

Resistivity survey across the Narmada-Son lineament and along the Sanwer-Borgaon traverse, Madhya Pradesh, central India

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ABSTRACT: Combined Schlumberger and equatorial Direct Current (DC) dipole soundings were conducted along the Sanwer-Borgaon traverse across the Narmada-Son lineament primarily to locate the shallow-level faults and fractures after two intraplate earthquakes that rocked Jabalpur and Khandwa in Madhya Pradesh, central India. The study area is covered by Deccan basalts overlying the Gondwana, Vindhyan and Bijawar sediments and the basement is of Bundelkhand granite. A 2D model from a 1D inversion of sounding data revealed that the thickness of the Deccan trap varies from 600 m to 1 km along the Sanwer-Borgaon traverse. Occurrence of abundant water within the subsurface formations in the Dulhar zone, and further south, one conductive thick zone, presumably due to highly weathered Deccan trap or intratrappeans, have been inferred. A sudden increase in depth of the basement north of the Narmada-Son lineament indicates that a major fault coincides with the Narmada River. Collinear dipole-dipole traverses were taken across the surface geological signature of faults. The survey was able to locate a couple of faults/fractures along the traverse within 2 km of the Earth's crust. The area appears to be a tectonically weak zone. Both resistivity sounding and profiling techniques proved to be very useful tools for understanding the lithology and structure below the Deccan trap.

1. Introduction

Alpin (1950), Alpin *et al.* (1966) first brought out the idea of DC (direct current) dipole soundings for deeper probing of the Earth. To avoid long cable lengths and other logistic difficulties faced in using a long electrode spread in the Schlumberger and Wenner configuration, DC dipole came as an alternative with relatively short cable lengths for deeper probing. Since then Anderson and Keller (1966), Jackson (1966), Keller (1966), Keller and Frischknecht (1969), Zhody (1969) used DC dipoles for deep probing. In DC dipoles, four prime parameters are: (i) length of the current dipole $AB = L$; (ii) length of the potential dipole $MN = l$; (iii) dipole separation, i.e. the distance between the midpoints of the current and potential electrodes $OO' = r$; and (iv) dipole angle θ (Fig. 1).

In general, six widely used DC dipoles are: (i) equatorial dipole, (ii) parallel dipole, (iii) perpendicular dipole, (iv) azimuthal dipole, (v) radial dipole, and (vi) axial or collinear dipole (Fig. 1). The general expression for all DC four electrode configurations are as follows:

$$K = \frac{2\pi}{\frac{1}{AM} - \frac{1}{BM} - \frac{1}{AN} + \frac{1}{BN}} \tag{1}$$

We designate this geometric factor as K_{actual} . The approximate geometric factors for different bipole-dipole configurations are:

$$K_{parallel} = \frac{2\pi r^3}{Ll} \cdot \frac{1}{3\cos^2\theta - 1} \tag{2}$$

$$K_{perpendicular} = \frac{2\pi r^3}{3Ll} \cdot \frac{1}{\sin\theta \cos\theta} \tag{3}$$

$$K_{azimuthal} = \frac{2\pi r^3}{Ll \sin\theta} \tag{4}$$

$$K_{radial} = \frac{\pi r^3}{Ll \cos\theta} \tag{5}$$

$$K_{equatorial} = \frac{2\pi r^3}{Ll} \tag{6}$$

(Alpin *et al.*, 1966)

For the equatorial dipole $\theta = \pi/2$. Both parallel and azimuthal dipoles become an equatorial dipole and perpendicular and radial dipoles become null array at $\theta = \pi/2$. At $\theta = 0$, parallel and radial dipoles become axial dipoles and perpendicular and azimuthal dipoles become null arrays. Dipole field dies down inversely as the cube of distance. Therefore, the measured potential ΔV_{MN} reduces downwards rapidly with dipole length r . Fig. 2 shows the variation of potential with varying dipole length and dipole separation. One can plan a dipole survey assuming a 200 to 300 microvolt-range measurement in a potential dipole. Koefoed (1979) had shown the connecting relation between the apparent resistivity obtained for the Schlumberger configuration and that obtained using the parallel dipole configuration

$$\rho_{app. dip. par} = \rho_{app. Schl} - \frac{\cos^2\theta}{3\cos^2\theta - 1} r \cdot \frac{\partial \rho_{app. Schl}}{\partial r} \tag{7}$$

where $\rho_{app. dip. par}$ is the apparent resistivity obtained using a parallel dipole configuration and $\rho_{app. Schl}$ is the apparent resistivity obtained using the Schlumberger electrode configuration, θ is the dipole angle and r is the half electrode separation i.e. $AB/2 = r$. Since a parallel dipole

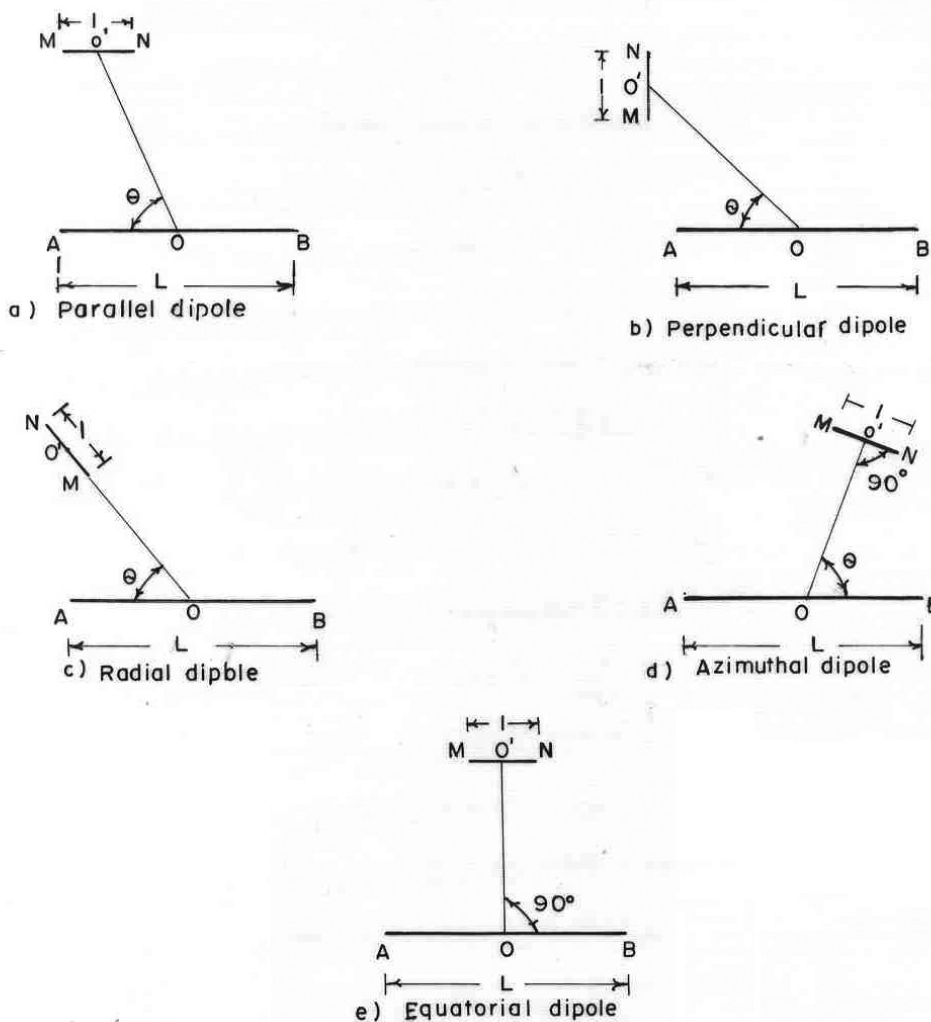


Fig. 1 - Parallel (a), perpendicular (b), radial (c), azimuthal (d) and equatorial (e) dipole configurations. Current dipole lengths ($AB = L$), potential dipole lengths ($MN = l$), dipole separation ($OO' = r$) and dipole angle θ are shown.

becomes an equatorial dipole at $\theta = \pi/2$, as mentioned, one gets the theoretical justification of attaching the equatorial dipole data with the Schlumberger data for deeper probing. Normally, the shallower part of the probing is done with Schlumberger and the deeper part with the equatorial dipole array. Inter-convertibility of dipole-apparent resistivities to Schlumberger apparent resistivities are discussed in Bhattacharyya and Patra (1968) and Koefoed (1979).

Hallof (1964) presented the idea of plotting apparent resistivity obtained from collinear dipole-dipole array in a pseudo net using the relation as follows:

$$\rho_a = K = \frac{\Delta V}{I} \pi a n(n+1)(n+2) \frac{\Delta V}{I} \tag{8}$$

where a is the dipole length and n is the dipole separation in the unit of dipole length.

In this paper, the authors have demonstrated how Schlumberger sounding data can be combined with equatorial dipole sounding for deeper probing, at least down to 2 km from the surface, generating 2D models from 1D inversions (Inman, 1975).

A collinear dipole-dipole tool, where both resistivity sounding and profiling are done together, generates a 2D model of the surface and locates faults and fractures. Very Fast Simulated Annealing (VFSA) (Ingber, 1993; Sen *et al.*, 1993), was used to generate 2D models.

With the advent of sophistication in magnetotellurics (MT) and audiofrequency magnetotellurics (AMT) the use of DC dipole has gone down considerably because of a larger logistic support one needs in man power and field surveys. A DC dipole survey will prove to be a better tool where the study area has a high cultural noise. CSAMT (Controlled Source Audiofrequency Magnetotellurics) remains a contender for DC dipoles. In a rugged terrain, DC dipoles may get preference over CSAMT on field logistics. With the advent of high precision GPS (Global Positioning System) and a large network of cell phones, a DC dipole survey has become considerably easier and the accuracy in the computation of apparent resistivity has increased.

The principal objectives of the present investigation are the delineation of both the shallow and deep geological structures. The dispositions of the different rock units in the area especially at depth and demarcate the zones of rifting.

2. Geology of the study area

The study area shows exposures of Archaean Bundelkhand granite (north of the Narmada River) and granite gneisses within the Bhandara craton (south of the Narmada River). Proterozoic sediments cover wide areas of the region. These are known as the Mahakoshal group, Bijawar group and Vindhyan group of sediments. The Mahakoshal group of sediments is composed of basic metavolcanics and metasediments. The late Proterozoic Vindhyan unconformably overlie the Bundelkhand granites and the Mahakoshal and Bijawar group of sediments. Phanerozoic Gondwana sediments and the Quaternary lameta and Bagh beds in turn overlie those older sediments (Jain *et al.*, 1995). Phanerozoic pre-Tertiary Deccan flood basalts cover most of the study area and they also overlie older sediments. The thickness of the flood basalts is of the order of 600 m to 1 km along the Sanwer-Borgaon profile. Major lineament, viz. the Narmada-Son lineament (NSL) which is represented by the Narmada River cut across the study area (Fig. 3). This is a major fracture in this continental shield area.

The NSL zone is bounded by latitudes 20°-24°N and longitudes 73°-81°E (whole stretch is not shown in Fig. 3) and is a high heat-flow zone [heat flow 85 ± 2.2 mW/m²: Ravi Shanker (1988, 1995)] with occurrence of several hot springs as well as other fractures and lineaments. This area has an essentially rift valley type of structure with major rifting of the continent and block faulting. The NSL comprises several ENE-WSW trending faults (Jain *et al.*, 1995; Venkata Rao *et al.*, 1995). Narmada South Fault (NSF), which passes through Khandwa, Narsingpur and Jabalpur. The Khandwa lineament lying concordantly to the south of the NSF marks the southern limit of the Narmada valley. It is a faulted contact between Narmada alluvium and the Deccan traps, implying recent activation.

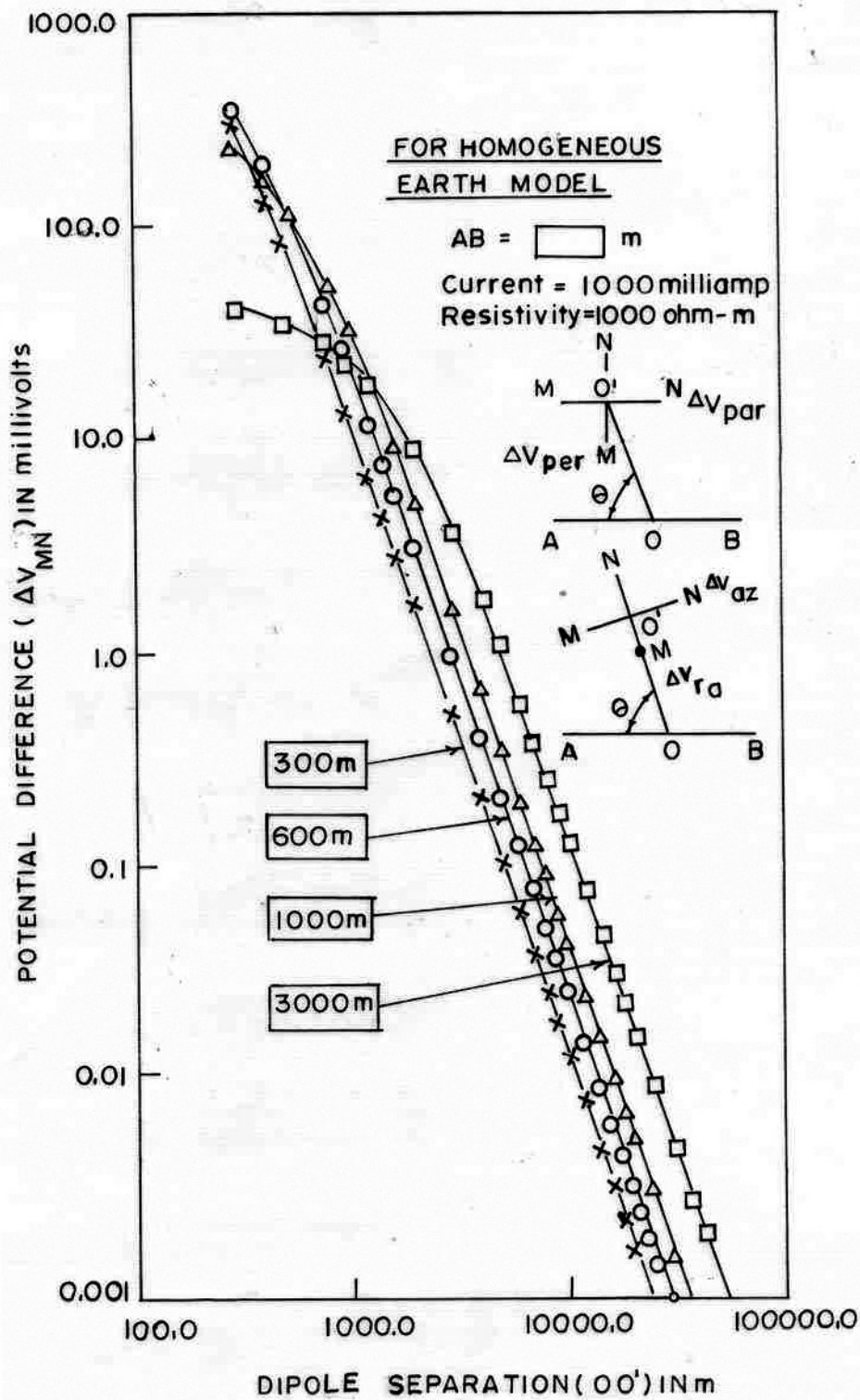


Fig. 2 - Decrease in the measured dipole potentials with dipole separations and dipole length.

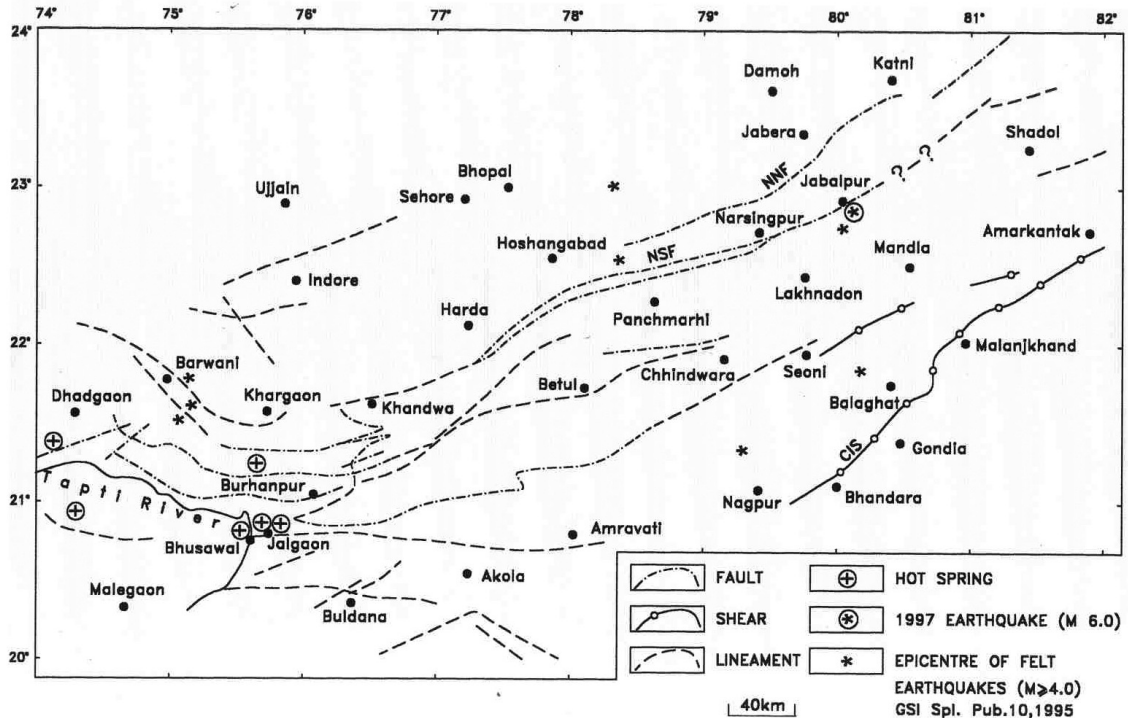


Fig. 3 - Lineaments, fractures and location of epicenters of several microearthquakes and earthquakes.

3. Field work

Fig. 4 shows the locations of the DC dipole-sounding field sites. The traverse extends from Sanwer to Borgaon. The stations were Dharampuri, Dudhiya, Umrikhera, Mhow, Choral, Balwada, Barwah, Omkareswar, Sulgaon, Kankariya, Dhangaon, Deshgaon, Chhegaon-Makhan, Dulhar and Borgaon.

The Scintrex 10 KVA time-domain-induced polarization equipment transmitter was operated using a 15 HP gasoline-driven generator which supplies power to the transmitter at 100 volt and 400 Hz. A 12 to 15 Ampere current was used for the field survey with a recording facility measuring down to 200 to 300 μ V (microvolt) potential in a Scintrex RDC-10 receiver. Empty tin cans of about 35 cm diameter were inside a dug hole filled with plenty of salt and water to reduce the contact resistance to less than 50 Ohm and a 12 to 15 Ampere current could be sent through the ground. A high power unit is a must for a dipole survey. Copper-Copper sulphate, non-polarisable electrodes were used for measuring potentials. A Schlumberger sounding was done with steel stakes and porous pots up to maximum electrode separation of 2 km; dipole separation was varied from 500 m to 10 km for each dipole sounding. Dipole sounding data were attached to the Schlumberger data at higher electrode separations. Bi-directional equatorial dipole soundings were done for 13 stations (Fig. 4), keeping the current dipoles at the center; the distance between the current and potential dipoles was increased on both sides till the potential

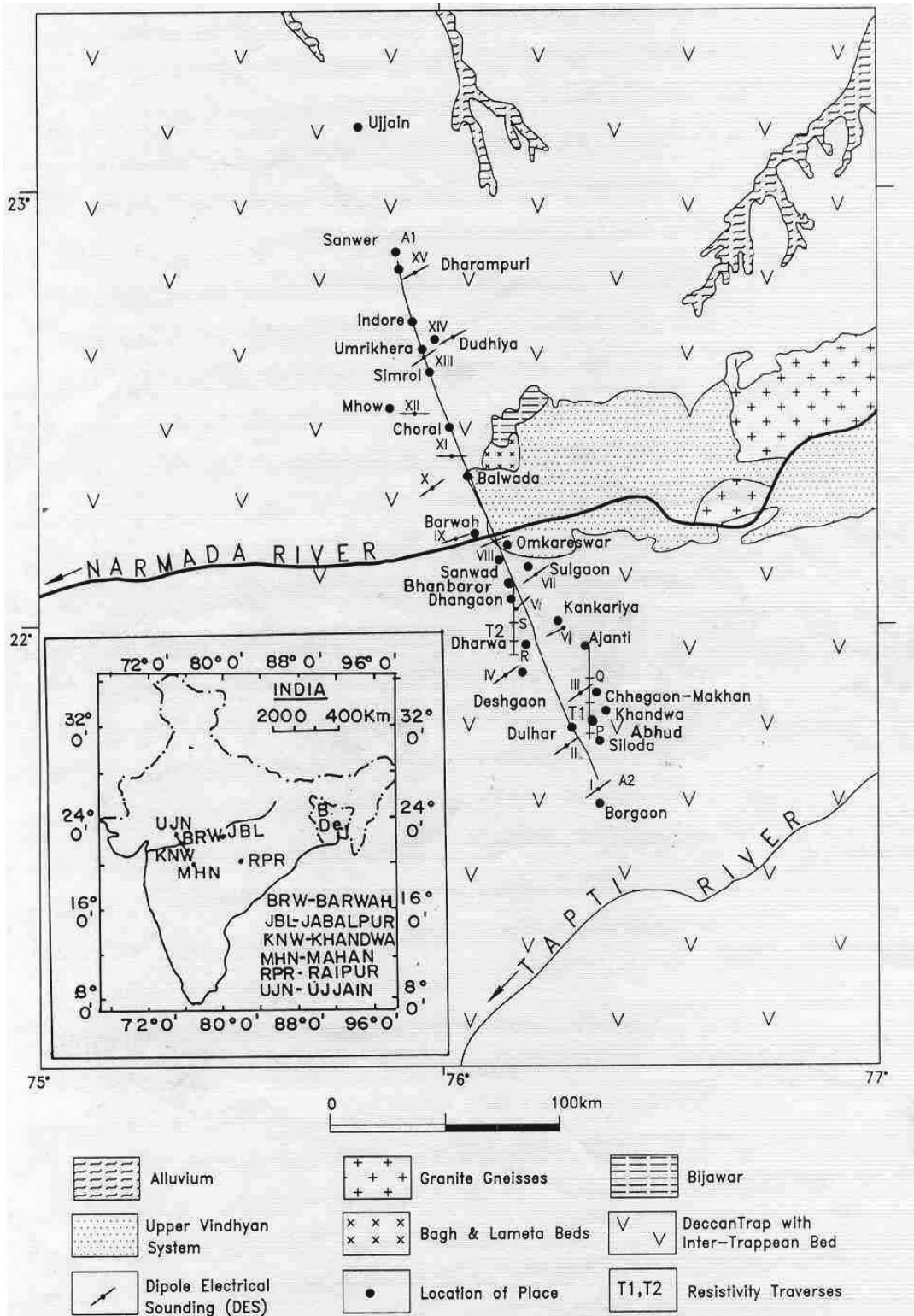


Fig. 4 - Locations of the DC resistivity sounding sites along the Sanwer-Borgaon traverse (A₁A₂); locations of the two collinear dipole-dipole traversing sites T₁ (east of main traverse A₁A₂) and T₂ (west of main traverse A₁A₂).

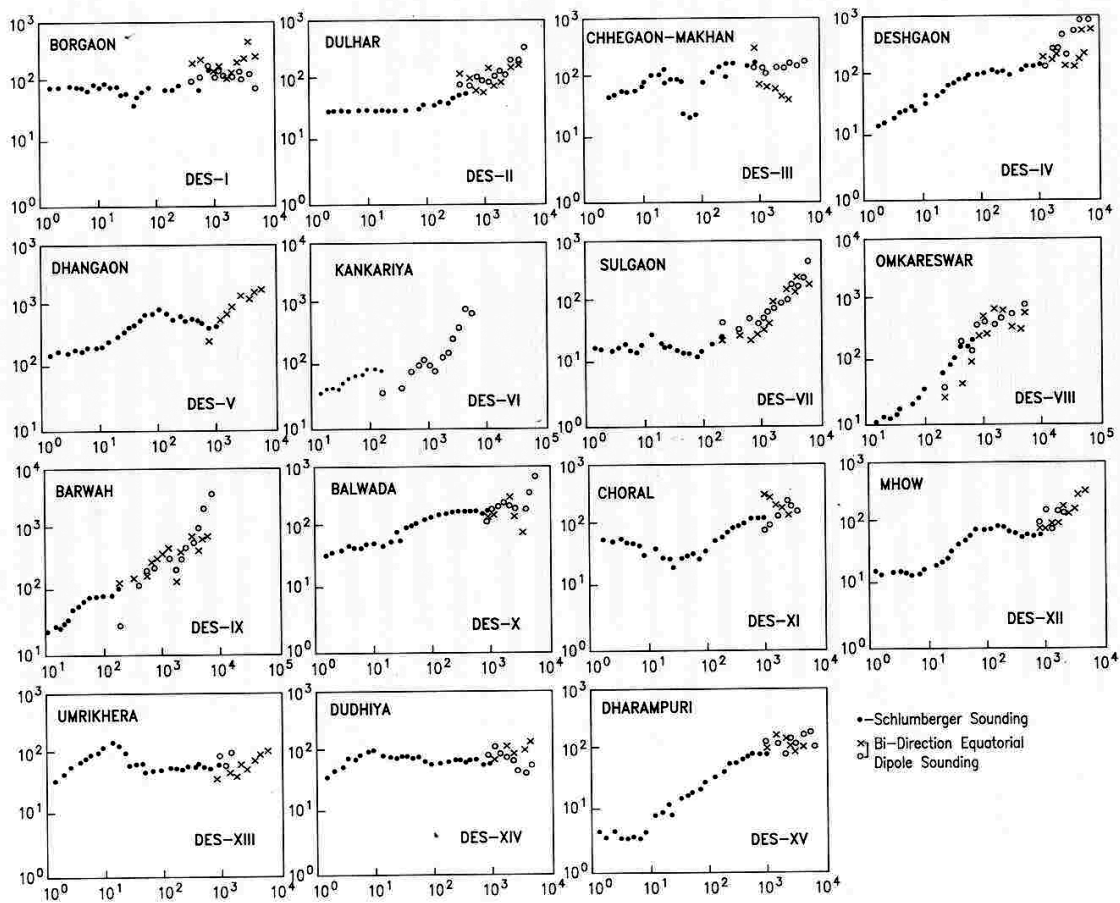


Fig. 5 - The combined Schlumberger and dipole-dipole sounding data for 15 stations along the Sanwer-Borgaon traverse (A₁A₂, Fig. 4), Madhya Pradesh, central India. Horizontal axes represents AB/2 for Schlumberger and r for the equatorial dipole array in m. Vertical axes represent apparent resistivity in Ohm-m.

remained measurable. In the field, a set up attempt is being made to keep $AB < \frac{1}{3} OO'$ and $MN < \frac{1}{5} AB$. For an equatorial dipole sounding $\rho_a = \frac{2\pi r^3}{Ll} \cdot \frac{\Delta V}{I}$ where $OO' = r$, $AB = L$, $MN = 1$, ΔV is the measured potential difference and I is the current flowing through the ground. Fig. 5 shows the fifteen combined Schlumberger and equatorial dipole sounding curves.

For a collinear dipole-dipole survey along traverses T₁ and T₂ they were conducted keeping both AB and MN (= a) equal to 500 m. The dipole separation n was varied from 1 to 10. The apparent resistivity is computed using Eq. (8).

4. Results and discussion

Bi-directional equatorial dipole sounding (BEDS) data indicates, qualitatively, the dip of the basement [Alpin *et al.* (1966) page 195; Bhattacharyya and Patra (1968) page 113]. It can be

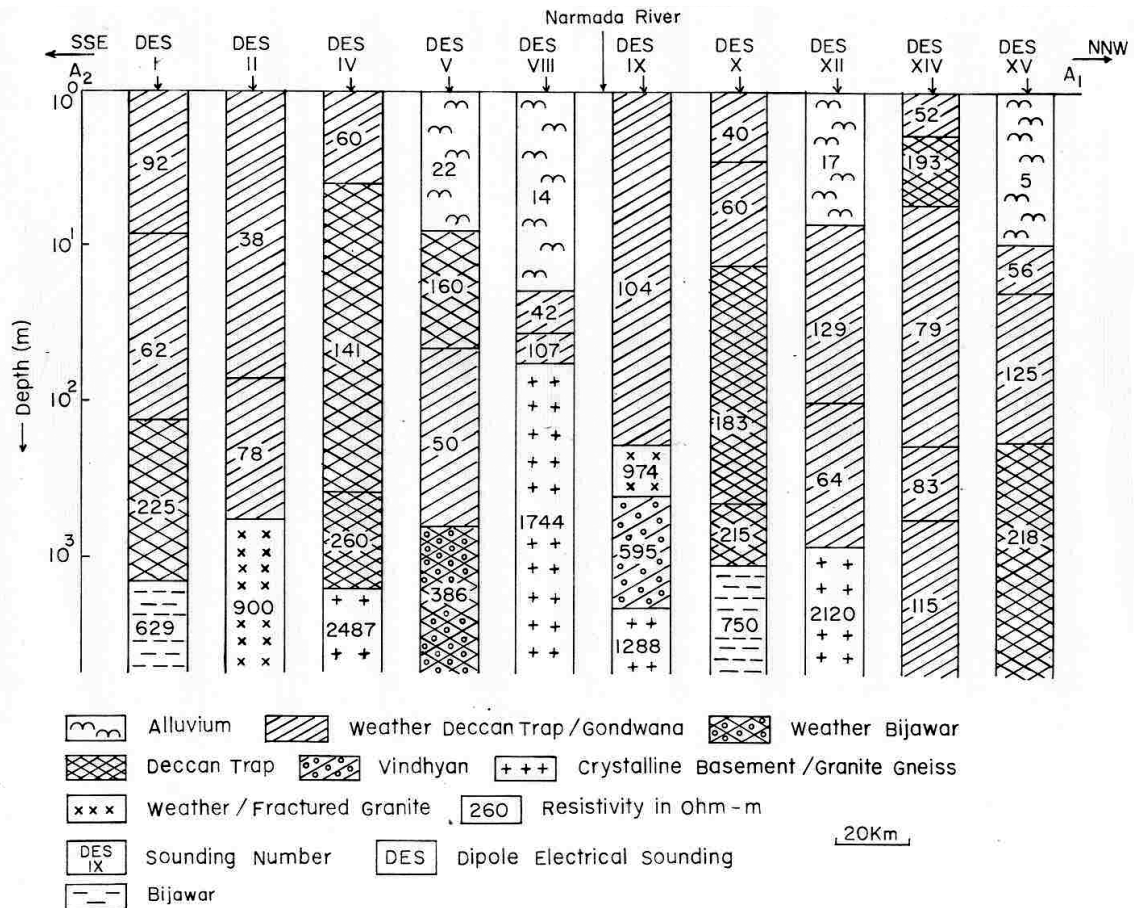


Fig. 6 - 1D geoelectrical models of the 15 stations along the Sanwer-Borgaon traverse (A₁A₂, Fig. 4). DES-1 Borgaon; DES-2 Dulhar; DES-IV Deshgaon; DES-V Dhangaon; DES-VIII Omkareswar; DES-IX Barwah; DES-X Balwada; DES-XII Mhow; DES-XIV Dudhiya; DES-XV Dharamपुरi.

estimated quantitatively also. Bi-directional equatorial dipole soundings data at stations Borgaon, Chhegaon-Makhan, Deshgaon, Choral show splits in bi-directional soundings indicating a dipping basement. BEDS data in both directions are averaged and attached to the Schlumberger data for 1D inversion.

Fig. 6 shows the 1D models of 15 stations obtained from partial curve matching and weighted ridge regression (Inman, 1975). Interpretation of resistivity data reveals that the thickness of the Deccan trap varies from a few tens of metres to more than 1 km. Bundelkhand granite marks the high resistivity basement. Formations of intermediate-to-low resistivity are the Gondwana, Vindhyan, Bijawar and Quaternary sediments. There is a presence of a high resistivity (>1000 Ohm-m) formation, at a relatively shallow depth (600-700 m) south of the Narmada River, whereas the same high resistivity formation occurs at a greater depth to the north of the river. But the basement has come up to a level of 61 m below ground level at the Narmada River. The steep gradient of the basement could possibly be attributed to a fault/rift zone. Therefore, Narmada-Son

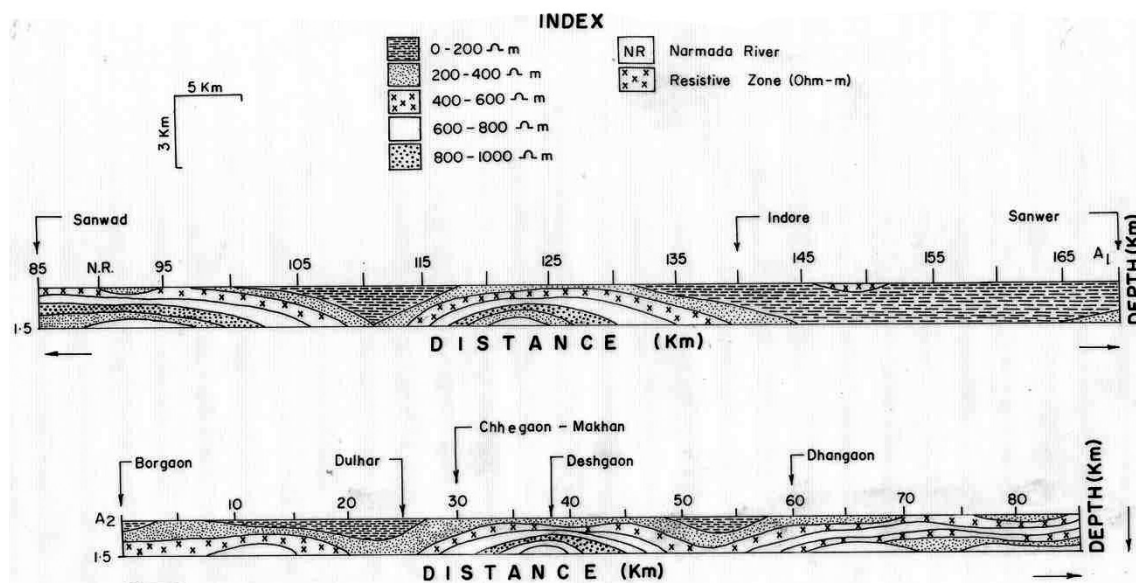


Fig. 7 - Shows the 2D geoelectrical model of the Sanwer-Borgaon traverse (A₁A₂, Fig. 4) obtained from a 1D inversion of the field data, it shows the variation of the thickness of the Deccan basalts.

lineament is a faulted zone. The Narmada River flows right over the fault. Some shallow-level resistivity soundings are done on the different exposures of rocks and an estimate of resistivities of the different rocks are made as follows. The range of resistivity of the different geological unit is given in Table 1.

Depths of the basement at different sounding points are given in Table 2.

Interpretation of resistivity sounding data has been carried out using the Ridge Regression technique after assuming a 2D model (Inman, 1975) and is shown in Fig. 7. There is a general increase in resistivity with depth in the area at least down to a depth of 750 m. At greater depths, resistivity of the formations decreases except in the areas south of Chhegaon-Makhan where no reversal of resistivity has been encountered. This could be explained by the presence of a fault zone around Chhegaon-Makhan. 2D modeling further indicates that the thickness of a conductive

Table 1 - Resistivity of the geological units.

Serial Number	Geological Units	Resistivity (Ohm-m)
1	Alluvium	10-25
2	Deccan trap	50-300
3	Gondwana	30-130
4	Vindhyan	400-500
5	Bijawar	600-900
6	Granite	>900

Table 2 - Depth of the basement.

Sounding number	Location	Depth to the basement towards NE	Depth to the basement towards SW	Apparent dip direction
DES-1	21°17'49" 76°16'18"	1548 m	1222 m	NE
DES-2	21°43'53" 76°16'01"	1340 m	816 m	NE
DES-3	21°53'22" 76°17'19"	656 m	420 m	NE
DES-4	21°53'22" 76°06'34"	3230 m	1274 m	NE
DES-7	22°08'34" 76°10'14"	980 m	485 m	NE
DES-8	22°13'21" 76°05'38"	35 m	42 m	SW
DES-9, Narmada river	22°14'27" 75°58'23"	1243 m	1415 m	SW
DES-10	22°20'18" 75°55'13"	1857 m	2790 m	SW
DES-11	22°36'21" 75°57'36"	273 m	1610 m	SW
DES-12	22°32'08" 75°51'31"	780 m	679 m	NE
DES-13	22°36'21" 75°53'29"	2467 m	812 m	NE
DES-14	22°40'54" 75°59'31"	919 m	652 m	NE
DES-15	22°53'06" 75°51'26"	226 m	340 m	SW

zone (weathered Deccan trap) is considerable in the Dulhar area. The zone is possibly saturated with water, thus lowering its resistivity considerably. In the Chhegaon-Makhan and Deshgaon sector, higher resistivity zones have been inferred due to the occurrence of a compact Deccan basalt. A similar geological set up is interpreted up to the 105 km mark, barring a small patch 9 km north of Deshgaon where thickness of weathered basalt is appreciable. One conductive thick zone, presumably due to highly weathered Deccan trap or intratrappean, is inferred at a 110 km mark. Similar rock types are again interpreted in the subsurface in the Indore-Sanwer sector. Considerable thickness of alluvium is also inferred close to the surface in the area (Indore-Sanwer).

Resistivity profiling with a maximum electrode separation of 6 km was carried out in the area along traverse T_1 (Fig. 8). 2D inversion of collinear dipole data were inverted using VFSA (Ingber, 1989, 1993; Sen and Stoffa, 1995). The structure of the VFSA is based on the work of Sen and Stoffa (1991, 1995) and Chunduru *et al.* (1994). The 2D model, along T_1 , indicates a series of faults/contacts (F_1 , F_2 , F_3 , F_4 and F_5) in the geoelectric section. The depth extent of these faults/contacts are within a distance of 500 m to 1 km. The entire traverse is over the Deccan basalt with resistivities varying from 100 to 150 Ohm-m. High-resistivity rocks are interpreted at

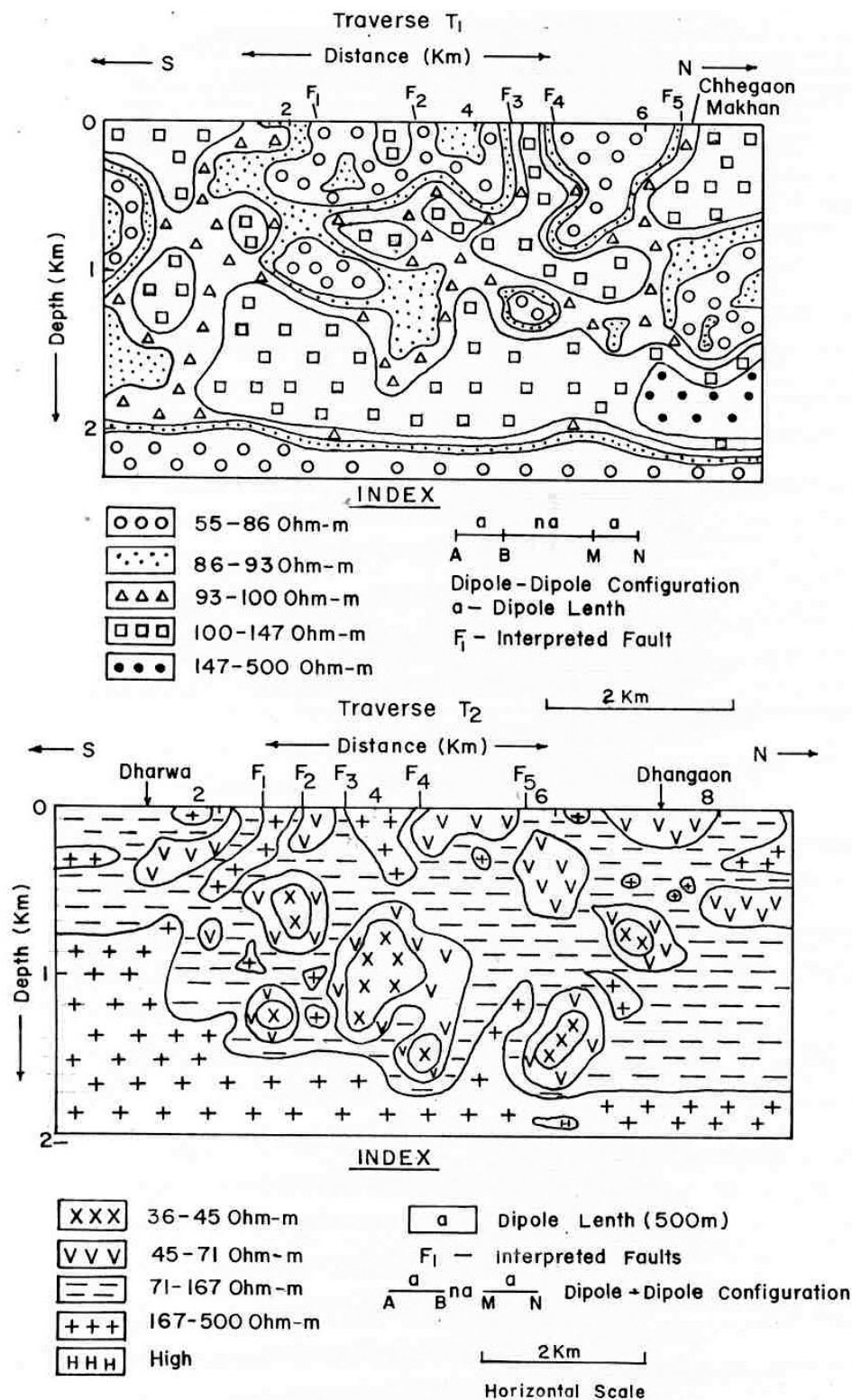


Fig. 8 - Two 2D geoelectrical models obtained from VFSA inversion of collinear dipole-dipole traversing data for the traverses T₁ and T₂ (east of main traverse and west of main traverse, Fig. 4).

a depth of about 2 km which is approximately the maximum depth that could be investigated by the survey.

A 2D model, along T₂ (Fig. 8), shows some distinct faults/contacts (F₁, F₂, F₃, F₄ and F₅). The lateral variation in resistivities in these 2D sections can be due to geological contacts/faults/lineaments revealed by the surface geology and tectonic map (Ravi Shanker, 1995). Thickness of the Deccan trap is found to be nearly 2 km in the north, reduced to 600 m towards south. The observation is also corroborated by the interpretation of sounding data. A few conductive pockets also noted in the model which could be due to intratrappeans or a water-saturated weathered trap.

5. Concluding remarks

Although DC dipole surveying is a less popular geophysical tool for deeper investigations, it is a helpful geoelectrical tool for high cultural-noise affected study areas where MT/AMT surveys fail. CSAMT may be a contender to challenging DC dipoles. A rugged terrain in a hilly area may make the CSAMT survey difficult, leaving DC dipoles as the only alternative. Geoelectrical surveying using direct current Schlumberger and equatorial dipole soundings yielded many interesting results. All the rock units in the area viz. unweathered Deccan basalt (Deccan trap), Gondwana, Vindhyan and Bijawar sediments and the granite basement are generally characterized by distinct resistivity values. Granite marks the high resistivity basement while the formations of intermediate-to-low resistivity are the Gondwana, Vindhyan, Bijawar and Quaternary sediments. The water-bearing rocks, weathered Deccan trap and compact Deccan trap in the subsurface are also delineated. There is a presence of a high resistivity (>1000 Ohm-m) formation at a relatively shallow depth (600-700 m) south of the Narmada River, whereas the same high resistivity formation occurs at a greater depth to the north of the river. But the basement has come up to a level of 61 m below ground level at the Narmada River. The steep gradient of the basement could possibly be attributed to a fault/rift zone. Therefore, NSL is a faulted zone. The Narmada River flows right over the fault. A DC resistivity survey (sounding and traversing) shows that the study area is full of major and minor faults. Since the area is a high heat-flow area (heat flow 85 ± 2.2 mW/m²) and this fractured plate is continuous, moving upwards to collide with the Tibetan plate, accumulation of stress and strain in the mid-plate may cause earthquakes in the future.

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