APPLICATION OF ANALYTIC SIGNAL TECHNIQUE TO INVESTIGATE THE GEOTHERMAL POTENTIAL OF IKOGOSI WARM SPRING IN EKITI AREA, SOUTHWESTERN NIGERIA

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Abstract

The Ikogosi Warm Spring area is characterized by superficial thermal manifestation represented by the warm spring with temperature of 38°C average. This work elucidates the geothermal energy resources and delineates the structural setting of the area using geophysical interpretation techniques of Analytic Signal and Spectral Analysis. Interpretation of aeromagnetic data indicates that the warm spring source is structurally controlled. The calculated average Curie point depth is 5.8 km. Generally, the results indicate that the Ikogosi Warm Spring area holds promising prospects for geothermal exploration.

Key words: *Ikogosi, geothermal*

1.0 Introduction

The Ikogosi Warm Spring is located approximately 2 km west of Ikogosi - Ekiti town in Ekiti West local Govt. Area of Ekiti State within the Precambrian Basement Complex of southwestern Nigeria (Adegbuyi and Abimbola, 1997) as seen on Figure 1. It has an altitude of 450 to 500 m. It is situated between lofty steep-sided and heavily-wooded, north-south trending hills about seventeen miles east of Ilesha, and about six and a half miles southeast of Effon Alaye (Rogers *et al.*, 1969). It lies on the geographic latitude of 7°35'N and longitude 5°00'E (Figure 1) within the central region of the area covered by this study.

More recently, investigations have been made for parts of the territory of Japan (by Okubo 1985, 1989, 1994), USA (by Mayhew 1985, Blakely, 1988), Greece (Tsokas *et al.*, 1998, Stampolidis and Tsokas 2002), Portugal (Okubo *et al.*, 2003), Bulgaria (Trifonova *et al.*, 2006) and Turkey (Dolmaz *et al.*, 2005, Maden, 2009). Spector and Grant (1970), analysing statistical properties of patterns of magnetic anomalies, have proven the relationship between the spectrum of observed anomalies and depth of a magnetic source by transforming the spatial data into frequency domain. Spector and Grant (1970)'s method was based on the assumption that the sources were considered to be independent collections of rectangular vertical prisms. For random magnetization, the radial average of the power spectrum of magnetization is constant. Shuey *et al.* (1977) suggested that the method of Spector and Grant (1970) was more suitable for regional application of magnetic anomalies. Okubo et al. (1985) emphasize that the rectangular prism is an appropriate geometry from which to develop the necessary theory, not a required geologic model. The method used here resembles the methods of Spector and Grant (1970), Okubo et al. (1985) and Trifonova *et al.* (2006) which examine the spectral knowledge included in subregions of magnetic data. Spector and Grant (1970) showed that the expected spectrum of an ensemble model was the same as that of a single prism with the average parameters for the collection. The objective of this research is to estimate the Curie point depth (CPD) based on spectral analysis of the aeromagnetic data and interpret the magnetic data using Analytic Signal approach.

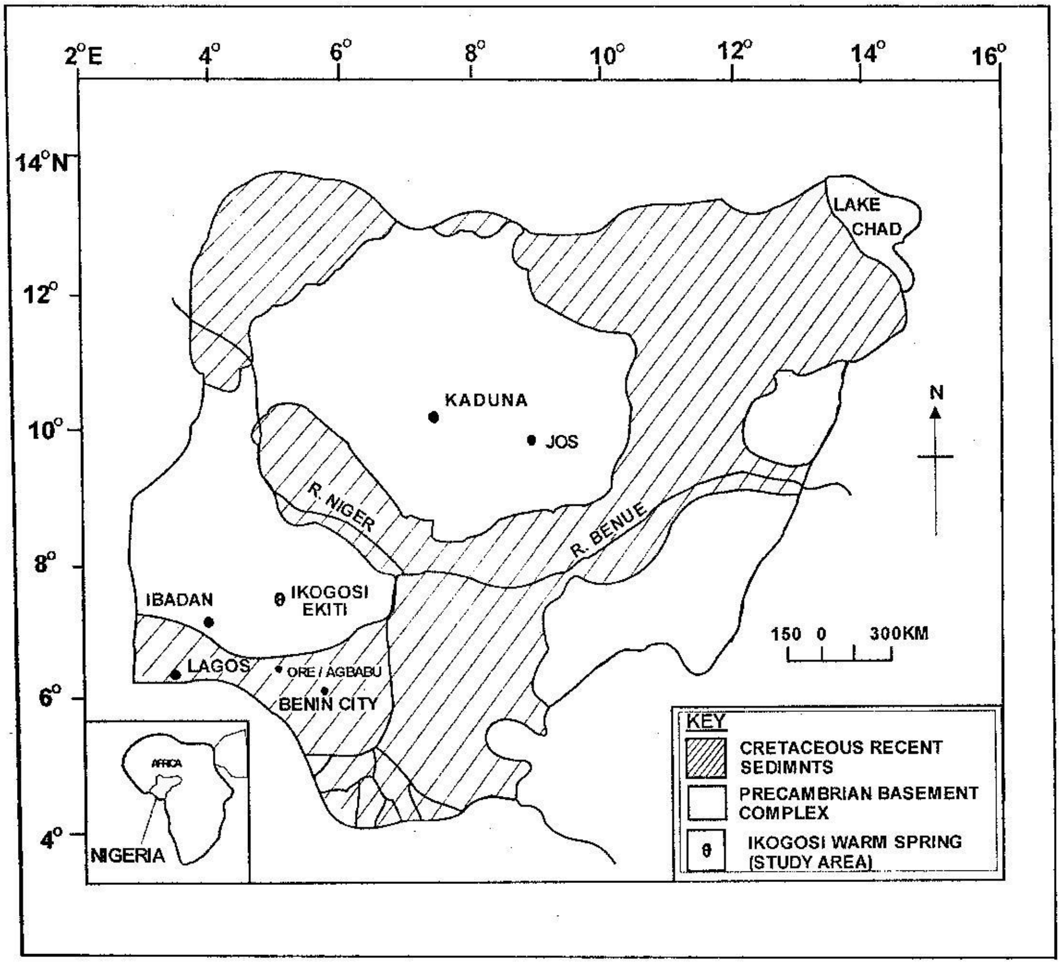

Figure 1. Location of Ikogosi Warm Spring in the basement complex of Nigeria (Adegbuyi and Abimbola, 1997)

2.0 *Geological Setting*

The geological setting of the Ikogosi area as described by Rogers *et al.* (1969) from published geological maps of the 1:250000 series (Iwo sheet No. 60 and Akure sheet No. 61) identified six perennial tributaries and two dry valleys (Fig. 2) which have approximately North-South linear arrangements for the area. The warm spring issues with a temperature of 38°C near the foot of the eastern slope of the North-South trending ridge from a thin quartzite unit within a belt of quartzite, quartz – mica schist and granulitic migmatite east of Ilesha.

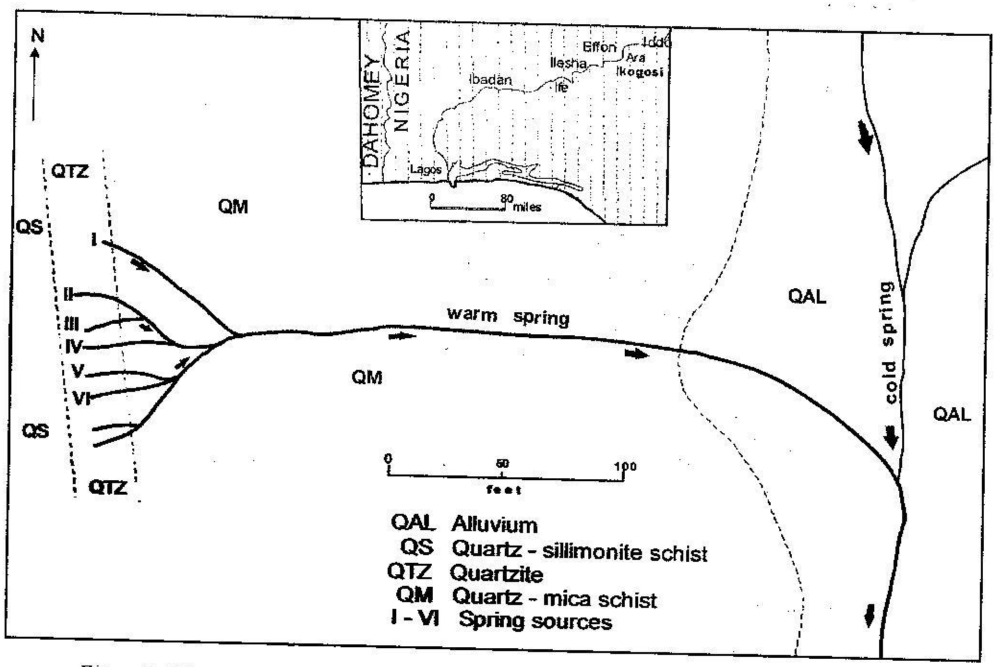

Figure 2. **Diagrammatic sketch of Ikogosi Warm Spring area showing sources (I-VI) and general geology (after Rogers *et al* 1969)**

The quartzite is part of the Okemesi quartzite member of the Effon Psammite formation belonging to the Ife - Ilesha schist belt of the Precambrian Basement Complex (Figure 1) of Nigeria (Adegbuyi *et al*., 1996; Loehnert, 1985). Field observations suggest the possibility that the springs issue along a fault. The Okemesi quartzite member is enclosed within the quartz schist units in the Effon Psammite formation which is characterised by a North-South trending ridge called the Effon Ridge (Adegbuyi, 1991; Odeyemi, 1991; Elueze, 1988). Numerous springs originate from the Okemesi quartzite member, some of them merging downstream to form spectacular waterfalls such as near Erin-Ijesha and Ipole-Ilero falls (Adegbuyi *et al*., 1996). The discharge of Ikogosi is about 25 l/s (25 litres per second) average value which appear to be constant throughout the seasons (Loehnert, 1985; Oteze, 1981; Adegbuyi *et al*., 1996). Chukwu-Ike and Norman (1977) and Mbonu (1990) believe that the intersections of the NNE–SSW epeirogenic belts with the NW–SE fracture trends in Nigeria coincide with the centres of warm springs like the Wikki (Bauchi State) and Ikogosi (Ekiti State) springs. The issue of the springs is controlled by permeability developed within the quartzite as a result of intergranular pore spaces coupled with fracturing of the relatively competent quartzites (Rogers *et al*., 1996).

3.0 Methodology

A high resolution aeromagnetic survey over the Ikogosi Warm Spring and its surroundings was conducted between 2004 and 2008 and published by the Geological Survey of Nigeria (GSN) on a map scale of 1:100000 series (Ilesha sheet No. 243, Ado-Ekiti sheet No. 244, Ondo sheet No. 263 and Akure sheet No. 264). Figure 3, shows the Total Field Aeromagnetic Anomaly Map incorporating the four sheets flown at 100m elevation. The flight interval was 500 m. Data from the aeromagnetic anomaly map were given in the Universal Transverse Mercator

(UTM) projections of coordinate system WGS84/UTM Zone 31N and were extracted from the map using GEOSOFT Oasis Montaj Viewer software as the maps were in GEOSOFT grid file format. The map had the regional geomagnetic field (IGRF 2006) and the effects of diurnal magnetic variations removed.

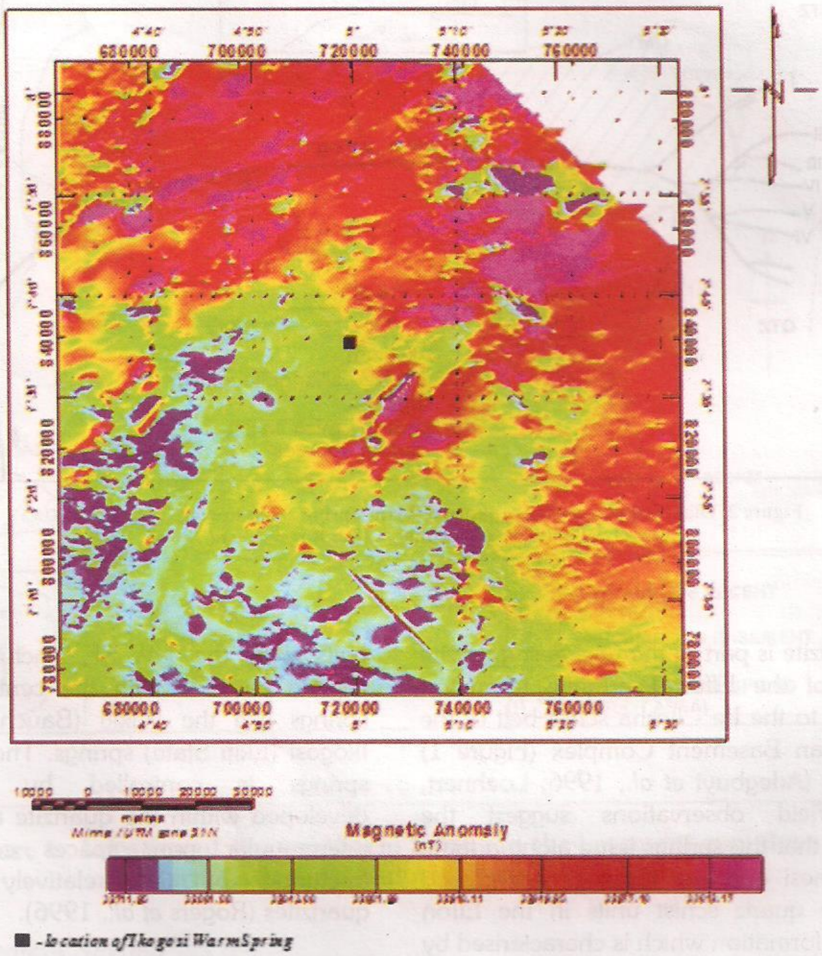

Figure 3. Total Field Aeromagnetic Anomaly Map of Ikogosi Warm Spring Area

3.1 Regional and Residual Separation

It was recognized that the Total Field Intensity map contains long wavelength components arising from regional structures and gross terrain features. These components could affect the centroid depth estimates (Trifonova *et al.*, 2006) and an attempt to remove them before evaluating the demanding parameters is made. In order to separate the regional and residual components in the Total Intensity map (Figure 3), the region of no data coverage (top right corner of the map) was filtered out and a best-fit polynomial of first degree was fitted to the aeromagnetic data using the least square technique. Figure 4 shows the resulting residual map obtained by subtracting the regional component from the Total Field values. It was the residual field that was then subjected to more intense study.

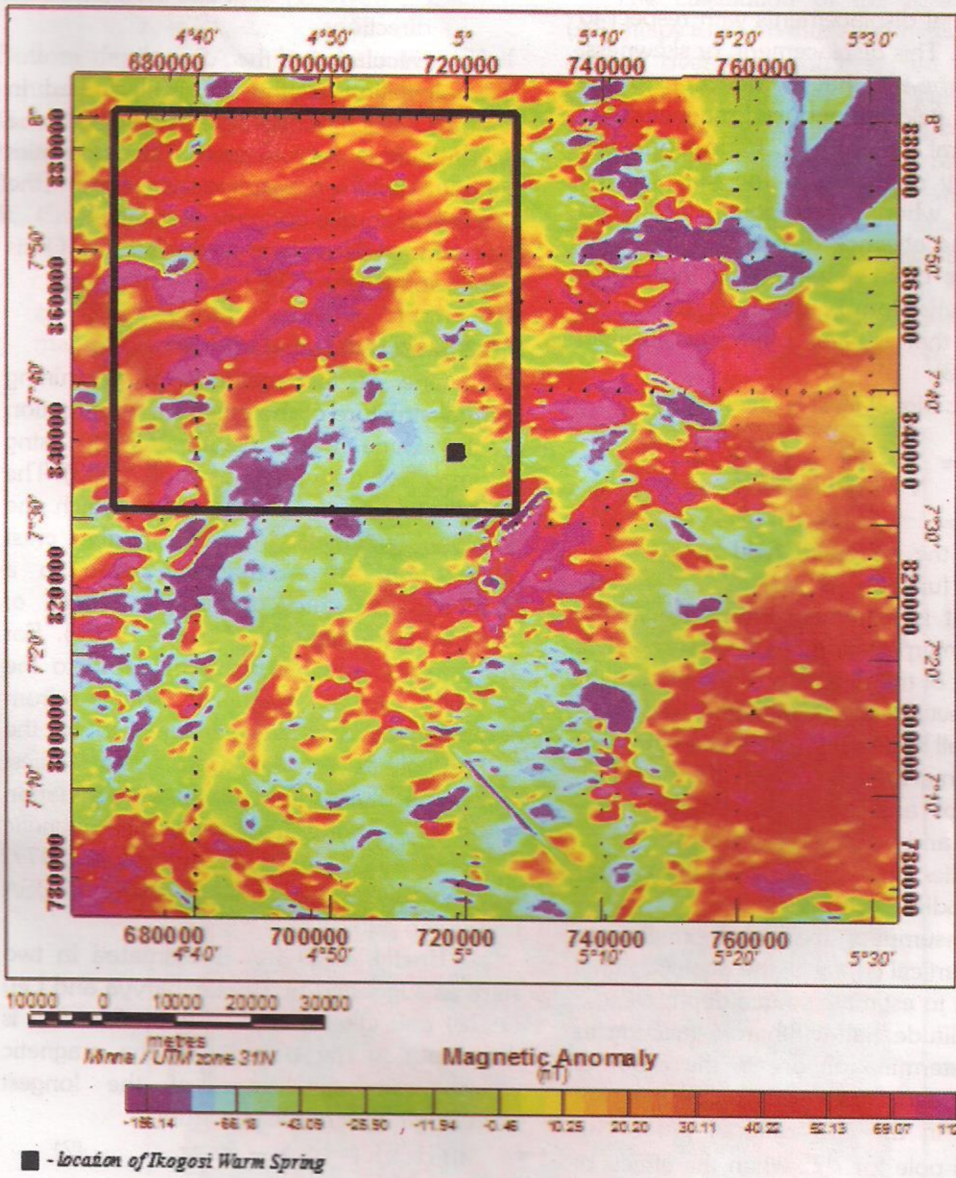

Figure 4. Residual Field Map showing sub region dimension (55 x 55km) slided across the map to obtained data for CPD calculation (inserted square)

3.2 Analytic Signal

The interpretation of observed magnetic anomalies is often complicated by their horizontal displacements with respect to their sources. This displacement, or skewness, results from the fact that the directions of the geomagnetic field and induced magnetization are, in general, not vertical. Repositioning of anomalies by reduction to the pole can be complicated, when magnetization inclination is low. In the absence of oriented magnetic samples, one often assumes that the source body magnetization is purely induced; an assumption that is very often not justified (Riedel, 2008).

The Analytic Signal (AS) is given by:

$$A(x,y) = \sqrt{\left(\frac{\partial T}{\partial x}\right)^2 + \left(\frac{\partial T}{\partial y}\right)^2 + \left(\frac{\partial T}{\partial z}\right)^2} \quad (1)$$

where T is the observed field at x and y. While this function is not a measurable parameter, it is extremely interesting in the context of interpretation, as it is completely independent of the direction of magnetization and the direction of the inducing field. This means that all bodies with the same geometry have the same analytic signal. Furthermore, the peaks of analytic signal functions are symmetrical and occur directly over the edges of wide bodies and directly over the centres of narrow bodies.

Under the assumption that the anomalies are caused by vertical contacts, the analytic signal can be used to estimate source depth using a simple amplitude half-width rule (accuracies in depth determination are in the order of 30%). This avoids the difficulties that are often faced in the conventional process of reduction to pole for ∂T, when the effects of natural remanent magnetization on the source magnetization distribution are usually unknown (Riedel, 2008).

The implementation of the AS calculation has three steps (Riedel, 2008; Roest, 1992):

- low-pass filtering of ∂T
- processing to obtain the gradients of ∂T with respect to the x, y and z directions
- calculation of the AS

The calculation of the AS is illustrated in Figure 6, which shows how it results in the determination of source characteristics without making assumptions about the direction of source body magnetization.

Processing was realized with Geosoft Oasis montaj software.

3.3 Spectral Analysis

One of the methods of examining thermal structure of the crust is the estimation of the Curie Point Depth (CPD), using aeromagnetic data (Dolmaz *et al.*, 2005). The CPD is known as the depth at which the dominant magnetic mineral in the crust passes from a ferromagnetic state to a paramagnetic state under the effect of increasing temperature (Nagata, 1961). For this purpose, the basal depth (depth to the bottom) of a magnetic source from aeromagnetic data is considered to be the CPD (Dolmaz *et al.*, 2005). The earliest papers on Curie point depth determination based on spectral analysis of geomagnetic data are those of Byerly and Stolt (1977) where analyses for different areas of USA have been published.

Briefly, CPD (z_b) is estimated in two steps as suggested by Bhattacharyyà and Leu (1975) and Okubo et al. (1985). The first is the depth to the centroid of the magnetic source from the slope of the longest wavelength part of the spectrum,

$$\ln H(s) = \ln A - 2\pi s z_o \quad (2)$$

where H(s) is the radially averaged power spectrum of the anomaly, s is the wave number, and A is a constant. The second step is the estimation of the depth to the top boundary (z_t) of that distribution from the slope of the second longest wavelength spectral segment (Okubo et al., 1985),

$$\ln H(s) = \ln B - 2\pi s z_t \quad (3)$$

where B is a constant independent of s. Then the CPD (z_b) of the magnetic source is calculated from equation (4) below

$$z_b = 2z_o - z_t \quad (4)$$

Bottom depth (z_b) can only be estimated if centroid (z_o) can be accurately determined. Consequently, the CPD estimates involve three stages as follows (Dolmaz et al., 2005):

1. Division into overlapping sub-regions,
2. Calculation of the radially average log power spectrum for each sub-region,
3. Estimation of the CPD from the centroid and top depth estimated from the magnetic source for each sub-region.

4.0 Results

4.1 Analytic Signal Map

The calculation of the Analytic Signal (AS) helps to re-orientate magnetic anomalies directly over their sources, and gives more detail compared to the Total Field Intensity, which is dominated by the superposition of neighbouring anomalies. To reduce short wavelength noise, the map was upward continued to 500 m and analytic signal analysis performed on the upward continued map. The main structures or deep-seated anomaly sources are highlighted in the displayed AS map, shown in Figure 5.

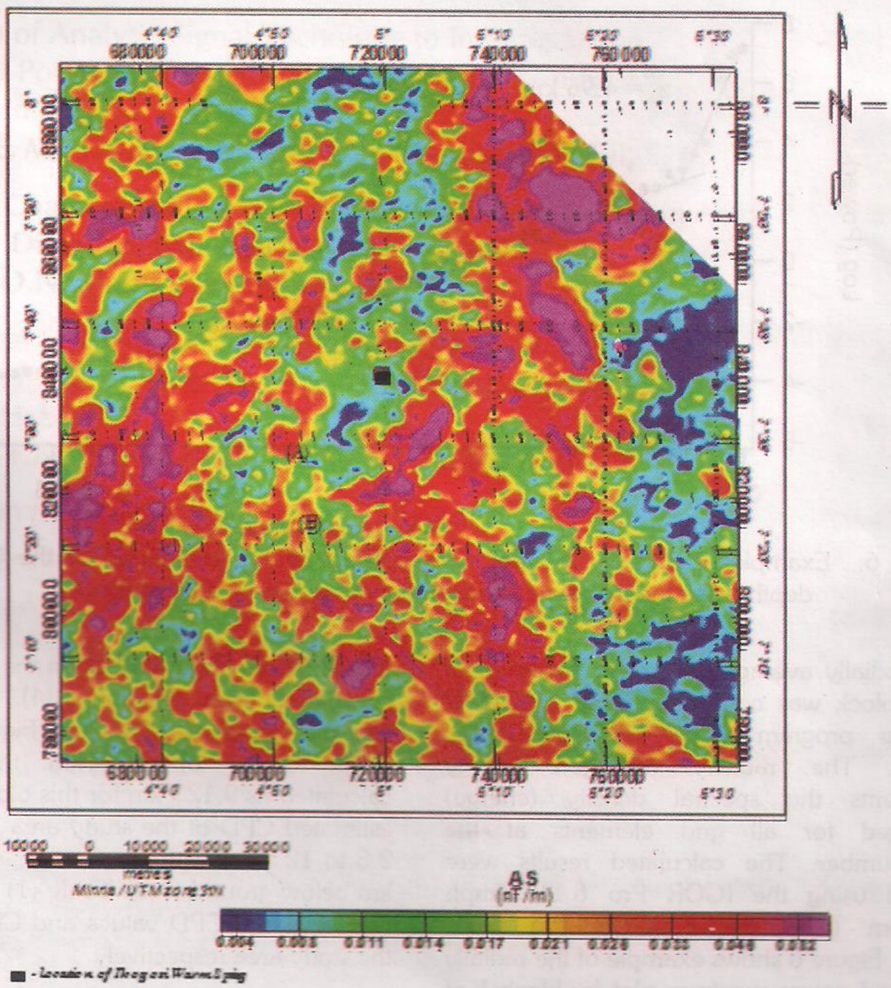

Figure 5 Analytic Signal Map of the Study Area

4.2 Map Division into Overlapping Sub-regions

In the estimation of depths to the Curie-temperature in Oregon, for example, Connard *et al.* (1983) divided a magnetic survey into overlapping cells (77 x 77 km) and calculated for each cell a radially average power spectrum. However, the spectrum of the map only contains depth information to a depth of length/2π (Shuey *et al.*, 1977). If the source bodies have bases deeper than $L/2\pi$, the spectral peak occurs at frequency lower than the fundamental frequency for the map and cannot be resolved by spectral analysis (Salem *et al.*, 2000). In this study, the overlapping operation is obtained by sliding a sub-region dimension (55 x 55 km) across the entire magnetic map at strategic magnetic anomaly regions and about 22 overlapping blocks each being 55 x 55 km in length were obtained.

As stated earlier, estimation of the bottom depths could be approached in two steps (Bhatacharyya and Leu, 1975, 1977). The first is the depth to the centroid (z_o) of the magnetic source from the slope of the longest wavelength part of the spectrum (Figure 6). The second step is the estimation of the depth to the top boundary (z_t) of that distribution from the slope of the second longest wavelength spectral segment (Okubo *et al.*, 1985).

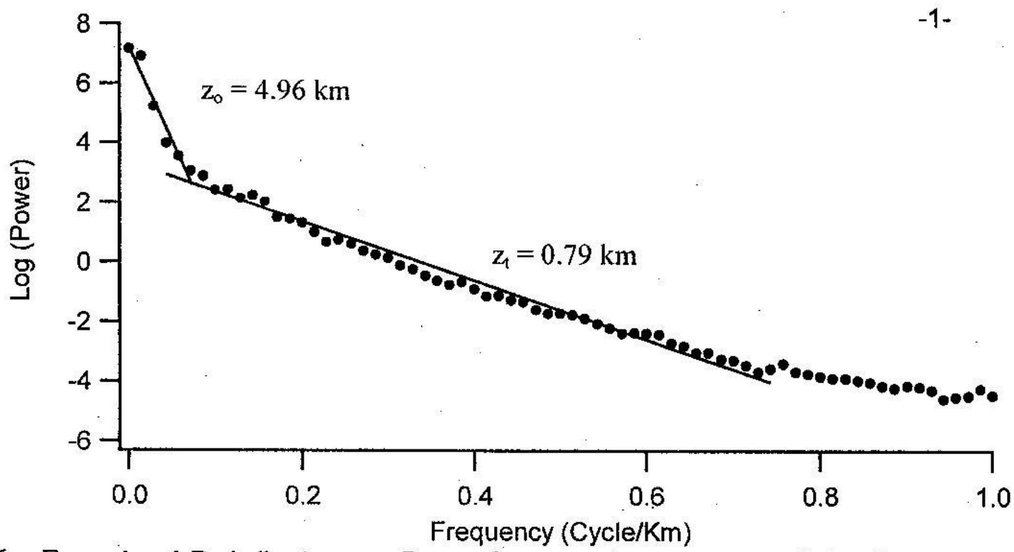

Figure 6: Example of Radially Average Power Spectrum for estimation of the Curie point depth using the two dimensional magnetic anomaly data of Block 1.

The radially average log power spectrum of each block was computed using MAGMAP filtering program (GEOSOFT MAGMAP, 2007). The radially averaged energy represents the spectral density (energy) averaged for all grid elements at the wavenumber. The calculated results were plotted using the IGOR Pro 6.11 Graph Program (WaveMetrics IGOR Pro 6.11, 2009). Figure 6 shows example of the radially averaged power spectrum plot for block 1 of the 22 blocks (Figure 4). Then the CPD (z_b) is calculated from Equation (4). From the centroid depth of 4.956 km (Figure 6) and depth to the top 0.788km, the CPD is calculated as 9.123 km for this block. The 22 estimated CPD of the study area range from 2.5 to 12.5 km with an average value of 5.7 km below ground level. Table (1) and Figure (7) shows the CPD values and CPD map of the study area respectively.

Block	Location		Source Depth		Curie Point Depth (km)
	Longitude X (°)	Latitude Y (°)	Depth to the top (km)	Depth to the centroid (km)	
1	4.77	7.80	0.79	4.96	9.12
2	5.02	7.80	0.85	2.97	5.08
3	5.12	7.79	0.83	2.69	4.54
4	5.21	7.64	1.33	2.13	2.94
5	5.27	7.72	0.65	2.90	5.16
6	5.28	7.49	0.58	2.28	3.98
7	5.09	7.40	0.62	3.15	5.67
8	5.28	7.27	0.63	3.00	5.38
9	5.15	7.27	0.63	2.98	5.33
10	4.77	7.27	0.73	4.68	8.64
11	4.77	7.40	0.78	3.74	6.70
12	4.77	7.60	0.81	4.38	7.95
13	4.97	7.77	0.86	6.69	12.53
14	5.10	7.67	0.89	2.87	4.84
15	4.99	7.34	0.68	4.62	8.55
16	5.08	7.62	0.77	2.82	4.88
17	4.99	7.56	0.61	1.96	3.31
18	5.28	7.79	0.61	1.59	2.56
19	5.21	7.79	0.62	1.69	2.50
20	4.97	7.36	0.64	3.26	5.84
21	4.77	7.55	0.79	3.54	6.28
22	5.19	7.80	0.88	2.92	4.95

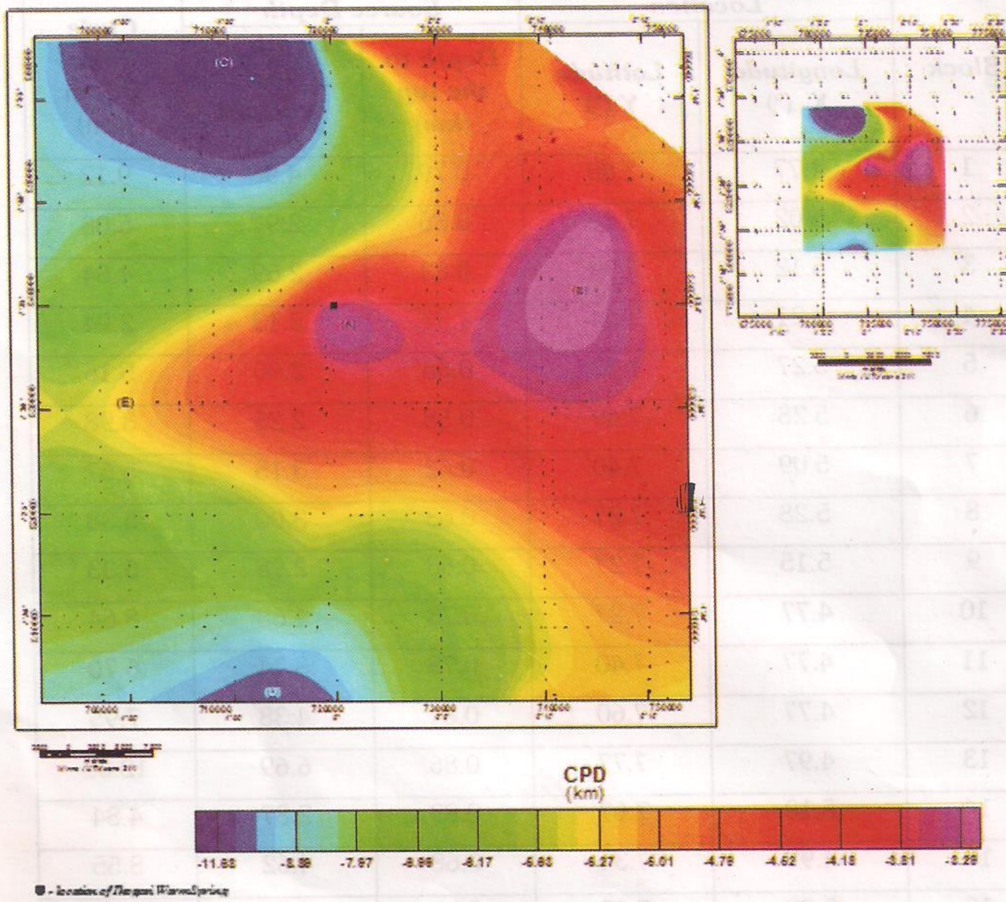

Figure 7. Curie Point Depth Map of the Study Area.
Points A and B indicates shallow CPD's,
points C, D and E indicates deeper CPD's.

Magnetic - Survey data are routinely interpreted by estimating source depths or locations (Vacquier *et al.*, 1951). Studies have shown that the Curie Point Depth is linked to geological context. Tanaka *et al.* (1999) pointed out that the Curie Point Depths are shallower than about 10 km at volcanic and geothermal areas, 15-25 km at island arcs and ridges, deeper than 20 km at plateaus, and deeper than 30 km at trenches. The presence of the warm spring in the study area qualifies the area for the first description. The Curie Point Depth estimates range between 2.5 km and 12.5 km (Table 1) with an average value of 5.8 km. This shallow CPD implies an average thermal heat flow of 273.5 mW/m^2 in the area. Estimated depths to the top and bottom (CPD) of the crust are detailed in Table 1. According to Ross *et al.* (2006), places where heat flow information is inadequate, the depth to the Curie temperature isotherm may provide a proxy for temperature-at-depth. The map in Figure 7 shows the CPD for the Ikogosi Warm Spring area, determined by applying a minimum curvature algorithm to the CPD values in Table 1. In particular, depths to the base of magnetic crust determined from sub-regions centred over the Ikogosi Warm Spring area are generally shallower than those determined for areas farther from the warm spring source. This results show that the Ikogosi Warm Spring area has relatively high geothermal potential.

Figure 5 is the result obtained from the Analytic Signal technique and it displays the main structures or deep seated anomaly sources obtained from the total field intensity data. As the area sampled for the CPD estimation was limited due to the overlapping technique employed, there was need to determine the analytic signal of the whole area under study. High magnetic contrast can be seen around the Ikogosi Warm Spring area (Figure 5) compared with the surrounding survey area. This corresponds with the shallow Curie point depths and high heat signatures obtained in the area (Figure 7). Some E-W and NW-SE feature can be observed on the map. A NE-SW striking anomaly feature (A) and (B) could be due to geologic features (e.g. faults) cross-cutting the Ikogosi Warm Spring area indicating that the warm spring may be issuing from a fault. The analytic signal is useful in locating the edges of the magnetic source bodies, particularly where remanance, and/or low magnetic latitude complicates interpretation (Whitehead and Musselman, 2005).

From our analysis, we conclude that the warm spring source is structurally controlled. We also found out that the study area is characterized by shallow Curie point depths. The results obtained in this work have provided important geophysical/geological results which are useful to further geothermal exploration.

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