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APPLICATION OF SPECTRAL ANALYSIS TO DETERMINE THE MAGNETIC SOURCE DEPTHS IN IBARAPA DISTRICT, OYO STATE, SW NIGERIA

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ABSTRACT

The method of spectral analysis was applied to the total aeromagnetic intensity data covering the district of Ibapara, located on the Nigeria Basement Complex in Oyo State, SW Nigeria. Prior to the spectral analysis, inclined magnetisation was converted to vertical, reduced to the pole and filtered out in order to more correctly reflect spatial location and morphology of magnetic sources over geological bodies, and enhance the effects of shallower sources over deeper ones. The data was divided into blocks and sub-blocks, and was spectrally analysed for the depths to the deep- and shallow-seated magnetic sources. The Curie-point-depths computed from these depths vary between 20.8 and 32.73 km, indicating that the magnetized basement rocks are at different elevations and are probably block faulted. The correlation of shallow Curie-point-depth with the Older Granites inferred that the low Curie-point-depth is due to magmatic intrusion in the highly deformed migmatite unit, the main geologic unit. The surface heat flows derived from the Curie-point-depths vary between 40.82 and 62.84 with a mean of 50.10 mW m^{-2}, with areas having high surface heat flow presumed to be areas of recent intrusions where the elevated heat has transformed appropriate minerals to sapphire, tourmaline and aquamarine. Correlations of the surface heat flows and the average geothermal gradients on one hand and the Curie-point-depth on the other, unlike global compilation, yielded close empirical relations that are attributed to homogeneous geology of the area.

KEYWORDS: Magnetised Basement, Curie-point–depth, Geothermal Gradient, Surface Heat Flow

INTRODUCTION

The Ibarapa District, Oyo State, SW Nigeria, extends over three Local Governments Areas, namely, the Ibarapa East, the Ibarapa Central and the Ibarapa West Local Governments as well as the part of Ido Local Government Area. This area falls within 7^o 41” 59.9’ to 7^o 27” N and 3^o 22” 35’ to 3^o 48” 21.8’ E, covering an approximate surface area of 1,330.853 km^2 (Fig. 1).
The geomagnetic method is a non-invasive exploration method that has a wide range of applications in engineering and environmental studies ranging from locating voids, metal containers and other concealed masses, to mapping dikes, faults and fractures that act as conduits for ground water flow. Aeromagnetic survey maps the variation in geomagnetic field, which in turn reflects the changes in the magnetic minerals in the subsurface rocks. Magnetic minerals can be mapped from the surface to great depths in crustal rocks depending on dimension, shape, and the magnetic property of the rock.

This research was carried out with the aim of determining the subsurface depth to source of magnetic anomalies by analysing the spectrum of the magnetic field computed using Oasis Montaj® software. It is hoped that the analysis will highlight the basement relief and morphology as well as delineate the geologic structures associated with the rocks underlying the area. It also hopes to determine the curie depth of the area and hence estimate the geothermal gradient and the surface heat flow.

GEOLOGY

The Ibarapa area is situated on the Nigerian basement complex. The complex forms a part of the Pan-African mobile belt, and lies between the West African and Congo Cratons and south of the Tuareg Shield (Black, 1980; Obaje, 2009). The area is metamorphic terrain dominated by migmatite-gneiss, which appears to be the oldest unit from field relations. There are the occurrences of amphibolite schist and biotite granite-gneiss, with quartzo-feldsparthic veins occurring as

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near-linear intrusions (Fig 1).
Migmatite–gneiss rocks form about 90 % of the outcrops, and are at some locations fractured and weathered. They are affected by exfoliation process resulting in screens or talus at the base of the outcrops. The outcrops are also characterised by pegmatitic intrusions and quartz veins, as well as by fractures and faults. Foliation, lineation and migmatitic structures which include folds of various kinds were also observed. The general orientation of the rocks is NE-SW with moderate dip. Minerals are separated into light and dark bands with the light bands being feldspars and quartz while the darker bands contain biotite-mica, muscovite-mica and hornblende. The micaceous minerals produce a shiny surface on hand specimen and are medium to coarse grain and hard but tends to split along the plane of foliation (Abraham et al., 2014). Biotite-granite gneiss that make up 4 % of the outcrops are restricted to the western part of the area, and trends nearly N-S. It is characterized by sink holes probably resulting from differential chemical weathering. The outcrops are low lying in most places but may be ridged and domed in few places. It is light in colour except where it is dominated by mafic alternations.
The schists form extensive bodies characterized by preponderance of quartz rubbles and disaggregated mica sheets over the eastern part of the area. They are white to light grey in colour, coarse grained with large crystals of quartz and large intergranular muscovite plates. They also largely pelitic and contain very little feldspathic minerals. They display well-defined schistosity that makes them easily split, and contain mica flakes distributed in wavy lines which alternately meet and separate into sheets. In hand specimen, the schists are light in colour, fine-to-medium grain and consist of plagioclase, quartz, muscovite, biotite, epidote, chlorite and opaque minerals.

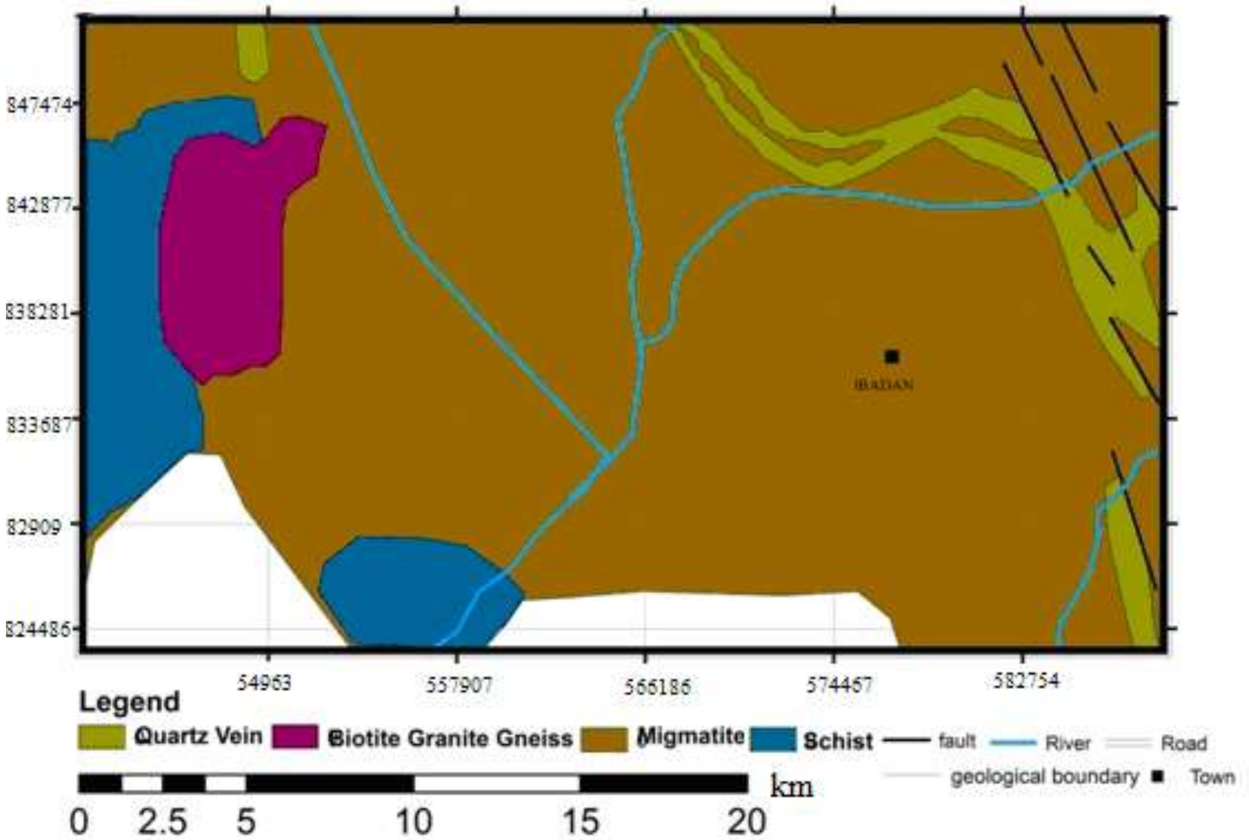


Fig. 1. Geologic map of study area.

Quartz veins that may be up to two feet in thickness and many tens of feet in length filled fractures of the dominant migmatite-gneiss unit. These are predominant in the western part of the area, and are believed to have formed by metamorphic differentiation that operated according to the concretion and solution principles. They appear as simple, clean cut bands or they grade into highly irregular and anatomising vein-complexes, some of which are sharp, straight veins while others are curved, folded, irregular, lenticular or pod-like. All the lithologies have appreciable contents of the elements aluminium, iron, magnesium, sodium, lithium, or potassium in variable proportions, and give magnetic susceptibilities that ranges from high to low.
Several fold types are observed, particularly on the migmatites, where they are commonly observed on the top of the outcrops and having different thickness. The quartz veins, suspected to belong to different ages, are also intensely folded, with the folds being of uniform thickness at crest, limb and trough. The rocks are also fractured, with a few sinistral strike-slip faults with the fault planes filled with felsic materials localized on outcrops and striking at angles of 120^{o}. Other micro faults strikes are observed at various angles (Ibrahim et al., 2015). Aquamarine, tourmaline and sapphire gemstones were found in veins and in disseminated pegmatitic bodies (Musbau, 2014).
Although migmatite–gneiss, biotite-granite gneiss and schists form the main basement outcrops, the study area is mostly covered by laterite and sands of thicknesses ranging from 0 to 100 m derived from the weathered basement (Adabanija et al., 2013). These

basement covers include minerals with appreciable susceptibility (Adagunodo et al., 2018) that registers on high resolution aeromagnetic data (Olasunkanmi, et al., 2018).

DATA COLLECTION AND PROCESSING

The total magnetic intensity (TMI) data over the district was obtained from Nigerian Geological Survey Agency, NGSA in digital form. The data was collected between 2003 and 2009 by Fugro Airborne Surveys® using Scintrex CS3 caesium vapour magnetometer with a resolution of 0.01 nT flown at 500 m line spacing and 5000 m tie-line spacing, and a terrain clearance 80 m. To convert inclined to vertical magnetisation so as to reflect the information of the spatial location and morphology of magnetic geological body, the gridded data was reduced to the pole, using the method of Silva (1986), and assuming a declination of -3o and an inclination of -10o for the area. The data was also filtered out to enhance the effects of shallower sources over deeper ones in line with Xu et al. (2009), including removing diurnal magnetic variations as well as the regional field.

The resulting residual data was first divided into four 50 by 50 km blocks and then into sixteen 25 by 25 km sub-blocks that overlap in line with Haln et al., (1976) for the purpose of spectral analyses that involved the Fourier transformation of the residual data and the computation of its energy spectrum using the Oasis Montaj® v6.3 software. Slopes of straight line segments fitted to the plots of the logarithms of the energy spectrum against wave number yielded depths of deep-seated, Z_o, and shallow-seated, Z_1, magnetic sources in the blocks in line with Byerly and Stolt (1977) and Onwuemesi (1997). The Curie point depth, Z_b for each block was subsequently computed as $2Z_0$-Z_1 (Table 1). Assuming a Curie point temperature of 580 °C, a surface temperature of 27 ^oC and a thermal conductivity of 2.5 W m^{-1} $°C^{-1}$, the average geothermal gradient and the heat flow in each block (Table 1) were computed from the Fourier law (Tanaka *et al*., 1999).

RESULTS AND DISCUSSIONS

The residual magnetic intensity map, (Fig. 2) broadly separates the study area into two, namely larger areas with intensities in the range of -113.4 to 24.7 nT and coloured blue to green that are interpreted to have low magnetisations, and smaller areas with intensities in the range of 24.7 to 147.5 nT and coloured yellow to purple that are interpreted to have high magnetisation. The higher magnetised areas suggest elevated presence of magnetite, and thus give suggestions on structures for possible mineral or ore emplacement.

The Curie Point Depth, CPD, Z_b, gives the average depth of the magnetic sources within an area, and its variations give indication of the possible heat flow pattern. Z_b in the study area vary between 20.8 and 32.73 km, and Fig. 3a gives the map view. It shows that Z_b in the area is undulating, indicating that the magnetized basement rocks are at different elevations in the subsurface, probably block faulted, and that the tectonic regime in the area is non-uniform. Shallow Z_b are correlated with Older Granite unit spotted in that region. This peculiar observation helps in inferring that the low CPD at the area is due to magmatic intrusion in the highly deformed migmatite unit. Hence the deep CPD in the eastern and in the western part of the study area could be a result of a thick crust and hence shallow basement depth. The CPD obtained was used to construct Curie isotherm map. This reflects the thicknesses of magnetic crust which indicate that, curie point is undulating under the study area. The average geothermal gradient in the study area, varies between 16.33 and 25.14 and has a mean of 20.04 ^oC km^{-1}.

Fig. 3b shows the map view of the surface heat flow, *SHF*, of the study area. It exhibits similar trends to map of the CPD, decreasing from the northeastern part toward the southwest. The areas with high *SHF* are presumed areas of recent intrusions where the elevated heat has resulted in the transformation of such minerals as sapphire, tourmaline and aquamarine occurs. Elevated heat has been attributed to bring about electron transfer between Fe^{2+} and Ti^{4+} when the two occupy the adjacent sides of the corundum crystal (Feral, 2009) to form Fe^{3+} and Ti^{3+} to transform it to the coveted blue from the black colour and decreases its magnetic susceptibility.

Because heat flow measurements are few or totally unavailable for many locations, including the study area, CPD-derived *SHF* provides alternatives. *SHF* in the area varies between 40.82 and 62.84 with a mean of 50.10 mW m^{-2}. Measurements from two sites on the West African shield in the Republic of Niger (Chapman and Pollack, 1974) have yielded values of 18 ± 2 and 22 ± 2 mW m^{-2} while measurements from the Ririwai ring complex, Nigeria, also on the West African shield yielded a value of 38.55 ± 1.68 mW m^{-2} (Verheijen and Ajakaiye, 1979). Comparatively therefore, the CPD-derived *SHF* in the study area are within the range of measured *SHF* values in the surrounding basements areas. CPD-derived *SHF* values of 122 – 333.052 mWm^{-2} from the Ankpa – Nsukka area, Lower Benue Trough, Nigeria (Udegbe et al., 2017), 393.875 – 1114.919 mWm^{-2} from the Garkida area and environs, NE Nigeria (Nur et al., 2011), 157.281 – 606.360 mWm^{-2} from the Central Benue Trough (Ibiene et al., 2019) and 470.238 to 1181.624 mWm^{-2} from Kebbi State, Nigeria (Taufiq et al., 2014), although from sedimentary, rather than, basement areas, are far outside the range expected *SHF*. Similarly, out of the expected range are values of 157.281 to 606.360 mWm^{-2} from basement area in the Cameroon (Mono et al., 2018). We suspect the CPDs in these studies have been overestimated. The CPD-derived *SHF* values of 63.82 to 141.88 mWm^{-2} from Guzabure and its environs, Chad Basin, NE Nigeria (Nwobodo et al., 2018) and 72.24 to 136.43 mWm^{-2} from Gubio, also in the Chad Basin, NE Nigeria (Dimgba et al., 2020) fall within the range reported by Ali and Onuoha (2017), and the CPDs are therefore viewed to be reasonable.

The relationship between the surface heat flow, *SHF*, and the CPD, Z_b, has been analytically indicated to depend not only on the Z_b, but also on the average thermal conductivity of the near surface rocks, *K*, their radioactive heat generation, H_0, and the characteristic drop-off depth of heat production, h_r, as well as on the surface temperature, T_0 and the Curie temperature, T_c, (Wang and Li, 2013), and is given as:

$$SHF = K\frac{T_c - T_o}{Z_b - Z_o} + {h_r}^2 H_o \frac{e^{-Z_b/h_r} - e^{-Z_o/h_r}}{Z_b - Z_o} + h_r H_o e^{-Z_o/h_r} \quad \ldots (1)$$

A correlation of the global compilation of the *SHF* from both continental and oceanic magnetic data against Z_b (Li et al. 2017) revealed scattering that is attributed to the diverse geological backgrounds and local structures, but which nevertheless gives good correlation for thermal conductivity values of 2.5 and 2.0 W $m^{-1}\ {}^{o}C^{-1}$ for the continentals and oceanic environments respectively. The plots of Z_b versus the *SHF*, and the average geothermal gradient, (Fig.4) however yielded close empirical binomial relations given as:

$$SHF = 157.08 - 5.8705Z_b + 0.0722Z_b{}^2 \text{........ (2)}$$

and

$$dT/dZ = 62.832 - 2.3482Z_b + 0.0289Z_b{}^2 \text{... (3)}$$

This attributed to the limited data and fairly homogeneous geologic environment from which the data is drawn as opposed to the global data. The result for the northern edge of the Congo Craton that lies in the central-east area of Cameroon (Mono et al., 2018) also exhibited similar close relationship between the three parameters. Similar close relations between Z_b on one hand and surface heat flow (*SHF*) and geothermal gradient (*dT/dZ*) on the other could also be deduced from Greece (Tselentis, 1991), Albania (Stampolidis, et al. 2005), Garkida and environs, NE Nigeria (Nur et al., 2011), Kebbi State, Nigeria (Taufiq et al., 2014), Ankpa and Nsukka areas of Lower Benue Trough, Nigeria (Udegbe et al., 2017), Central Benue Trough (Ibiene et al., 2019), Sokoto Basin, NW Nigeria (Ezekiel, 2019) and Guzabure and its environs (Nwobodo et al., 2018) and Gubio (Dimgba et al., 2020) both in the Chad Basin, NE Nigeria. All these are from limited and fairly homogeneous geologic environments. Results of a study from the Yunnan Province and adjacent areas (Wen et al., 2019), although from a limited and fairly homogeneous geologic environment, produced similar scattering as the global compilation.

CONCLUSION

The application of spectral analysis to the aeromagnetic data from the Ibapara District of Oyo State, SW Nigeria to investigate the basement relief and morphology and delineate geologic structures revealed that the Curie-point-depth, Z_b, is undulating, indicating that the magnetized basement rocks are at different elevations in the subsurface, probably block faulted, and that the tectonic regime in the area is non-uniform. Estimated surface heat flow, *SHF*, are within the range of values from the surrounding basements areas, and the map view exhibits similar trends to the map of Z_b. Areas of high heat flow correlated with areas of recent intrusions where the elevated heat has resulted in the transformations of gems such as sapphire, tourmaline and aquamarine. Plots of Z_b versus the *SHF*, and the average geothermal gradient, unlike global compilation, yielded close empirical relations that are attributed to homogeneous geology of the area. Similar close relations are also predicted for many other localities both within and around Nigeria and in other international area. Estimated surface heat flow, *SHF*, are within the range of values from the surrounding basements areas, and the map view exhibits similar trends to the map of Z_b. Areas of high heat flow correlated with areas of recent intrusions where the elevated heat has resulted in the transformations of gems such as sapphire, tourmaline and aquamarine. Plots of Z_b versus the *SHF*, and the average geothermal gradient, unlike global compilation, yielded close empirical relations that are attributed to homogeneous geology of the area. Similar close relations are also predicted for many other localities both within and around Nigeria and in other international area.

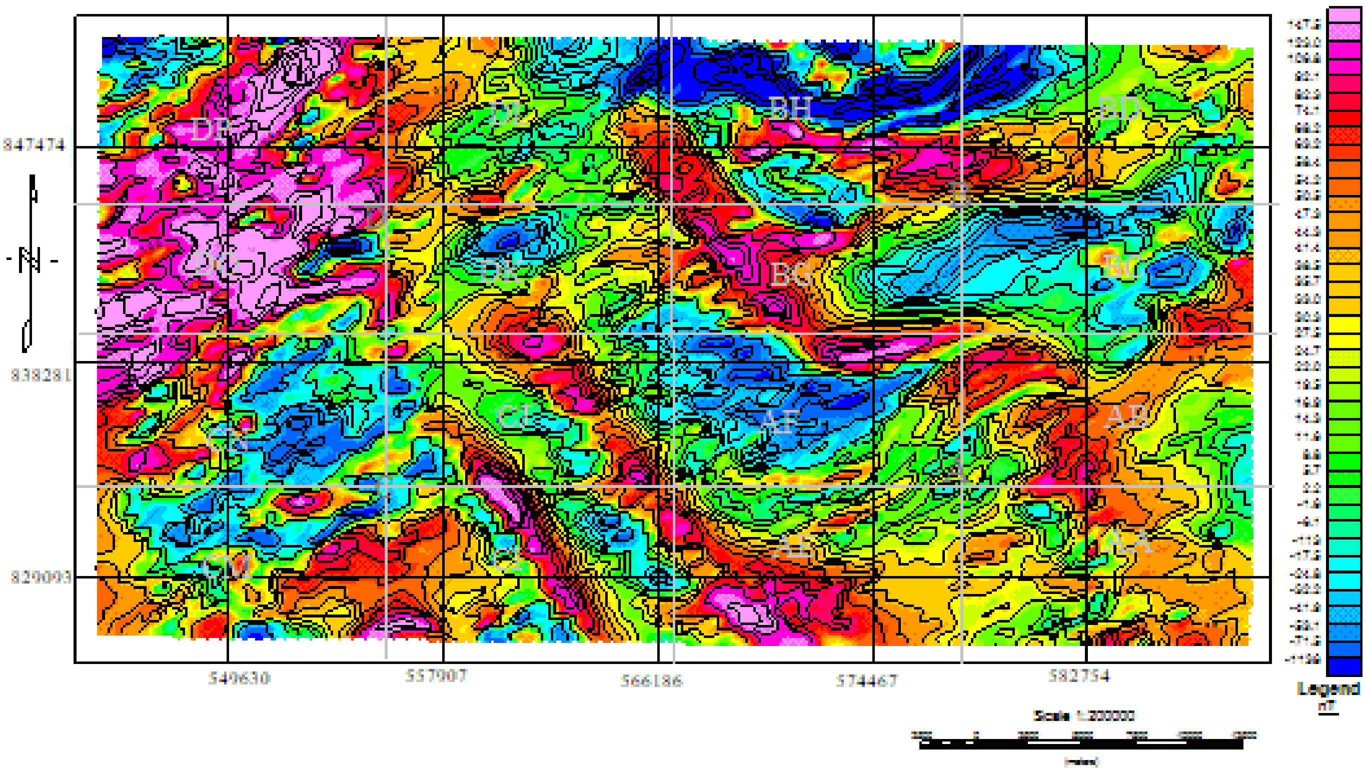
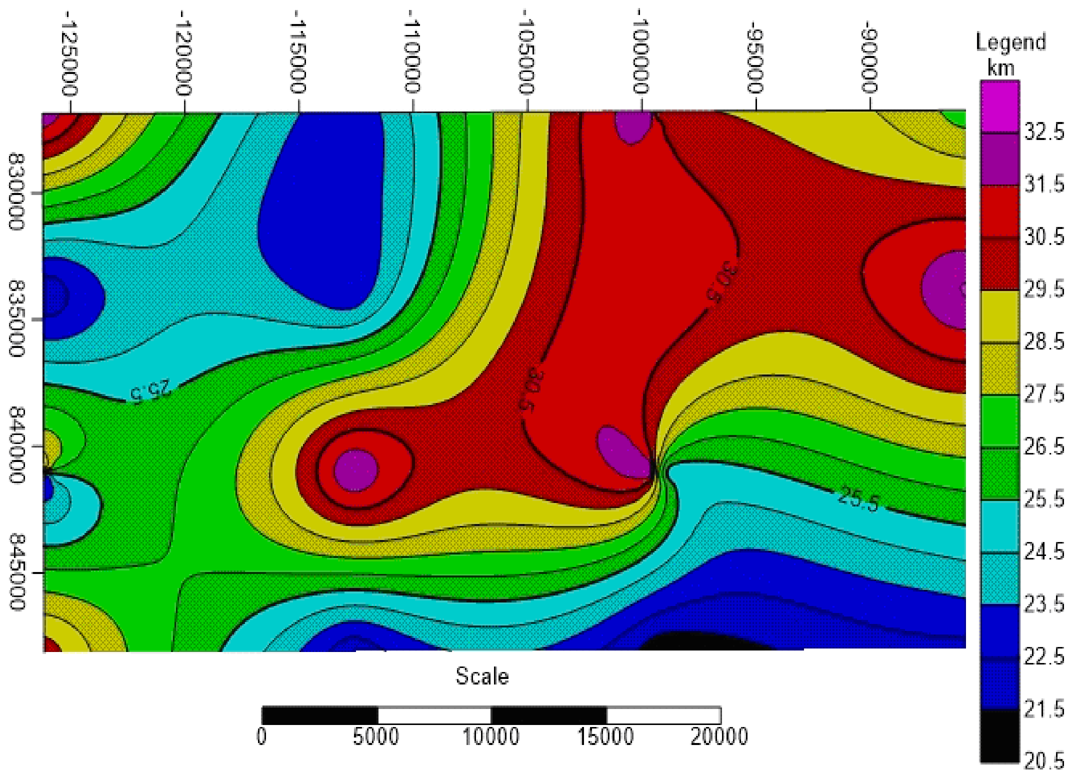


Fig. 2. Residual TMI map of the Ibapara area, Light gray lines and letters indicate data blocks and sub-blocks.

Table 1. Depths to deep, Z_0, and shallow, Z_1, magnetic sources, and Curie point, Z_b, geothermal gradient and heat flow, H, at the various data blocks and sub-blocks.

Block	**Z_0** (m)	**Z_1** (m)	**$Z_b=2Z_0-Z_1$** (m)	**Geothermal gradient** ($^oC\ km^{-1}$)	**Heat flow** ($mW\ m^{-2}$)
A	14.93	0.50	30.36	18.21	45.54
AA	15.37	0.55	31.29	17.67	44.18
AB	10.99	0.41	22.39	24.70	61.75
AE	11.35	0.53	23.23	23.81	59.51
AF	16.62	0.59	33.83	16.35	40.87
B	16.48	0.46	33.42	16.55	41.37
BC	10.70	0.60	22.00	25.14	62.84
BD	11.52	0.78	23.82	23.22	58.04
BG	12.80	0.50	26.10	21.19	52.97
BH	13.97	0.51	28.45	19.44	48.59
C	16.48	0.54	33.50	16.51	41.27
CI	10.99	0.49	22.47	24.61	61.53
CJ	11.51	0.55	23.57	23.46	58.66
CM	14.44	0.50	29.38	18.82	47.06
CN	11.55	0.50	23.60	23.43	58.58
D	16.48	0.42	33.38	16.57	41.42
DK	16.06	0.62	32.74	16.89	42.23
DL	16.65	0.57	33.87	16.33	40.82
DO	14.98	0.47	30.43	18.17	45.43
DP	13.74	0.58	28.06	19.71	49.27

a.



b.

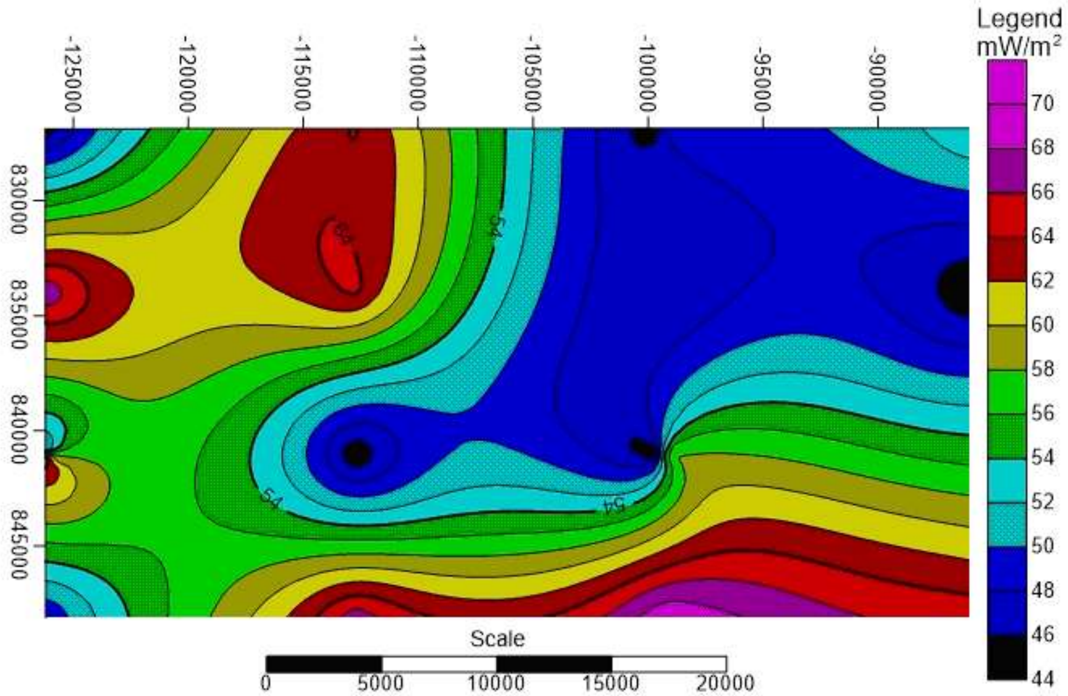


Fig. 3. Maps of (a) Curie depth, (b) Heat flow in the study area

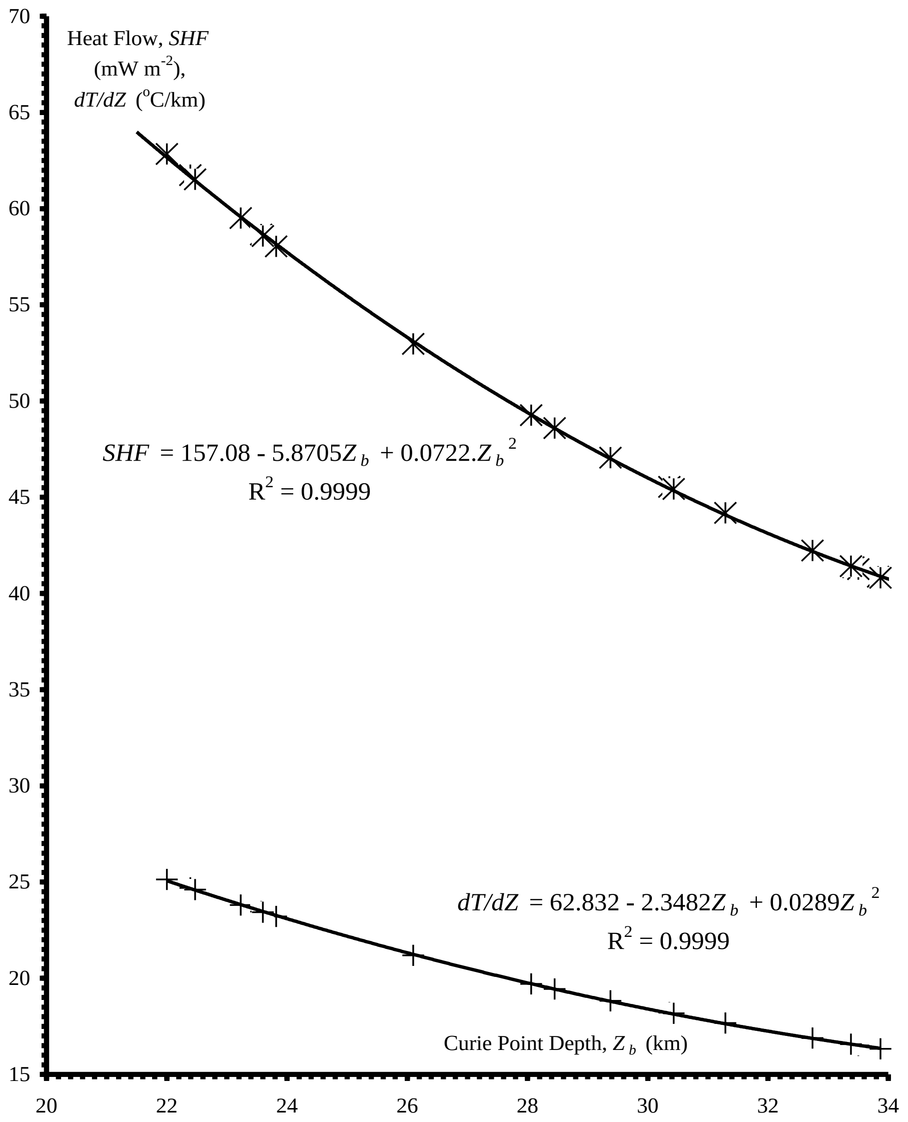


Fig. 4. Plots of Curie point depth, Z_b versus geothermal gradient, *dt/dZ* and surface heat flow, *SHF*

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