Crustal geoelectric structure and the focal depths of major stable continental region earthquakes in India

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The Indian peninsular shield, in particular the Deccan Volcanic Province, has experienced significant seismicity during the past three decades, with the Koyna (M_w = 6.3), Latur (M_w = 6.2) and Jabalpur (M_w = 6.0) events of moderate magnitude. Focal depths of these stable continental region (SCR) earthquakes vary over a wide range from around 6 to 35 km. Corresponding to the wide range of focal depths reported, the electrical structure as deduced from magnetotelluric studies seems to vary considerably among these regions and suggests existence of different subsurface conditions and operation of different mechanisms. While the Latur and Koyna events occurred in a relatively thick and high resistive upper crust, the Jabalpur earthquake had its focus in a conductive region at Moho levels. It is suggested that electrical characterization of crust through electromagnetic imaging helps in broadly demarcating tectonic domains characterized by differing rheology and heterogeneity.

Keywords: Electrical structure, focal depths, rheology, SCR earthquakes.

A large number of earthquakes have been recorded in the shield regions of the world. This resulted in re-examination of properties of the stable continental crust and also earthquake-generation processes. With a large amount of data from seismic profiling, tomography, gravity and electromagnetic induction over traverses across continental crust, several models including fluid trapping and magmatic underplating were evoked[1,2] to provide ensemble models of crustal properties. These models and mechanisms have contributed to understanding of causal mechanisms for intraplate seismicity.

During the last few decades, there have been three moderate and several minor earthquakes in the Deccan Volcanic Province (DVP) in the Indian shield region. The 10 December 1967 Koyna earthquake in western India, the 29 September 1993 Latur event in south central India, and the 22 May 1997 Jabalpur earthquake in central India constitute the three moderate SCR events with $M_w > 6.0$ that occurred in the Indian peninsular shield over a span of three decades besides the recent 26 January 2001 Bhuj earthquake. Figure 1 shows the location of these three events. In addition, several smaller magnitude events were also recorded in peninsular India.

Interestingly, all the three events have occurred in the DVP, a vast basaltic lava cover occupying large tracts of western part of the Indian peninsula. The most impressive feature of the SCR events is the wide variation of their focal depths. This indicates existence of different rheological, structural and environmental conditions associated with these events. Gangopadhyay and Talwani[3] have provided an excellent account of the association of different kinds of stress concentrators. Though reactivation of pre-existing fault is a well-established model for SCR earthquakes, other mechanisms may also be involved[4,5]. These might arise due to different subsurface conditions related to thermal, structural and physical environment like presence of fluids[6–8], which might lead to anomalous conditions of stress concentration. We analyse here, from the available geological and geophysical knowledge, the nature of subsurface lithology, structure and physical environment, in particular the electrical conductivity images in the vicinity of the three earthquakes and discuss their possible relationship to the variation of focal depths.

The 10 December 1967 (22 h:51 min:24.3 sec GMT) Koyna earthquake is perhaps the first medium size (M_w = 6.3) recorded SCR earthquake of the Indian peninsular shield. Its epicentre (17°39.6′N, 73°55.8′E) is located on the western margin of the DVP where the Deccan trap cover is fairly thick which is estimated to be between 1 and 2 km. The event was inferred to be due to reactivation of a NNE–SSW trending strike slip fault with a left lateral movement, aligned almost parallel to the Koyna river. Since there was no proper network of seismic stations in this region, the source parameters could not be obtained accurately and the focal depth estimates of this event vary between 6 and 32 km[9,10]. The seismic activity subsequent to the 1967 Koyna earthquake continued over a very long time with events occurring in the magnitude range $M < 1$ to $M > 5.0$ and the region is still active. Subsequent establishment of an array of digital seismic stations in the Koyna–Warna area of western India facilitated a more accurate determination of the source parameters of recurrent seismicity in this region. A study of small earthquakes with this array gives focal depths ranging from 1 km to as much as 15 km[11], indicating that the entire depth range up to 15 km is seismogenic. Both deep seismic refraction studies and regional gravity studies conducted in the Koyna region indicate a normal crustal structure typical of shield regions. Seismic refraction results[12] along the Guhaghar–Sangole profile, which traverses across the Koyna fault, indicate Moho depths around 38 km, as also normal crustal velocities, 6–7 km/s (Figure 2). Velocity modelling studies for the Koyna region indicate, however, a low velocity layer at a depth of about 15 km[13]. However, recent tomographic imaging of the region, using the closely spaced array, indicates the presence of a high velocity body of considerable depth beneath the Koyna seismogenic zone[14].

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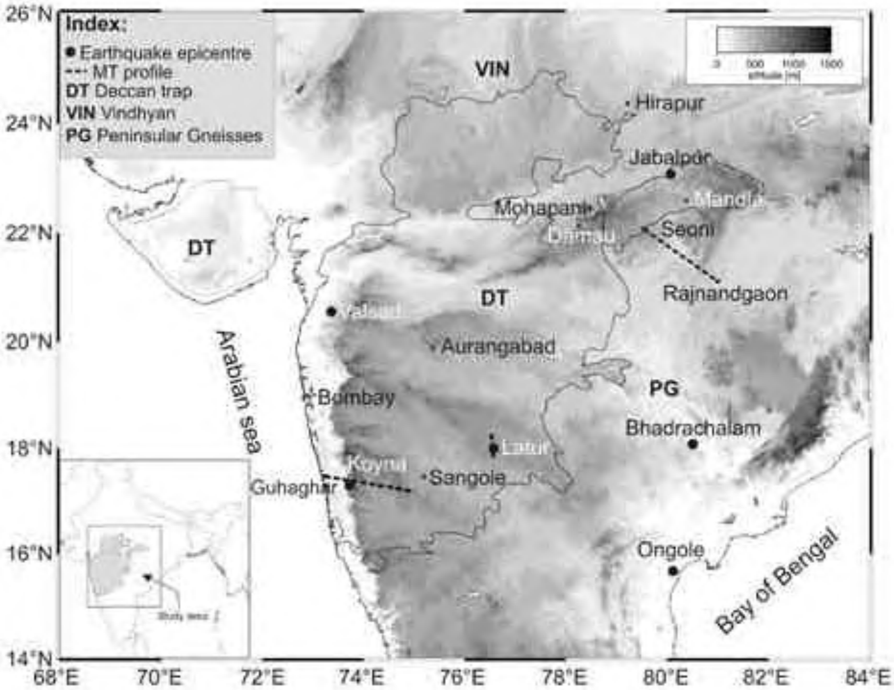

Figure 1. Location of epicentres of major SCR earthquakes in peninsular India along with magnetotelluric profiles. Also shown are the broad geology and the topography of the area.

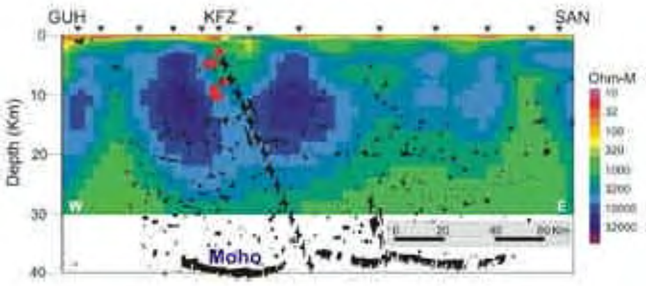

Figure 2. West-east subsurface geo-electric section across Koyna region from Magnetotellurics[16]. Red dots indicate the hypocentres from Koyna seismic network[47]. Projected is the crustal cross section from deep seismic refraction. (GUH = Guhaghar, KFZ = Koyna fault zone, SAN = Sangole).

The regional gravity field does not suggest any significant anomalous crustal structure, except that the gravity field is characterized by a strong negative gradient at the west coast, located further west of the Koyna fault. Krishna Brahmam and Negi[15] interpreted the trends in the gravity map of India to suggest the presence of a rift-like structure. However, studies of the deep structure by seismic tomography and magnetotelluric (MT) imaging of electrical conductivity of the region[16] are not in agreement with such a model.

An MT study was carried out during 1998 field campaign along the 192 km E–W traverse, cutting across the NNE–SSW trending Koyna fault[16]. A total of 16 MT sites were occupied along this traverse and wide band 10^3 Hz–10^{-3} Hz measurements were carried out. Figure 2 shows the 2D geo-electric section obtained along this traverse. The geo-electric section tends to show a high resistive thick upper crust characterized by a block structure with individual blocks assuming different resistivities. The crustal geo-electric structure in the Koyna earthquake epicentral region in general is similar to that of the Latur region[8], except that no significant anomalous conductive feature is observed in the hypocentral region, though there are indications of a shallow vertical and moderately conductive feature coincident with the fault plane (Figure 2). It may also be noted that the hypocentres tend to fall at the boundary of this conductive zone.

The M_w 6.2 Latur earthquake of 29 September 1993 (22 h:25 min UTC) has its epicentre located on the eastern margin of the Deccan trap province in the South Central India (18°N, 76°33′E) (Figure 1). The event is considered to be one of the most devastating SCR events claiming about 11,000 lives[17] and is also one of the very few SCR earthquakes that generated a surface rupture[18]. Its focal depth is about 6.8 km[19]. This earthquake, unlike the Jabalpur event, occurred in a region which does not have any history of crustal extension and is considered a part of the highly stable Indian peninsular shield. The focal depth is relatively shallower compared to other events like the Koyna, Jabalpur, Bhadrachalam and Ongole earthquakes of the Indian shield, though the estimates for the latter events are not well-constrained[20].

MT studies conducted in the epicentral region of the Latur earthquake indicated that the thickness of trap varies from 200 to 400 m and that the trap lies directly over the granite–gneissic basement[8]. These estimates indeed agree closely with the results of deep drilling at Killari[21] that show a column of 338 m thick trap resting directly over hard granite–gneissic basement. The results from the borehole drilled at Killari to intersect the fault plane also show a displacement of 6–7 m in the Deccan trap column across the fault zone. The geothermal data available, though sparse, in this part of the Indian shield show normal geothermal gradients (42 mW/m^2) and this is confirmed by the borehole thermal logging results from Killari carried out subsequent to the occurrence of Latur earthquake[22]. One of the most interesting results that emerged from the MT study in the Latur region is the detection of a well defined upper crustal conductor in the epicentral region of the Latur earthquake (Figure 3). The depth of this conducting zone is estimated to be around 6 to 8 km[8], which is the general extent of the aftershock zone of the Latur earthquake[23]. The upper crustal conductive feature detected is interpreted to be a fluid-enriched fractured rock matrix in the hypocentral region of the Latur earthquake[6].

The regional crustal structure in the Latur earthquake region is thus characterized by (i) flat regional gravity field, (ii) normal crustal velocity, (iii) normal heat flow, (iv) high resistive crust and presence of a well-defined upper crustal electrical conductor at the hypocentral depths. All these observations show that the Latur earthquake region lies in an otherwise highly stable, cold and tectonically undisturbed region of the Indian peninsular shield, with a normal crustal structure and the shallow upper crustal conductor is the only anomalous feature.

The epicentre of the Jabalpur earthquake is located in one of the most important tectonic features of the Indian peninsula, namely the Narmada–Son–Lineament zone (NSL), a region believed to have undergone crustal extension. Several geological and geophysical studies were carried out in the NSL region under the 'CRUMANSONATA'

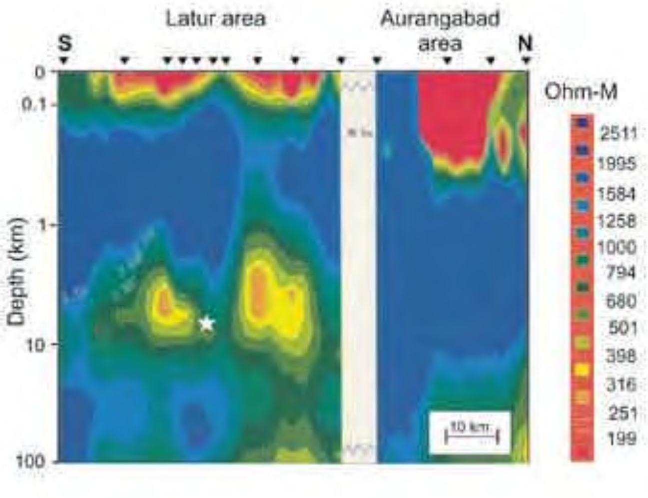

Figure 3. Subsurface geo-electric section in the Latur earthquake area from magnetotellurics[6]. '*' indicates the hypocentral location (6.8 km) of Latur main shock of magnitude 6.3 (source: USGS[19]).

project of the Geological Survey of India, which provided valuable information[24]. The NSL region characterized by a graben and horst structure exposes a wide range of geological formations spanning Proterozoic to Upper Cretaceous. A linear belt of exposures of a wide range of geological formations in this zone has been interpreted to be due to repeated re-activation of the linear Narmada belt. The NSL zone is demarcated by two boundary faults, viz. the Narmada north and Narmada south faults (Figure 4).

Source parameters of the Jabalpur earthquake have been determined, based on a data set obtained from a well-distributed array of seismic stations equipped with state-of-the-art wide band digital data-acquisition systems[25,26]. The earthquake, which occurred on 22 May 1997 at 4 h:2 min:30.8 sec (IST) with its epicentre at 23.08N, 80.06E, located about 20 km south of Jabalpur in central India, has a moment magnitude (M_w) of 6.0. The focal depth is estimated to be 35 km[25]. The reactivation of the deep seated Narmada south fault is inferred to be responsible for the Jabalpur earthquake. A high density mafic intrusive body in the lower crust in the form of a 'rift pillow' was invoked to explain the deep focus earthquake in the Amazon rift basin[27]. Similarly the Narmada–Son region being an ancient/failed rift, the Jabalpur earthquake could be explained in terms of a 'rift pillow' as the cause for stress concentration[28,29].

The Narmada south fault is generally considered to be a very deep fracture extending to Moho depths. The deep nature of the Narmada south fault is indicated by the inferred presence of ultrabasic and alkaline intrusives along the fault[20]. Based on interpretation of gravity 'highs', presence of high-density intrusives are inferred in this zone[30]. The seismic refraction results along the five traverses cutting across the Narmada–Son region including the Hirapur–Mandla profile – which passes through the epicentral region of Jabalpur earthquake – indicate that both Narmada North and South faults are fundamental crustal faults reaching Moho levels[31]. In addition, these faults have also been inferred to be fundamental since they have created volcanism and deposits of Mahakosal group[25]. Recent 2D crustal velocity modelling results[32] using travel time and amplitude data of deep seismic sounding along the Hirapur–Jabalpur–Mandla across the NSL provided seismic velocity structure that requires a high velocity (6.5–6.7 km/s) layer in the upper crust. Thickness of this layer ranges from 6 to 9 km while the depths range from above 6 km in the northern half of the traverse to about 9 km in the region south of Jabalpur. This has been interpreted to be due to emplacement of high velocity/high-density magma in the upper crust through deep-seated fractures.

MT results from this region show (Figure 5) that the crustal section in this zone is characterized by a thin high resistive upper crust (>10,000 Ohm-m) overlying a more conductive (<500 Ohm-m) crustal column, i.e. the conductive crustal column commences from very shallow depths, at places as shallow as 6 to 7 km[33]. MT study in the Jabalpur

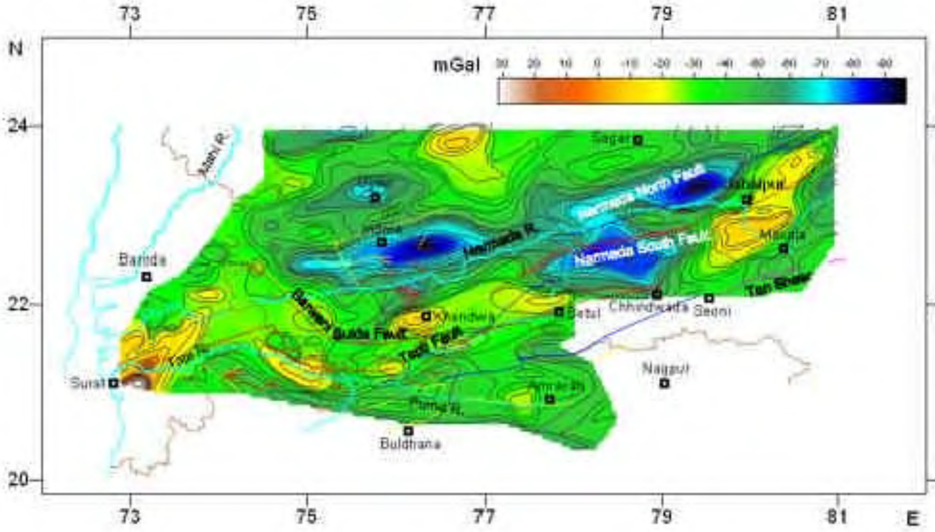

Figure 4. Bouguer gravity map of central India[24], with expression of major faults in the NSL zone.

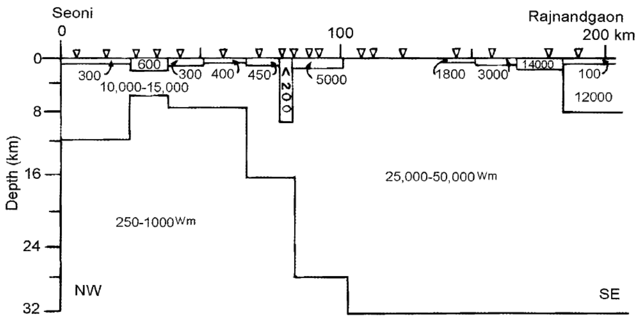

Figure 5. 2D geo-electric section across Narmada-Son Lineament (Narmada south fault) from magnetotellurics[33].

region[34] delineated two crustal conductors (~30 Ohm-m) below the Deccan volcanics, one in the immediate south of Jabalpur and the other about 40 km southeast of Jabalpur. They attributed the high electrical conductivity to fluids in the upper crust. The entire NSL zone is characterized by moderate heat flow and hence should be warmer as compared to the surrounding colder crust.

The geophysical signatures of the crustal structure in the Narmada–Son region in general are thus characterized by (i) gravity 'highs' aligned along the NSL zone, indicating presence of high density materials at deeper levels, (ii) high velocity (~7 km) at lower crustal depths from deep seismic sounding studies, and also the deep nature of the NSL boundary faults, (iii) moderately high heat flow environment, (iv) relatively thin high resistive upper crust overlying a conductive lower crustal column. Thus the density and velocity structure of subsurface section as derived from gravity and deep seismic sounding investigations clearly point out that the crustal section at deeper levels in the NSL zone is characterized by high density, high velocity material, while the MT results indicate that it is electrically conductive as well.

In Latur and Koyna regions (Dharwar craton), the MT results bring out a thick high resistive crust, indicating that the brittle nature of material, extends to much deeper levels, as much as 25–30 km. On the other hand, in the Jabalpur earthquake, for the NSL region the MT 2-D geo-electrical section indicates a rather thin high resistive brittle upper crust in general, followed by a conductive lower crust. The interface between the high resistive upper crust and the underlying conductive region obtained through MT imaging is generally considered to be a brittle–ductile transition[35]. The MT sounding results brought out this difference, broadly depicting the thickness variation of brittle upper crust in Indian SCR regions.

Though the lower crust is generally considered to be aseismic because of the increased temperatures, it is often suggested that notwithstanding the warmer subsurface conditions, the lowermost part of the crust may still be suitable for seismogenic processes. This is inferred to be due to inherent strength of materials at Moho depths, which is greater than that for the upper crustal materials at the same temperatures and pressures. Thus there could be two distinct seismogenic zones[36,37], one in the brittle upper crust and the second in the lower crust near Moho levels. In the case of the SCR events in Indian peninsula, the Latur earthquake has a shallow focal depth of less than 7 km and occurs in a highly resistive brittle upper crust. The hypocentre of the Koyna earthquake is also located in the high resistive part of the upper crust but at a relatively deeper level, approximately 15 km deep. On the other hand, the Jabalpur event is a deep focus earthquake with its estimated focal depth of 35 km, which is very close to Moho and is located in an electrically conductive environment. Occurrence of deep focus earthquakes in stable continental regions is not uncommon. Other deep focus SCR events include the Solberg event from the Baltic shield[38], the Aruhem land earthquake of Australia[39] and those discussed by Simpson[2]. Occurrence of a great number of mid-to-lower crustal earthquakes in active and stable continental regions indicates that at least in some SCR regions, the lower part of the crust, despite its warmer conditions, is still suitable for stress accumulation and could become seismogenic[2,40,41].

The regional variation of cut-off depth of seismicity is known to be correlated with the thermal structure of the crust. Indeed an inverse relationship between surface heat flow and focal depth has been reported, for example for earthquakes of central east America and the northern Kinku district of Japan[42]. But such a relationship between focal depth and surface heat flow does not however seem to be apparent for some of the deep focus earthquakes from western Australia[39] as also from southern Zambia[43]. Similarly in the present case, the Jabalpur event with its large focal depth occurs in a moderately high heat flow region, as observed in deep boreholes at Damoh and Mohapani (49 mW/m^2). The phenomenon of occurrence of deep focus earthquakes in stable continents, where heat flow has been constrained, presages the inapplicability of linear relationship for heat flow within the crust in these regions[41].

Deep seismic sounding studies conducted along five traverses across the NSL clearly bring out anomalous lower crustal rocks with higher P-wave velocities of nearly 7 km/s, interpreted to be representing a shallow transition zone[31]. Consistent with these results gravity anomalies in this region also indicate possible presence of heavier ultrabasic rocks at lower crustal depths. The geo-electric structure from MT modelling results[33,34] indicates a moderately conductive lower crust starting from around 10–15 km down to Moho levels. Contrary to conventional interpretation, it may be pointed out that the observed higher conductivities for the lower crust, observed in Jabalpur epicentral region, need not necessarily represent a wet crust, but could also be a manifestation of magmatic underplating at lower crustal depths[44]. Occurrence of conductive ultrabasic lithology may thus be inferred at Moho depth levels in the Jabalpur region. Seismic reflectivity observed along the DSS traverses in the NSL zone is also consistent with the hypothesis of magmatic underplating in this zone[31].

Possible presence of heavy ultrabasic material inferred to exist at deeper levels in the NSL zone represents a competent lithology. Crustal rheological model studies[45] show that the region corresponding to the focal depth levels of Jabalpur earthquake (~35 km) would behave like a brittle layer if we assume a 6 km thick mafic material (underplating between 32 and 38 km) for a surface heat flow value of $\cong$ 55 mW/m^2 and strain rates of $10^{-14} s^{-1}$. This in turn must have facilitated the creation of seismogenic environment at near Moho levels, wherein the medium can accumulate significant amount of strain. Accordingly the deep focus Jabalpur event could be categorized as that belonging to the second seismogenic zone of Chen and Molnar[36] in the depth range of 30–40 km. The Jabalpur event also qualifies for the category of SCR events occurring in a palaeo-rift zone, since the NSL zone itself is a lithospheric segment that has undergone extension and represents a zone of reactivation over a long period since Precambrian[4,46].

Additionally, it is seen that the geophysical signatures inferred to represent the deep-seated seismogenic ultra-basic layer, viz. high crustal velocity, higher electrical conductivity, gravity ‘highs’ fall in a linear belt which is (Figure 4) parallel to the ENE–WSW oriented NSL trend in this region. This linear belt is located adjacent and runs parallel to the Narmada south fault providing a favourable environment for continuation of the second, i.e. deeper seismogenic zone, near Moho levels all along the NSL. This would explain the observation that the Narmada south fault is seismically more active than its northern counterpart.

It is apparent that in the regions of crustal extension like the rift zones, passive margins, etc. the presence of significant gravity highs, abnormal velocities of the lower crust, coupled with conductive nature of crustal rocks down to deeper levels point out to possible presence of stronger ultramafic bodies at near Moho depths. Hence change of rheological conditions may be expected in the lowermost crust, favouring development of seismogenic conditions at these levels. In the presence of deep faults, under these crustal conditions, the occurrence of SCR seismicity at deeper levels is thus possible. On the other hand, the thick high resistive granite–gneissic upper crustal layer representing the typical normal subsurface structure of stable continental regions, needs anomalous features like the fluid enrichment of existing fault zones, highly heterogeneous lithologies, etc. for development of anomalous stress concentration conditions to trigger seismicity. The MT imaging, which brings out the geo-electric structure and with it the configuration of brittle/ductile interface, should help classifying areas of SCR seismicity belonging to different subsurface heterogeneities and rheological conditions.

The following are conclusions from the present study: The three significant SCR seismic events – Koyna, Latur and Jabalpur – have their hypocentres located in different geo-electrical crustal conditions. While the first two events have their hypocentres in a thick high resistive upper crust representing thick brittle crustal column, the Jabalpur event has originated in a conductive environment at Moho levels. MT studies brought out a well-defined upper crustal conductor located in the hypocentral region of the Latur earthquake, which is interpreted to be a fluid-filled fractured rock matrix. The MT results from the Koyna region present a crustal geo-electric model near the Koyna fault, that brings out a thick high resistive upper crust characterized by a block structure of differing resistivities. The Koyna fault region, unlike the Latur region, does not show any significant upper crustal conductor except that the fault itself is associated with a shallow vertical conductive feature, possibly due to presence of water in the fault zone.

It is shown that magnetotellurics helps in deciphering different crustal rheological conditions by mapping resistive/conductive interfaces. Fluids play significant role in the generation of SCR seismicity as shown in the case of Latur earthquake and also to some extent in the case of Koyna earthquake. Magnetotellurics is shown to be highly effective in detecting such fluid-enriched zones in the high resistive upper crust of SCR region in the form of well-defined upper crustal conductors.

The Jabalpur earthquake known to be associated with the Narmada South fault is inferred to have occurred at near Moho depths in a region characterized by high density, enhanced velocity, high conductivity corresponding to mafic/ultramafic lithologies. It is inferred that this zone representing brittle rheological conditions at these depth levels provide a seismogenic environment and extends all along the Narmada South fault, thus making it to be seismically more active than its counterpart, the Narmada North fault.

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Early Cambrian trace fossils from the Tal Formation of the Mussoorie Syncline, India

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A significant assemblage of trace fossils is presently described from the lowermost Quartzite member of Upper Tal Formation, in addition to earlier described trace fossils from Himachal Pradesh. The most common trace fossils described here are *Monomorphichnus* isp, *Dimorphichnus* isp., *Dimorphichnus* isp A, *Diplichnites* isp A, *Planolites* isp, *Skolithos* isp, *Merostomichnites* isp, *?Neonereites* isp, along with various scratch marks and burrows. The present assemblage could represent the middle to upper part of the Early Cambrian.

Keywords: Cambrian, *Dimorphichnus*, *Diplichnites*, *Monomorphichnus*, trace fossils.

In the western Lesser Himalaya, the Tal Formation is an important lithostratigraphic unit of the Neoproterozoic–Cambrian sequence (Blaini–Krol–Tal succession), which consists mainly of black shales, chert, siltstone and Quartzite. Our study area is located on the Mussoorie–Dhanaulti road section, exactly on the 0 km milestone of Batagad. It shows exposures of huge Quartzite with sandstone shale intercalations and represents the lowermost member (Quartzite member) of Upper Tal Formation (Figure 1). Trace fossils reported and described here are preserved within these sand–shale intercalations.

It is well known that trace fossils present in the Neoproterozoic–Cambrian boundary sections in the worldwide localities are generally well-preserved and well-diversified[1–7], and the boundary is defined by the first appearance of the trace fossil, *Treptichnus pedum*[5]. Recent studies in the Mussoorie hills of Uttaranchal have revealed several trace fossil-bearing sections, especially in the arenaceous sandstone–shale beds of the Upper Tal Quartzite member. The best preserved section is along the Mussoorie–Dhanaulti road section. The traces are mostly in the form of burrows and tracks along with scratch marks and are identified mainly as *Monomorphichnus* isp, *Dimorphichnus*

Figure 1. Field photograph showing fossiliferous horizon.

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