in the Latur earthquake aftershocks seismograms recorded at epicentral distances of 30-60 km. Figure 4 depicts some seismograms of aftershocks at 30 to 48 km distance. The Pc phase lags behind the Pg phase by 0.6 to 0.8 sec indicating the presence of an LVL at a 7 to 10 km depth. Mueller and Landisman (1966) had originally discussed such phase 'lags' as an evidence of LVL in the upper crust. Wenzel and Sandmeir (1992) interpreted existence of a Pc phase in the seismic refraction profile records obtained for the Black Forest region of South-West Germany as an evidence for the presence of fluids in the crust. Krishna et al (1989) also reported existence of the Pc phase (they call it P2P) in the records of deep seismic profiling carried out in the western part of DVP near the Koyna region in western India, from which they have inferred an LVL between 7 and 10 km.

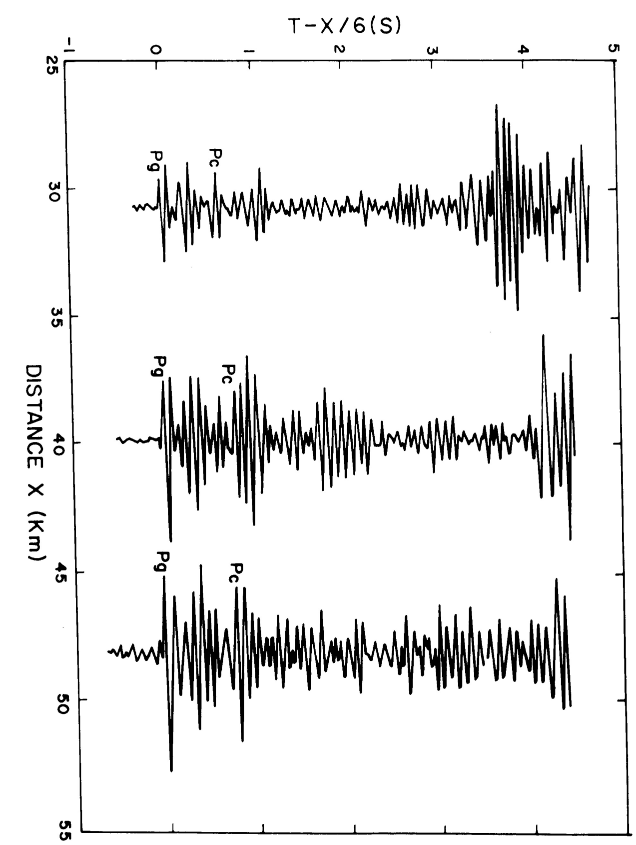

Figure 4. Seismograms of a few aftershocks of the Latur earthquake recorded at the digital seismograph station NGD, consistently revealing the Pc phase arriving 0.6 - 0.8 sec after the Pg phase.

Discussion and conclusion

A variety of causes could result in high electrical conductivity in the crust, e.g. fluids, carbon/graphite, partial melt, high temperature etc. (Jones, 1987 and 1992). However Hyndman (1988) and Gough (1992) pointed out that for areas that have been reactivated in the Phanerozoic period, fluids may be a more favourable cause for anomalously high conductivity. Existence of an LVL also supports presence of fluids. For this reason some authors have recommended carrying out electrical and seismic surveys together (Wenzel & Sandmeier, 1992 and Hyndman & Shearer, 1989). In this context it is pertinent to note that the Latur region of the Indian shield might have been mobilized during the Cretaceous-Tertiary transition as a consequence of the Deccan Trap episode. The interstitial water in the crust is presumably released due to dehydration of hydrated minerals like chlorite, zeolites etc (Jodicke, 1992). Other sources like meteoric water that could seep downward into the deeper levels of fractured rock might also contribute to upper crustal fluids. Accordingly, the conductive feature detected below the hypocentral zone of Latur earthquake could be interpreted as a fluid-filled subsurface rock matrix in the upper crust. A detailed gravity survey carried out by Mishra et al, (1994) shows a well defined low of 5 m.gal in the vicinity of epicentral area which strikes a near NW-SE direction and has a width of about 6 to 8 km. This is in line with the MT interpretation of a high conductive zone between 6 and 10 km depth as the presence of fluids in a fractured rock could reasonably cause the observed mass deficiency.

The results of the present MT study, supported by seismics and gravity, provide an evidence for the existence of a shallow fluid-filled zone in the upper crust below the hypocentral region of the Latur earthquake. Similar results have been reported for earthquake zones elsewhere. For example Gajewski et al, (1987) conclude that the LVZ of Urach body lies directly below the focal area where the strongest earthquake occur in Germany.

The inferred stress regime, including due to uplift of the Deccan Plateau, triggered by erosion of basalt cover is likely to be confined in the upper part of the crust. Existence of a low velocity, high conductivity fluid filled layer will enhance stress concentration in the uppermost part of the crust leading to mechanical failure. Unloading of the crust due to erosion and the consequent changes in stress regime was suggested to be a possible cause for Latur earthquake (Johnston 1993, personal communication). Results reported here support this hypothesis.

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