Delineation of Crustal Structure of Mahanadi Basin from Ground Magnetic Survey

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Abstract: Ground magnetic surveys were conducted over the Mahanadi basin covering an area of 21,000 km². Both total field and vertical field data were collected at 5 km interval, mainly to study the deeper regional features. Total field anomaly map prepared after correcting for the IGRF and external field variations, shows a combination of NE-SW, E-W, and NW-SE trends. To identify magnetic sources related to different depths, various transformations have been applied to the total field anomaly map. The second vertical derivative and downward continued map showed that the NE-SW and E-W trends are related to ridges and depressions of the coastal basin, implying that these are shallow features. The deeper features evidenced from upward continuation showed NW-SE trends. Thus, the Mahanadi delta is composed of two structural units associated with different tectonic events. These NW-SE trends may possibly be associated with the extension of Mahanadi graben underneath the coastal basin. The study reveals that the shallow NE-SW to E-W trends are superposed on the deeper NW-SE trends formed prior to the break-up of Gondwanaland, and the former trends resulted due to the dismemberment of Gondwanaland. A comparison with DSS studies conducted over Mahanadi delta and Lambert graben of East Antarctica showed that the deeper features can be correlated with an intracrustal layer related to a velocity of 6.4 km/s-6.6 km/s at an average depth of 6.5 km, seen in both the areas. Analysis of aeromagnetic data over Lambert graben of East Antarctica will help reconfirm our observation.

Keywords: Magnetic anomalies, Crustal structure, Mahanadi basin, Eastern Ghats, Lambert graben, Gondwanaland.

INTRODUCTION

The Eastern continental margin of India (ECMI), characterized by several sedimentary basins, evolved following the dismemberment of Gondwanaland in Mesozoic. These sedimentary basins were formed in Late Jurassic to Miocene as a result of the southeasterly drainage associated with the northward anticlockwise drift of India from southern latitudes to its present position. These basins were intracratonic, pull-apart type during their initial stage of formation, but later on became pericratonic. The common features in all the sedimentary basins in the East coast of India is the faulting of the Precambrian basement which led to basin subsidence along down-to-basement faults (Sastri et al. 1974). The sedimentary fill in these basins, ranging in age from Jurassic to Pliocene, includes deltaic transitional marine sediments, carbonates, clastics etc. In order to throw light on the evolution of ECMI and hence to reconstruct the Gondwanaland, knowledge of the structure, tectonics and sedimentation history of these sedimentary basins plays a vital role.

The Mahanadi basin is the northernmost of the four major sedimentary basins in Peninsular India, the others being Cauvery, Palar, Krishna-Godavari. Mahanadi basin is contiguous with the West Bengal basin. These basins together constitute the ECMI. Being petroliferous, the Mahanadi basin has assumed considerable importance in recent years. This basin is a pericratonic, rifted basin developed around one of the triple junctions (East coast of India, Mahanadi graben and Lambert graben) along the East coast of India (Chowdhary and Tripathy, 1996). Compared with other basins in the ECMI, the Mahanadi basin is less studied, and has little data on the regional tectonic elements. As a part of the programme to study the structure and tectonics of the sedimentary basins of India, the Indian Institute of Geomagnetism carried out a ground magnetic survey over the Mahanadi basin. Particular emphasis was laid on studies of basins covering the ECMI. A survey was conducted over Krishna-Godavari basin and the results were very exciting. In the Krishna-Godavari basin, we were able to isolate the NW-SE trends extending below the coastal basin for the first time from the analysis of ground magnetic anomalies (Rajaram et al.
The Mahanadi basin has also a similar kind of tectonic set up. Therefore, the main aim of this study is to separate out the sources at different levels responsible for the anomalies and to throw light on the tectonic evolution of the basin. Also, an attempt has been made to look into the deeper tectonics in order to analyze the presence of cross trends, if any, and their role in the evolution of the basin.

The ground magnetic survey commenced in the first week of October 1999 and was abruptly terminated due to the disastrous cyclone that hit Orissa coast on 29th October. We dedicate this paper to all the people who lost their lives, shelter etc. in that cataclysmal cyclone.

GEOPHYSICAL BACKGROUND

Mahanadi basin, lying between 19.5° and 21° N and 85.5° & 87° E, covers an area of 50,000 sq km of which nearly one fourth is in the onshore and rest in the offshore. The onshore basin covers the Mahanadi delta lying in Orissa State. Figure 1 compiled from Verma (1991) and Fuloria (1993) show the geology and tectonics of the area. A major part of the Mahanadi onshore basin is covered with alluvium. Towards the west of the basin, vast tracts of granites, kholondals and anorthosites are exposed. These exposures strike in NE-SW or ENE-WSW and belong to the Eastern Ghat Group. The Lower Gondwana sediments occur to the northwest of Athgarh. The Upper Gondwana sediments are seen as detached outcrops closer to the coast between Cuttak and Bhubaneswar.

On the basis of available geological/geophysical evidences, Baishya and Singh (1986) divided the Mahanadi delta into a series of ENE striking depressions and ridges. These include the Cuttack depression and Paradeep depression, separated by the Bhubaneswar ridge. Further south is the Puri depression separated from Paradeep depression by the Nimapara uplift. Herst and graben structures leading to subsidence followed by uplift were formed in the basin due to tensional forces in the Late Jurassic (Sastri et al. 1974). Late Carboniferous to Triassic sedimentation in this Paleoicoic rift is fluvial and continental in nature. Early Cretaceous marine transgression facilitated maximum sedimentation in the basin. A deep well drilled (Tewari, 1998), in the Cuttack depression shows Quaternary to Early Miocene sediments to a depth of ~850 m, followed by Early Cretaceous volcanics (~100 m thick), and sediments (~950 m thick) up to the drilled depth of 2992 m. The crystalline basement has not been penetrated.

The continental basement is traversed by a number of major faults having ENE-WSW, NNE-SSW and NNW-SSE trends. It appears that those having ENE-WSW trend had the maximum influence on the basin formation and its configuration. These faults parallel to the present day coastline divided the basin into several ridges and depressions. The NNE-SSE trending faults divide the basin into transverse blocks. Genetically the transverse faults, according to Fuloria (1993), are older than the longitudinal faults.

METHODOLOGY

The survey area lies between latitude range of 19.5° and 21° N and longitude range of 85° and 87° E, covering a total area of 21,000 sq km. This includes the whole of Mahanadi basin and the adjoining Eastern Ghat Mobile Belt. A small part in the northeastern portion (20.5° to 21° N and 86.58° to 86.95° E) was left out, since the survey was discontinued due to the cyclone disaster. Proton precession magnetometer was used to measure total field (P). The measurements were taken at an interval of 5 km and were dictated by the access to roads. At each observation point, ten to twelve readings were taken and the average value computed. A total of 280 observation points covered the area. Data distribution is superposed on Fig.2. Some of the data gaps are due to inaccessible hilly and marshy terrain. Magnetic observatory at Hyderabad (17.7° N; 83.35° E) served as the base station, where the magnetic elements (H, Z, D) are continuously monitored for the purpose of reduction of data.

Anomaly Map Preparation

The observed total field (F) values contain contributions from the main core field, the crustal field and the external current systems. Hence, to isolate the crustal anomaly, we need to remove the contributions due to the main core field and the external current systems. IGRF-1995 (IAGA, 1996) was used to represent the main field at each observation point. For the representation of the external field variations, the magnetograms of Hyderabad Observatory, corresponding to survey period was used. The variation in H and Z values due to external field was obtained from the magnetograms for the events corresponding to the date and time of recording done at field. In our experience of working with coarse data spacing ground surveys and aeromagnetic data over Peninsular India up to 17° N, we have found that the two data sets, when gridded with the same grid interval, match reasonably well. For the Krishna-Godavari basin, Rajaram et al. (2000a) showed that ground data can be supplemented with aeromagnetic data. Therefore, the small part left out due to disaster was filled with aeromagnetic data. Data over the uncovered small part of the area was filled up from the aeromagnetic map of Babu Rao et al.
(1982) that was reproduced by Mishra et al. (1984) and redigitized at 5 km interval. A total of 65 data points have been incorporated into the ground map. The published aeromagnetic map was not corrected for variations due to the main core field. We, therefore, corrected this data using IGRF coefficients, before incorporating into our map. The combination of the ground and aeromagnetic anomaly values was gridded using a 5 km X 5 km grid, since the data were random. The gridded anomaly values were plotted against the latitude and longitude to obtain the total field anomaly map (Fig.2). It may be added that the inclusion of the aeromagnetic data did not bring about any major changes in the general character of the map.

Map Analysis

The total field anomaly map (Fig.2) represents a mixture of short and long wavelength anomalies with amplitude ranging from -250 to 600 nT with a combination of NW-SE, NE-SW and EW trends. The sediments of about 3 km thickness above the basement are likely to be non-magnetic and therefore, the magnetic anomalies may reflect the basement topography. As the magnetic latitude of the Mahanadi basin is around 20° N, the magnetic highs do not directly correspond to the basement highs and vice versa. The NW-SE trending high amplitude long wavelength anomaly (H1) on the northwestern part of the anomaly map falls on the crystallines. This anomaly is evident in the gravity anomaly as well and interpreted as due to the outcrops of khondalites seen in this area (Verma, 1991). Another high amplitude medium wavelength anomaly (H2), seen to the north of Jaganathpur trending in E-W direction, when compared with the geology and tectonic map of the region, falls on the eastern end of the Cuttak-Chandbali depression. It may probably reflect a change in lithology in this region. No other major long wavelength anomalies are observed in the anomaly map. Several short wavelength anomalies are observed. The anomaly to the northwest of Chilka Lake may be probably due to the anorthosite exposures in that region.
The other short wavelength high amplitude anomalies may be possibly due to subsurface anorthosite intrusives. Other anomalies seen in the total field cannot be correlated with the known surface geology. The khondalite exposures do not show any prominent magnetic anomalies, probably due to their low susceptibility, as reported by the measurements of Subrahmanyan and Verma (1981).

**DATA TRANSFORMATION**

Transformation operations tend to enhance certain characteristics of the source that help in understanding the nature of the source (Blakely, 1995). The crustal magnetic anomalies represented at any point contain contributions from an ensemble of sources going right up to the depth of the Curie isotherm (Rajaram et al. 2000b). The isolation of the contribution from different sources gives a better understanding of the distribution of magnetic materials with depth. The varying amplitudes and wavelengths seen on the anomaly map of the total field data (Fig.2) can be from magnetic sources at different depths. Hence to isolate the sources responsible for these trends vis-a-vis the depth, the anomaly map was subjected to various transformations. To get an idea of the sources at relatively shallow depths, the total field magnetic anomaly map has been subjected to second vertical derivative and downward continuation; and for regional structures, upward continuation has been done. All the programmes used for transformations were adopted from Blakely (1995) and the results rechecked using Geosoft (1999) software. Since these transformations take resort to Fourier domain, precautions were taken to pad the data wherever necessary.

The second vertical derivative map (Fig. 3) of the total field anomaly map that enhances the shallow sources, show NE-SW to ENE-WSW trends. These trends are in conformity with the rock exposures on the western side of the study area belonging to Eastern Ghat Group as well as the trend of the ridges and depressions in the sedimentary basin.

![Fig.3. Second vertical derivative map, showing the NE-SW to EW trends associated with shallow features. Contour interval 50 nT/sq.km.](JOUR.GEOL.SOC.INDIA, VOL. 60, SEPT. 2002)
The anomalies associated with the anorthosite exposures are evident in the derivative map. The thick band of contours running NE-SW from north of Chilka Lake to south of Kabadabanda is the fault limiting the basin to the west—the basin margin fault. This fault was not delineated by gravity studies and geologically the contact is further to the west (Fig.1). The high amplitude anomaly (H2) falling on the eastern side of Cuttak-Chandbali depression appears in this map suggesting shallow sources. The NW-SE high amplitude long wavelength anomaly (H1) on the northwestern side of the anomaly map (Fig.2) is not evident, indicating deeper source and not due to the exposed kholaldites, as evidenced from the Bouguer anomaly map (Verma, 1991). The anomaly map continued downwards (Fig.4) to different levels also showed the same features as the second vertical derivative map. The anomaly values start oscillating beyond 2.5 km suggesting it as average depth to the shallow sources.

The maps are continued upwards to different levels to enhance the long wavelength anomalies. Figure 5 represents the anomaly map continued to 10 km above mean sea level. The transformed anomaly map shows NW-SE trends. The NE-SW and EW trends evident on the total field anomaly map (Fig.2) are not apparent in the continuation map. These can possibly be the cross faults that divide the basin into transverse blocks as discussed by Fuloria (1993). On comparison with the regional geology and tectonic map, it was found that this trend can possibly be the extension of the Mahanadi graben underneath the Mahanadi delta. Lower Gondwana sediments are exposed on the northwestern part of the study area (Fig.1). The high amplitude EW anomaly north of Jaganathpur is not evident in the upward continued map, suggesting a shallow source.

**DISCUSSION**

The total field anomaly map and its transformations give a general idea about the distribution of magnetic sources in and around the Mahanadi delta. The NE-SW and the EW trends are shallow and are superposed on the much deeper
NW-SE trends. This is supported by the results of Fuloria (1993) that the NNW-SSE trending transverse faults are older than the NE-SW trending longitudinal faults. Analysis of the onshore and offshore aeromagnetic data by Babu Rao et al. (1982) identified three distinct belts characterized by different magnetic anomaly patterns as reported by Mahadevan (1994). A comparison with Bouguer anomaly map reproduced by Verma (1991) shows that although the ridges and depressions of the coastal basin are clearly brought out by the gravity anomaly map, there is hardly any reflection of the NW-SE structure so clearly visible in the magnetic total field anomaly map. This implies that the change in density between various depth layers is smaller when compared with the change in susceptibility associated with the structures. The shallow NE-SW trends are trends associated with the Eastern Ghat orogeny and these have played a vital role in the evolution of the coastal Mahanadi basin, as in Krishna-Godavari basin (Rajaram et al. 2000a). The Eastern Ghat Group formed the basement for the deposition of sediments in the basin. Integrated results of gravity, magnetic and DSS throw light on the fact that the basement below the sediments is granites/gneisses and not khondalites. The deeper NW-SE trends, when compared with the regional geology and tectonic map, appear to coincide with the Mahanadi graben of the pre-Gondwana period. Lower Gondwana exposures are seen northwest of Athgarh (Fig.1). While the NE-SW and EW trends are the result of rifting and drifting of India from Antarctica, the NW-SE trends are formed prior to the break up of Gondwanaland. From our studies, it appears that in this part of the ECMI the Eastern Ghats have possibly been reactivated and are thrust over the Mahanadi graben.

Correlation with DSS Studies

Three DSS profiles by NGRI shot across the Mahanadi delta, east of longitude 81.5° covering buried Gondwana and coastal sedimentary basins (Kaila et al. 1987) provided data on the nature of the crust beneath the delta. The location
of the profiles (I,II,III) is superposed on the upward continuation map (Fig.4). Crustal velocity model of profile I shows P-wave velocity of 5.9 km/s at 1.1 km, probably representing the granitic basement. The velocity jump to 6.45 km/s at around 6 km was inferred to be a change in velocity within the granitic layer, while the velocity of 7.1 km/s and 8.1 km/s is respectively correlated with Conrad (20.5 km) and Moho (34.5 km). The other profiles differ from profile-I only at shallow depths up to the basement. Three markers A,B and C are delineated in all the three profiles at an average depth of 6 km, 12 km and 20 km respectively. The reflector A, associated with the velocity jump from 5.9 km/s to 6.45 km/s at an average depth of 6 km, was attributed to a change in composition of the basement, which may vary from granitic to charnockitic, gabbroic or anorthositic. From the DSS studies, the extent and trend of this reflector are not identified. It can be seen that the reflector A falls well within the limit of the NW-SE trending structure obtained from the upward continued map. Also, a change in basement from granitic to either charnockitic, gabbroic or anorthositic will depict a magnetic signature. Thus, it is inferred that the deeper NW-SE trends obtained from the present study corroborate well with reflector A deduced from DSS studies. This may possibly be the extension of the older tectonic elements beneath the coastal basin. DSS studies conducted over the Lambert Glacier (Fedorov et al. 1982) in East Antarctica, also show a velocity structure (6.4 km/s - 6.6 km/s), at a depth of around 5 8 km, which may be related to the marker A observed in Mahanadi basin. The DSS results are consistent with the Lambert graben in the MacRobertson Land of East Antarctica, having been a part of Mahanadi graben prior to the breakup of Gondwana land. Unfortunately, there are no published results of the magnetic studies over East Antarctica to correlate with our studies. Aeromagnetic studies over East Antarctica would provide very valuable information in this context. Thus, a combination of magnetic data together with other geophysical data like the seismic, gravity etc could go a long way to help build the tectonic evolution of the plates.

SUMMARY

We find that the Mahanadi basin is made up of two structural domains, from the analysis of magnetic data. The ridges and depressions forming the coastal Mahanadi basin having NE-SW to ENE-WSW trends are shallow features that are superposed on deeper NW-SE features. The shallow features reflect the Eastern Ghat structural trend and hence the Eastern Ghat Group underlies the alluvial covered area of the Mahanadi delta. The khondalites, one of the main units of the Eastern Ghat Group, do not give rise to noticeable magnetic response, possibly due to their low susceptibilities, also evidenced in the South Indian shield (Harikumar et al. 2000; Subrahmanyan and Verma, 1981). Hence we believe that the granites and gneisses of the Eastern Ghat Group underlie the alluvium covered areas of the coastal basin.

The deeper NW-SE feature corresponds well with Marker A deciphered from DSS studies over Mahanadi basin, and this can possibly be the extension of Mahanadi graben into the offshore underneath the coastal basin. Therefore, it appears that in this part of the Eastern continental margin of India, the Eastern Ghats have possibly been reactivated and are thrust over the Mahanadi graben. This expression of deep features gives further support to the theory that prior to the breakup of Gondwanaland, the Son-Mahanadi graben of Peninsular India was contiguous with the Lambert graben of East Antarctica (Fedorov et al. 1982).

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