Magnetotelluric survey across Singhbhum granite batholith

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Abstract. Magnetotelluric soundings have been carried out across the archaean terrain of Singhbhum granite batholith from Bangriposhi to Keonjhar for a distance of about 100 km. One-dimensional inversion models reveal that the depth of the moho varied between 23 and 40 km. The depth of the lithosphere asthenosphere boundary varied from 58 to 76 km. A zone of higher electrical conductivity detected at the base of the lower crust just above the moho is present along the entire profile. Signals within the range of 0.25 to 600 seconds, which crossed the coherency threshold of 0.8 to 0.9, could be stacked. Resistivity ranges of the crust mantle silicates below Singhbhum granite batholith vary over a wide range. Resistivity ranges are (i) 30,000–80,000 ohm for Singhbhum granite phase II, (ii) 2,000 to 9,000 ohm-m for Singhbhum granite phase III, (iii) 250 to 2,200 ohm-m for lower crust (iv) 3,000 to 47,000 ohm for the upper mantle and (v) 200 to 2300 ohm-m for the asthenosphere. Sharp break in electrical resistivity at the (i) upper crust-lower crust (ii) lower crust upper mantle and (iii) lithosphere-asthenosphere boundary is obtained along the entire profile. Signals could see up to 100 km below the granite batholith. Singhbhum granite phase II and III could be demarcated on the basis of resistivity. Low resistive zones in the lower crust and upper mantle might have formed due to (i) water (ii) combined effect of water and carbon and (iii) high temperature and partial melt.

Keywords. Magnetotelluric survey; Singhbhum granite batholith; inversion model; magnetometer array.

1. Introduction

Electrical conductivities of the crust and the upper mantle, like seismic velocity, density and magnetic susceptibility are important constraints on the physical properties for mapping large scale crust-mantle structures which may throw some light on the processes of crustal evolution. With the recognition of a distinct ancient crustal block (iron ore craton) in the Singhbhum-Orissa region of eastern India (Sarkar and Saha 1959), attention of many geologists has been drawn to this region to study the structural, petrological and geochronological aspects of this Archaean terrain. Some of the oldest exposed rocks of the earth viz older metamorphic group (OMG) and older metamorphic tonalite gneiss (OMTG) (3800 million years) are reported from this area (Basu *et al* 1981). The crust under this iron ore craton is reported to have evolved over 3.0 Ga ago. Saha *et al* (1988), and Ghosh *et al* (1986) have given the evolutionary sequence of this region, which is dominated by the Singhbhum granite batholith and other batholiths during Archaean time. Mayurbhanj granite was emplaced along the eastern flank of the Singhbhum granite during Proterozoic time. An active sequence of geological events in this region from C 3.8–0.9 Ga has been worked out (Cf. Saha *et al* 1988). The Singhbhum-Orissa iron ore craton contains

batholithic bodies of granites and granodiorites as well as Archaean-Proterozoic volcano-sedimentary supracrustals and some mafic intrusives. This cratonic block is bounded by the arcuate copper belt thrust zone in the north and the Sukinda thrust zone in the south. It is surrounded in the east and north by the relatively high grade metamorphic satpura belt and in the south by the granulite facies Eastern Ghat belt.

The major crust-forming events in the Singhbhum craton were complete by 3.0 Ga and the major crustal growth continued up to 950 Ma (Saha *et al* 1988). The area under investigation is geologically one of the most well studied areas of the world. Therefore, the readers are referred to the original papers (Saha *et al* 1984, 1988; Saha and Roy 1984a, b, 1988; Ghosh *et al* 1986) for geological information.

Except for detailed gravity measurements of Verma *et al* (1984), no significant geophysical work has been reported on this shield area. Therefore, the electrical characterization of this ancient cratonic block of eastern India was chosen as one of the major problems in this project. Accordingly, magnetotelluric sounding and magnetometer array studies were proposed for the area and the programmes were jointly undertaken by the Indian Institute of Technology Kharagpur, the Indian School of Mines Dhanbad and the Indian Institute of Geomagnetism Bombay. Attempts to throw light on the evolutionary history of the Singhbhum granite batholith, based on geochronological work have been made by Basu *et al* (1981), Saha *et al* (1986) and Bakshi *et al* (1987).

2. Field work and one-dimensional inversion model

Single site magnetotelluric field was surveyed across the Singhbhum granite batholith along the NE-SW profile (figure 1). Location of the observation points is also shown in the figure. The field sites were chosen about 1 to 2 km inside from National Highway No. 6 to avoid any cultural noise as far as practicable. The distances between the observation points varied from 6.50 to 15 km. The total length of the traverse was about 100 km.

Metronix (MMSO2E) system was used for field measurements. Two pairs of silver-silver chloride electrodes were placed at a distance of about 100 m each in two mutually perpendicular directions (east-west and north-south) to measure the electric field components E_x and E_y . Magnetic fields (H_x and H_y) are measured along the east-west and north-south directions putting the induction coils in horizontally dug grooves. Induction coils were aligned and levelled with a prismatic compass and spirit level.

The period of measurement ranged from 0.25 to 4096 seconds in this equipment. Measurements were done in three bands LF1 (256 to 4096 s), LF2 (8 to 256 s) and LF3 (0.25 to 8 s). Figures 2 to 4 show the samples of time series in LF3, LF2 and LF1 bands. Observations at one field station were taken for about 12 hours; overnight observation was preferred to day-time observation in summer. Monovariate coherency threshold for $E_x - H_y$ and $E_y - H_x$ was kept at 0.85. Coherency threshold should be kept within 0.8 to 0.9 (Kurtz and Garland 1976; Kaufman and Keller 1981; Rankin and Pascal 1985a, b). Lesser the value of $H_x - H_y$ coherency, more stable will be the computed impedances. The value of this coherency should preferably be 0.6 (Swift 1969; Rankin and Pascal 1985a, b). Typical field values of apparent resistivity, phase and the monovariate and bivariate coherencies for the stations Dudura and Dari are presented in tables 1 and 2. Figures 5 to 8 show the apparent resistivity and phase

Figure 1. Location map of the study area and the observation points.

Figure 2. Time series, LF3 band, location village Dari, dated 24.4.88.

Figure 3. Time series LF2 band, location village Dari, dated 24.4.88.

curves for the station Dudura and Dari for Z_{xy} and Z_{yx} . Figures 9 to 12 show the one-dimensional (1D) MT inversion results for Z_{xy} and Z_{yx} with optimum rotation. Observations of only two stations are presented in this paper on account of space limitations. Optimum rotation of the impedance tensor is given to minimize $Z_{xx}^2 + Z_{yy}^2$ and maximize $Z_{xy}^2 + Z_{yx}^2$ (Vozoff 1972). Since Singhbhum granite is a huge batholithic body, the 1D model and inversion with optimum rotation angle is justified on the central part of the body (Jones and Hutton 1979). Figure 13 shows the geoelectric section drawn on the basis of the mean depths, thicknesses and resistivities obtained from rotated Z_{xy} and Z_{yx} .

Figure 4. Time series LF1 band, location village Baliaguda, dated 6.5.88.

MT observations were taken with a single measurement without any remote reference facility. Out of 30 stacks in the frequency bands, 12 to 20 s at the different frequencies could be retrieved at different observation points. Long-period observations greater than 600 seconds did not cross the coherency threshold. The present investigation depth was therefore restricted to a maximum of 100 to 150 km. Signals with a period range of 1.33 seconds to 5.33 seconds were weaker and in most of the soundings, no signals were stacked. This zone is generally called the dead zone.

3. Interpretation

Electrical resistivities of granites and granodiorities varied from 2,500 ohm-m to nearly 100,000 ohm-m. Although the *in situ* resistivity of the order of 10^5 ohm-m for crust mantle silicates is a little on the higher side, several workers (Kurtz and Garland 1976; Vanzijl 1978; Kurtz 1982; Beamish 1986) have reported such higher orders of resistivity. Resistivity of the Singhbhum granite phase II (3.3 billion years) is considerably higher than that of Singhbhum granite phase III (3.1 billion years). MT section could demarcate the boundaries of phases II and III granite. Phase II granite is older, more acidic, with low density and low level of radioactivity. Phase III granites are assumed to be the recrystallization products of phase II granite. Therefore, phase III part is richer in uranium and thorium content and mafic minerals. MT signals with a 4 HZ frequency did not see the top 10 km of the granite batholith.

Low resistive zone at the base of the lower crust was present in the entire survey area. Crustal conductors in the continental shield areas were reported by several workers (Keller *et al* 1966, Mitchell and Landisman 1971, Adam 1978, Vanzijl 1978, Jones 1982a, b). The presence of crustal conductors in the shield areas has become more a rule than an exception. The reason for the conductive lower crust may be due to: (i) graphite mineralization (ii) water in the lower crust (iii) fractures, fissures

Table 1. Typical field values for station Dudura.

Period in sec	Apparent resistivity				Phase				Monovariate coherencies		Bivariate coherencies	
	RHO-xy	DRHO-Xy	RHO-Yx	DRHO-Yx	Phase xy	D Phase yx	Phase yx	D Phase yx	$E_x - H_y$	$E_y - H_x$	$H_x - H_y$	$E_x - E_y$
682.68	291.9	595.2	839.3	112.2	20.0	20.4	62.5	4.1	0.671	0.994	0.118	0.482
512.0	883.5	855.3	1019.1	168.3	47.2	22.8	61.3	5.0	0.915	0.992	0.112	0.754
341.3	389.6	312.0	1321.5	269.5	52.3	20.9	60.4	6.1	0.962	0.991	0.187	0.899
256.0	1287.3	995.6	1318.0	404.7	67.7	26.1	62.2	9.5	0.940	0.984	0.305	0.843
170.67	262.19	547.0	1605.9	184.5	41.5	43.3	63.8	3.6	0.733	0.980	0.191	0.763
128.0	1992.7	1234.8	1734.7	131.5	84.5	26.1	60.9	2.3	0.866	0.988	0.071	0.775
85.33	1485.3	276.9	1827.0	47.16	64.3	5.9	61.0	0.7	0.980	0.996	0.080	0.917
64.0	1575.7	260.6	2000.7	49.5	62.9	5.2	61.1	0.75	0.977	0.996	0.014	0.879
42.67	10212.5	3322.5	2248.8	85.0	—	—	59.2	1.1	0.524	0.987	0.177	0.225
32.0	—	—	2293.3	171.9	—	—	56.9	2.1	0.388	0.951	0.173	0.090
21.33	2634.7	254.10	2903.4	157.4	64.1	3.0	62.0	1.6	0.943	0.971	0.086	0.569
16.0	2791.4	524.0	2762.1	382.2	60.5	5.7	60.0	4.1	0.859	0.876	0.281	0.667
10.67	2089.1	1309.5	3673.8	463.3	57.1	17.8	59.0	3.7	0.894	0.969	0.363	0.870
8.0	3844.8	1466.3	2450.4	313.5	65.9	12.5	65.4	10.8	0.711	0.777	0.179	0.280
5.33	22610.9	20613.4	2226.6	2505.5	82.2	37.4	40.1	22.6	0.844	0.878	0.305	0.586
1.33	4521.1	977.4	6005.8	617.1	67.8	6.7	51.8	2.6	0.757	0.935	0.216	0.119
in Hz												
1.0	5603.0	900.1	6243.4	443.5	60.6	4.8	54.9	1.9	0.838	0.967	0.174	0.067
1.5	7162.0	929.2	8082.5	493.0	57.7	3.7	51.4	1.5	0.873	0.959	0.082	0.267
2.0	6483.8	1100.1	8560.8	639.5	55.4	4.7	50.3	1.88	0.780	0.944	0.119	0.166
3.0	7794.3	862.3	8694.7	474.0	57.8	3.2	43.3	1.18	0.779	0.931	0.087	0.173
4.0	8899.5	895.0	9252.60	558.5	54.0	2.5	38.6	1.1	0.808	0.915	0.038	0.215

Table 2. Typical field values for station Dari.

Period	Apparent resistivity				Phase				Monovariate coherencies		Bivariate coherencies			
	RHO-xy	DRHO-Xy	RHO-Yx	DRHO-Yx	Phase xy		D-Phase		Phase xy yx	D-Phase yx	E_x-H_y	E_y-H_x	H_x-H_y	E_x-E_y
					xy	yx	yx	yx						
341-33 s	1033.9	302.8	681.2	209.1	58.5	8.5	54.0	8.2	0.976	0.970	0.030	0.270		
256.00	444.5	1120.9	764.1	146.6	64.8	81.8	65.6	6.2	0.989	0.989	0.129	0.222		
170.67	785.4	1205.0	1096.5	301.8	79.6	61.0	64.1	8.83	0.782	0.978	0.687	0.692		
128.00	1418.5	1362.2	840.4	294.5	57.7	27.7	58.3	10.2	0.820	0.969	0.647	0.632		
85.33	2084.7	548.7	1227.9	145.9	65.8	8.8	62.1	3.6	0.930	0.986	0.313	0.348		
64.00	1850.2	1068.3	1450.6	291.1	75.5	21.8	63.5	6.3	0.934	0.989	0.801	0.841		
42.67	2562.4	412.4	1806.6	168.8	71.5	5.7	62.5	2.9	0.923	0.969	0.394	0.536		
32.00	3442.8	540.0	2171.3	222.9	69.1	5.4	64.1	3.2	0.980	0.965	0.426	0.571		
21.33	3887.5	744.2	2558.0	280.7	64.6	6.1	63.7	3.4	0.867	0.932	0.436	0.599		
16.00	2939.7	1303.0	2409.3	603.5	69.3	15.3	61.6	7.7	0.723	0.831	0.634	0.775		
10.67	3210.5	1911.8	2841.2	1350.7	58.6	17.4	61.0	14.5	0.893	0.898	0.601	0.657		
2.67	5556.2	1825.6	3872.9	770.2	59.2	9.7	60.9	6.0	0.712	0.872	0.066	0.257		
2.00	8391.9	2369.6	4721.2	746.8	56.3	7.9	61.1	4.8	0.884	0.924	0.103	0.436		
1.33	9247.1	1420.9	5595.7	580.80	58.4	4.4	57.1	2.9	0.849	0.905	0.148	0.491		
1.0 Hz	12580.4	1608.3	6556.1	645.0	57.5	3.6	56.5	2.7	0.876	0.914	0.138	0.416		
1.5	12259.5	1031.4	6721.2	384.3	52.6	2.2	55.6	1.5	0.868	0.928	0.115	0.341		
2.0	12773.3	983.6	7706.8	379.7	51.2	1.9	52.2	1.2	0.882	0.943	0.111	0.277		
3.0	14055.22	828.3	8598.1	331.1	48.7	1.4	48.3	0.9	0.877	0.939	0.201	0.298		
4.0	13255.1	819.0	8455.3	328.7	44.0	1.3	43.7	0.8	0.870	0.936	0.206	0.278

Figure 5. MT apparent resistivity (ρ_{xy}) and phase (ϕ_{xy}) vs time-period; location Dudura. Figure 6. MT apparent resistivity (ρ_{yx}) and phase (ϕ_{yx}) vs time period; location Dudura.

Figure 7. MT apparent resistivity (ρ_{xy}) and phase (ϕ_{xy}) vs time period; location Dari. Figure 8. MT apparent resistivity (ρ_{yx}) and phase (ϕ_{yx}) vs time period; Location Dari.

Figure 9. One-dimensional inversion model for ρ_{xy} (rotated clockwise 5°); true resistivity vs depth; location Dudura.

Figure 10. One-dimensional inversion model for ρ_{xx} (rotated clockwise 5°); true resistivity vs depth; location: Dudura.

1-D Inversion resistivity in ohm - m

Figure 11. One-dimensional inversion model for ρ_{xy} (rotated clockwise 15°): true resistivity vs depth; location Dari.

Figure 12. One-dimensional inversion model for ρ_{yx} (rotated clockwise 15°); true resistivity vs depth; location Dari.

and intergranular porosity of 0.1 to 0.01% (iv) partial melt pockets (v) hydrated minerals including clays and (vi) radiogenic heat. Adequate weightage can be given to three distinct possibilities in the absence of heat flow and deep seismic sounding data.

(i) Partial melt at the lower crustal depth at 8–9 kb pressure and about 500 to 600°C temperature is not expected unless the anomalous high heat flow supports the existence of partial melt. Practically no heat flow data of this region are available. Rao *et al* (1976) reported relatively high heat flow in the Singhbhum shear zone. Singh and Negi (1982) opined that the upper mantle temperature increases beneath the Indian shield as one goes towards the north from the peninsular gneisses in south India. They suggested the moho boundary to be 850°C to 950°C beneath the Singhbhum granite. This proposition is against the generally accepted idea that the mantle below the shield areas is cooler than those of the continental and oceanic upper mantle. However, opinions in favour of higher heat flow through the continental shield areas have been expressed by some (Verma *et al* 1966; Beck and Sass 1966; Sass *et al* 1968; Carte and Van Rooyen 1969; Jaeger 1970) and those in favour of colder upper mantle beneath the shield area have been expressed by others (Lee and Uyeda 1965; Polyak and Smirnov 1968; Haroi and Simmons 1969; Lachenbruch 1970; Lachenbruch and Bunker 1971).

The geothermal gradient below the granitic crust varies from 15° to 30°C per kilometer near the surface and decreases gradually with depth leading to the temperature of about 500 to 600°C near the moho boundary. Most of the cases granites grow in the crust itself by fractional crystallization of the basaltic magma which in turn originates from the pyrolyte partial melts in the upper mantle. One can, therefore, set 20 km arbitrarily as the unknown depth of the floor of the Singhbhum granite batholith (Turner and Verhoogen 1951) leaving room for the amphibolite/granulite facies rocks to occupy the lower crustal depth. Although gabbro and amphibolite melt at 650°C and 700°C respectively at 8 to 9 kb pressure, Wyllie (1977) showed experimentally that a little fraction of water can significantly reduce the melting point of the crust-mantle silicates. Shankland and Waff (1977) demonstrated experimentally that a small increase in melt fraction in a partially molten silicates can significantly increase its electrical conductivity. Therefore, the presence of partial melt in the conducting layers is a distinct possibility.

(ii) Reasonably good reports of the presence of water in the upper, lower crust and upper mantle are available in the papers by Hyndeman and Hyndeman (1968), Mitchell and Landisman (1971), Fyfe *et al* (1978), Shankland and Anders (1983) and Haak and Hutton (1986). Water can come to the upper and lower crust through fractures and fissures. However, the presence of water in the lower crust and upper mantle does not demand its percolation from the surface. Water can originate within the crust from (i) muscovite in the presence of quartz (ii) epidote minerals in the presence of quartz (iii) chlorite in the presence of K^+ and Al^{+++} ions (Mitchell and Landisman (1971) and (iv) CO_2 in the presence of methane ($CO_2 + CH_4 \rightarrow 2C + 2H_2O$ (Ballhaus and Stumpft (1985). Water can come from serpentines (Stesky and Brace (1973) and other hydrated minerals (Drury and Hyndeman 1979). Retrogressive metamorphism due to downward percolation of water in anhydrous acidic granulite leading to the formation of serpentines can also account for the increased conductivity. Therefore, the presence of water for one or more reasons in the crust and mantle as a continuous phase can explain the decrease in resistivity of the lower crust.

(iii) Alabi *et al* (1975), Garland (1975) and Sternberg and Clay (1977) have mentioned

that the electrical conductivity in the lower crust and upper mantle may be due to graphite mineralization. Diamond originates at a depth of 150 km at roughly 1400°C and 30 to 40 kb pressure at the base of the lithosphere. Its phase transition from diamond to graphite occurs at a rapid rate above 1000°C (Clifford and Kennedy 1982). The origin of carbon and water from carbon dioxide and methane in the upper mantle (Ballhaus and Stumpft (1985) and upliftment of the carbon either by carbon dioxide or by Kimberlite pipes give clues to argue that upper mantle and lower crust contain carbon in ppm. Duba and Shankland (1982) mentioned that even a few ppm of carbon either in amorphous or crystalline form can form an interconnected phase and can significantly increase the electrical conductivity. Since graphite is a highly conducting mineral, breaking of carbon dioxide to carbon and water in the presence of methane (Woermann *et al* 1985) can explain the enhanced electrical conductivity. Here, the contribution comes from both carbon and water. Some weightage can be given to the presence of sulphur (Stanley *et al* 1977; Olhoeft 1981; Jiracek *et al* 1983) and magnetic oxides (Stesky and Brace 1973; Shankland and Anders 1983; Haak and Hutton 1986) which can explain the enhanced electrical conductivity in the crust.

Figure 13 shows the depth of the moho and lithosphere asthenosphere boundary obtained on the basis of breaks in electrical conductivity using Schmucker algorithm for 1D inversion. Although Vanzijl (1978), Kurtz and Garland (1976) and Jones (1982a, b) have shown that electrical conductivity can detect the moho and lithosphere asthenosphere boundary, discontinuities in seismic velocity and electrical conductivities may not coincide in all cases. Therefore, we call the moho and LA boundary as electrical moho and electrical lithosphere asthenosphere boundary.

Thicknesses of the crust and lithosphere on the basis of 1D inversion of MT data and avoiding high skewness [$S = (Z_{xy} + Z_{yy}) / (Z_{xy} - Z_{yx})$] stations are found to vary between 23 and 45 km and 45 and 80 km respectively. 1D inversion for low skewness stations for optimum rotation of the MT tensors Z_{xy} and Z_{yx} is taken with certain confidence. Averages of the interpreted depths obtained from Z_{xy} and Z_{yx} are used in figure 11. Some of the reported lithospheric thicknesses are (i) Cantwell *et al* (1965)—60 km (ii) Turner and Verhoogen (1951)—60 km (iii) Windley (1977)—100–150 km (iv) Pollack and Chapman (1977)—45–300 km (v) Gass *et al* (1973)—50–100 km (vi) Adam (1980)—70–80 km (vii) Adam *et al* (1982b)—50–80 km (viii) Cox and Hart (1986)—80 km (ix) Negi *et al* (1987)—38–186 km (x) Datt and Batten (1988)—60–250 km. Pollack and Chapman (1977) prepared the global heat flow and lithospheric map on the basis of 12th degree harmonic plot of heat flow data. They have shown the heat flow near Singhbhum craton is 60 mWm^{-2} and lithospheric thickness of about 75 km. One heat flow data from copper belt thrust zone of Singhbhum area are available which is $54.5 \pm 5 \text{ mWm}^{-2}$ (Ravi Shankar 1988). Following Chapman and Pollack's (1977) diagram on continental heat flow versus lithospheric thickness, the thickness of the lithosphere is also estimated to be about 100 km.

The wavy nature of the moho and lithosphere asthenosphere boundary obtained by 1D inversion is assessed at the moment to be due to the 3D effect in 1D inversion. All stations with high skewness have given higher values of layer thicknesses.

Lithospheric thickness as low as 45 km needs verification from DSS and heat flow studies. Such low lithospheric thickness suggests hotter upper mantle and crust; (Rao *et al* 1976; Singh and Negi 1982).

The present investigation was carried out with a single site MT system without

remote reference facilities. DC dipole sounding or audiofrequency magnetotellurics are necessary to pick up information up to 10 to 15 km from the surface because MT signals up to 4 HZ frequency did not see the top 10 to 15 km of the granitic crust.

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