JJEES

JJEES (2022) 13 (3): 215-222
ISSN 1995-6681

Jordan Journal of Earth and Environmental Sciences

Integrated Geophysical Study for Delineation of Structures Favorable to Uranium Mineralization in Al-Amerat, Sultanate of Oman

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Received 16 February 2021; Accepted 21 January 2022

Abstract

The spectroscopic results of the acquired Gamma-ray have indicated a moderately high concentration of radioactive minerals showing ~100 ppm of Uranium and ~1000 ppm of Thorium in the placer deposit in Amerat, near Muscat Sultanate of Oman. To identify the extension and structural parameters of the Formation, the area was further investigated with very low frequency electromagnetic (VLF-EM) and magnetics surveys along five profiles of approximately 200 m long 20 m apart (10 m measurement intervals). In-phase and quadrature components of the VLF-EM signal were recorded at two different transmitter frequencies (15.1 kHz and 16.4 kHz) as well as the total magnetic field. Processing and interpretation were carried out by well-known methods such as Euler deconvolution, Fourier spectral analysis, and also by Hilbert transform technique. Magnetics data resulted in a depth in the range of 5-20 m by Euler deconvolution and 6-12 m by Fourier spectral analysis whereas the VLF-EM signals have resulted in a depth in the range of 7.2 m-10.4 m by Karous and Hajelt (KH) filtering. On the other hand, the Hilbert transform technique estimated both the depth and width of the subsurface source in the range of 9.2 – 24 m and 19.5 – 66.5 m respectively. Thus, the overall analyses of geophysical data have revealed the possible Uranium bearing structures as deep as 5-24 m from magnetics and VLF-EM methods.

Keywords: *In-phase component, Uranium, Thorium, Fraser filter, Karous-Hjelt current density, Gamma spectroscopy.*

1. Introduction

Spectrometry is a well-established analytical technique that has been widely used for elemental composition analysis. A relatively recent development has been the availability of sophisticated digital instrumentation, which can be used for both direct in situ non-destructive analysis of samples also is readily transportable to field sites for use in a mobile laboratory style of operation (Povinec et al., 2005). Gamma-ray spectrometry is a surveying technique that allows the calculation of the heat produced during the radioactive decay of Potassium, Uranium, and Thorium within rocks (IAEA, 2003).

VLF-EM is a rapid, simple, and economical tool among all geophysical devices with the capability of being carried out on rough topographic areas. The device receives signals from 42 military navigation stations across the world and is a well-established technique for Uranium and other mineral exploration (Sharma et al., 2014). The subsurface targets of specific surveys are often small-scale structures buried at shallow depths (Karous and Hjelt, 1983). In addition, the magnetics method which is equally popular in mineral exploration is also an efficient and economical geophysical technique. Ramesh Babu et al. (2007) have successfully applied the magnetic method in association with the VLF-EM technique in delineating Uranium deposits in the Proterozoic basins of Raigarh district, India.

In Amerat, near Muscat, Sultanate of Oman, the investigation for uranium was carried out using the geophysical methods discussed above. In the study area, the slightly metamorphosed siliciclastic Amdeh Formation belongs to the Ordovician and is ~1700 m thick, outcropping in the Wadi Qahza area of Muscat. This geological section contains two small placer deposits, which represent a succession of shallow marine siliciclastic shelf facies, measuring around 3400 m in overall thickness. The Formation is characterized by well-bedded quartzite exhibiting tabular cross-beds and contorted bedding structures that were specifically investigated with a Gamma-ray spectrometry technique.

The initial investigation based on Gamma-ray spectroscopy has revealed a moderate concentration of Uranium as much as 100 ppm and Thorium around 1000 ppm with minor traces of Potassium near the Amerat area of Muscat, Sultanate of Oman. Further, to establish the spatial location of the structures that host these radiometric anomalies were investigated by magnetic as well as VLF-EM techniques, and then processed and interpreted results approximately yield a depth to subsurface source in the range of as 5-24 m are presented.

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2. Geology of the study area

The study area is a small hilltop highly uneven terrain covering an area of less than 200-300 square m encompassing the coordinates 23°17’57.6” N and 58°22’10.1” E. The heavy minerals of these placers dominantly consist of ilmenite ($FeTiO_3$), anatase (TiO_2), and zircon ($ZrSiO_4$). Hematite (Fe_2O_3) and apatite ($Ca_5(PO_4)_3F$) are relatively rare, although hematite stains reveal their presence through red internal reflections, and the presence of apatite is reflected through increased phosphorous levels. The oldest rocks of the eastern Hajar Mountains are exposed in the cores of two large anticlinal structures (e.g., Béchennec et al., 1993), the Jabal Akhdar and the Saih Hatat Domes, which formed during the Late Cretaceous during obduction of the Semail Ophiolite (Glennie et al., 1973, 1974; Searle and Malpas, 1980; Lippard et al., 1986; Searle and Cox, 1991; Hacker, et al., 1996; Goffé et al., 1998). The Amdeh Formation is an autochthonous unit and was exposed to gentle metamorphism, in which quartz-rich sandstones were transformed into the “Amdeh Quarzite” (Am4). This metamorphism may predate ophiolite obduction, probably during the Hercynian orogeny (Glennie et al., 1974; Beurrier et al., 1986). Exposures of the Amdeh Formation are restricted to the Saih Hatat Dome (Wadi Qahza is the study area in its western part of the dome encompassing 23°17’57.6” N and 58°22’10.1” E).

The Amdeh Formation represents a succession of shallow marine siliciclastic shelf facies, measuring at least 3400 m in overall thickness (Lovelock et al., 1981), in which Am4 is characterized by well-bedded quartzites exhibiting tabular cross-beds and contorted bedding structures. Am4 accumulated in a rapidly subsiding coastal environment during the Ordovician (Lovelock et al., 1981). There are also mafic intrusions of unknown age in this formation (Oterdoom et al., 1999). The source rocks for the placer deposits that contain ilmenite (>50%) > anatase > zircon > tourmaline (Knox, 2006) > monazite (Knox, 2006), hematite (<1%), and apatite (<1%), may be found in metamorphic and acidic plutonic rocks of the Omani basement, which may have shed detritus from exposed rift shoulders. The location of the study area as well as the geological map are shown in Figure 1.

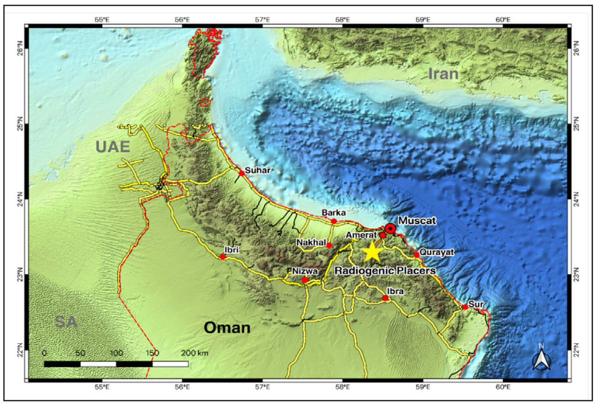

Figure 1. a. The location of the study area is Amerat near Muscat, Sultanate of Oman

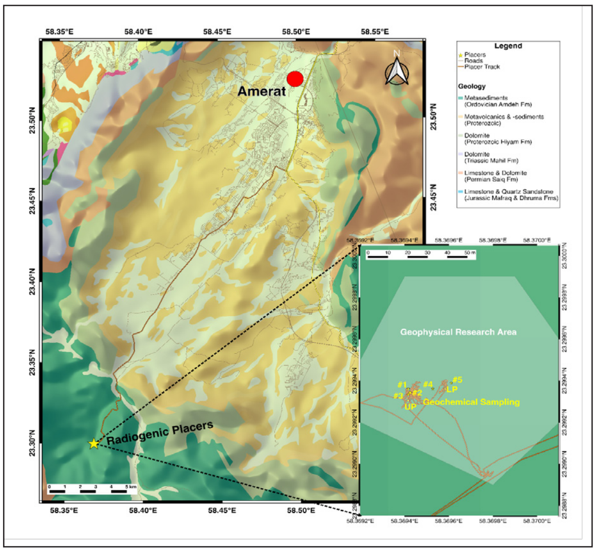

Figure 1. b.The geology of the study area with geophysical traverses.

Figure 1. (a) Location of the study area (b) and geological map.

3. Methodology

The magnetic method is a fast and simple technique that is extremely useful in mineral exploration. There are some renowned processing steps for processing and interpretation of magnetic data. Euler deconvolution (ED) and spectral analysis are widely used in potential field anomalies such as magnetic, gravity, electric, and electromagnetic fields to evaluate the depth and other parameters of the causative sources. Initially, the ED was proposed by Thompson (1982) and later extended by Reid et al. (1990), and improved by Keating (1998) and Mushayandebvu et al. (2004). ED has a wide range of applications (Gerovska and Araúzo-Bravo, 2003) and the popularity of this elegant method is due to its simplicity and ease of implementation and hence its choice for a quick initial analysis. Further, the radially averaged power spectral analysis has a wide range of applications in geophysical data processing and is perhaps the most common in potential field data for estimation of depth and other parameters of the subsurface geophysical structures (Hinich and Clay, 1968; Bhattacharyya and Leu, 1977).

Very low frequency electromagnetic (VLF-EM) is yet another useful technique with a wide range of applications in geological mapping and environmental issues as well as in mineral exploration. The VLF method uses 42 powerful remote radio transmitters across the world for military communications at frequencies range 15 to 30 kHz. Generally, the interpretation of the VLF-EM signal is based on qualitative analysis particularly based on Fraser and K-H filtering (Fraser, 1969; Karous and Hjelt, 1983) which are routinely used in many applications including Uranium exploration (Ramesh Babu et al., 2007). In the recent past, Sundararajan et al. (2011) have used the method of Hilbert transform as a semi-quantitative analysis of in-phase and out-of-phase components for the estimation of depth to the source.

4. Data Acquisition and Interpretation

The various geophysical data were acquired using a BGO Super RS-230 spectrometer, a G-859 mining magnetometer, and a portable VLF-EM receiver along 5 traverses of each 200 m at a measurement interval of 10 m and line interval of 20 m comprising a small area. Contour images of Uranium, Thorium, and Potassium concentrations along the indicated principal profile (PP) are shown in Figure 2. Further, the recorded Gamma-ray spectroscopic concentration of Uranium, Thorium, and Potassium along the principal profile (PP) is shown in Figure 3. A combination of Uranium, Thorium, and Potassium was used to create a ternary image, as shown in Figure 4.

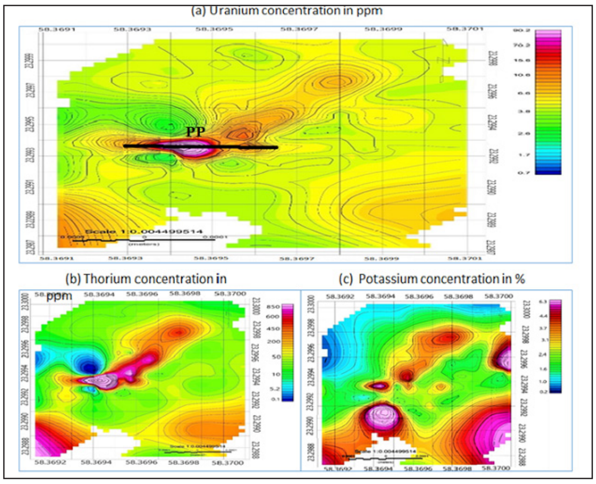

Figure 2. Contour map of (a) Uranium (b) Thorium and (c) Potassium concentrations recorded by Gamma-ray spectrometer.

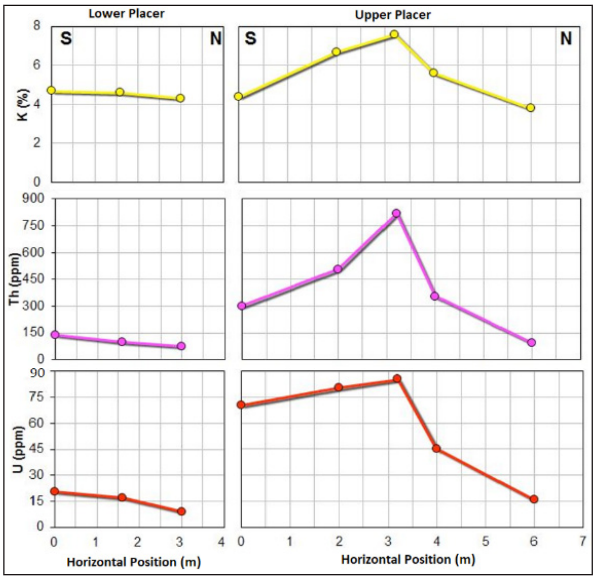

Figure 3. Recorded Gamma-ray spectroscopic concentration of Uranium, Thorium, and Potassium along the principal profile (PP).

Furthermore, the contoured map of a total magnetic field, as well as the amplitude of analytical signal that can delineate the subsurface target, are shown in Figures 5 (a and b). The depth to subsurface structures from magnetic anomalies was estimated based on two well-known methods such as spectral analysis and Euler Deconvolution (ED) which are shown in Figures 5 (c and d). Also, the in-phase component at two different transmitter frequencies indicate the spatial location of subsurface conductors and are shown in Figure 6 (a-b). The contour map of Fraser filtered in-phase and quadrature components for both transmitter frequencies of 15.1 kHz and 16.4 kHz are shown in Figure 7 (a-d). The signal was also subjected to Hjelt filtering (current density) which yields the depth to the source given in Figure 8 (a-f). In addition, the in-phase component of VLF-EM signals is used for Hilbert transform analysis to derive the depth to the source as well as width. All the five traverses (L1, L2, L3, L4, and L5) at transmitter frequency 15.1 kHz and L3 and L4 at transmitter frequency 16.4 kHz were subjected to Hilbert transform analysis and are shown in Figures 9 (a-g). For each traverse, the Hilbert transform of the in-phase component, and amplitude of the analytic signal that aids in the precise spatial location of the subsurface target were computed and shown in Figure (a-g). Further, the Hilbert transform of the principal profile (PP) of the VLF-EM in-phase component at a transmitter frequency of 15.1 kHz was also computed and shown in Figure 10. The depths to subsurface structures derived from magnetic and VLF-EM fields are shown in Table 1. Also, the depths derived from the Hilbert transform of in-phase components of all five traverses as well as the principal profile(PP) of the VLF-EM signal are given in Table 2. A brief procedural description of methods used in the interpretation of data is discussed hereunder.

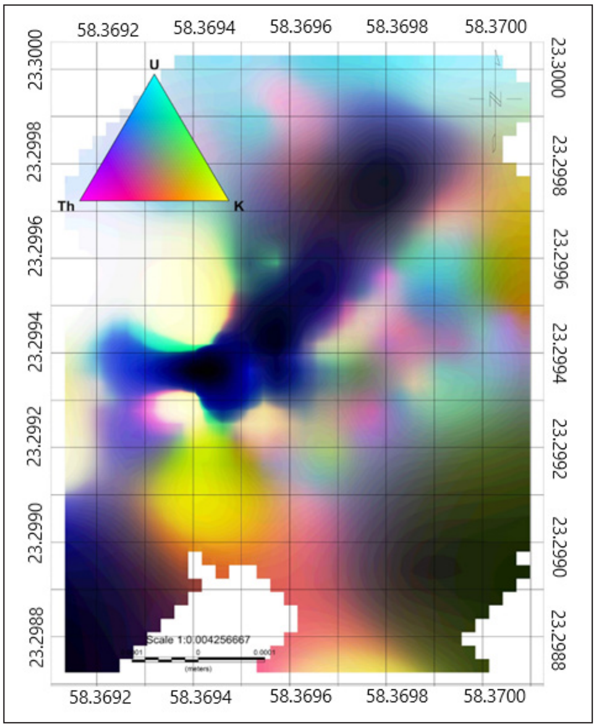

Figure 4. Ternary image of Uranium, Thorium, and Potassium

Table 1. The estimated depth of subsurface structures (in meters) from magnetic and VLF-EM fields.

Method	Magnetic	VLF-EM
Euler Deconvolution	5-20 m	-
Spectral Depth	6-12 m	-
Karous-Hjelt Depth	-	7.2-10.4 m

Table 2. The estimated depth of subsurface structures (in meters) was acquired by applying the Hilbert transform to VLF-EM signals.

Traverse/Transmitter Frequency →	15.1 kHz		16.4 kHz	
	Width(m)	Depth(m)	Width(m)	Depth(m)
L1	19.5	14		
L2	46	-		
L3	27.5	9.2	66.5	10.5
L4	35	-	27	9.5
L5	29.5	20.2		
Principal Profile of In-phase Component	35	24	-	-

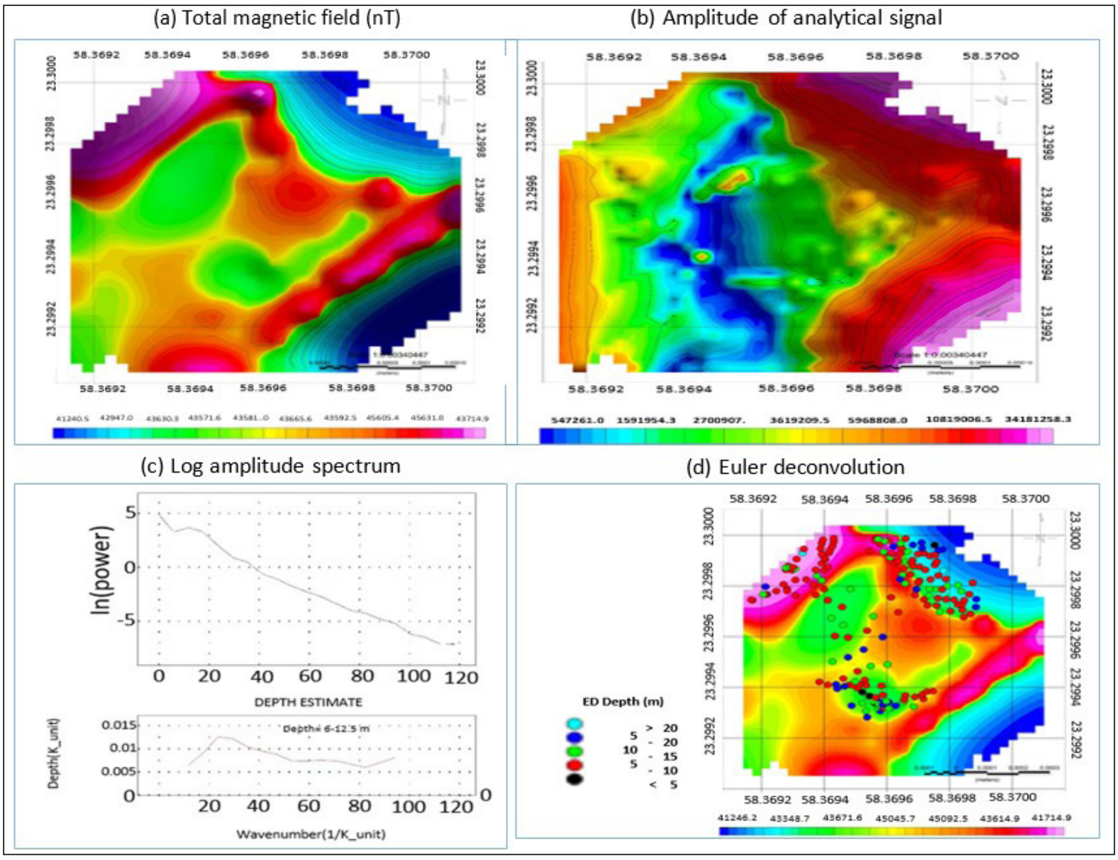

Figure 5. (a) Total magnetic field (nT) and (b) amplitude of the analytical signal of the magnetic field. Depth to subsurface structures by (c) Spectral analysis and (d) Euler Deconvolution

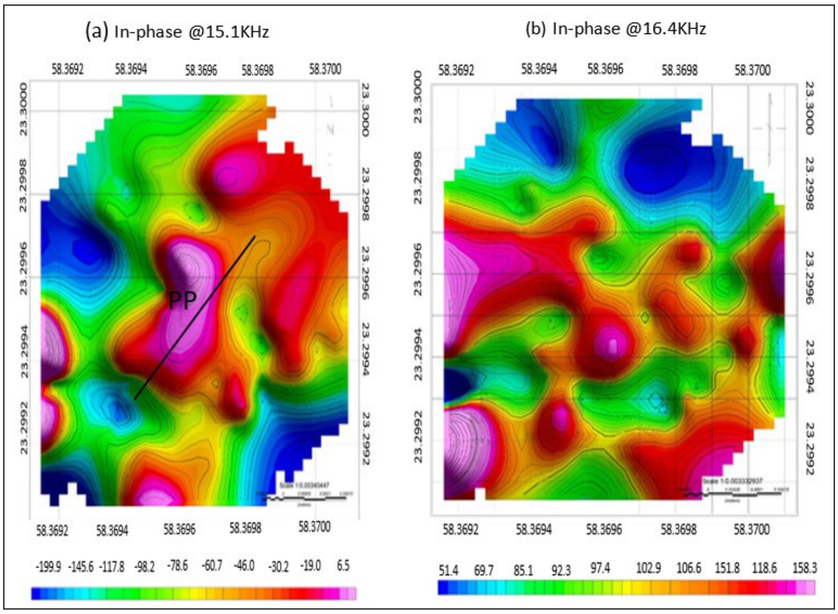

Figure 6. Contour image in-phase component of VLF-EM signal for transmitter frequencies of (a) 15.1 kHz and (b) 16.4 kHz.

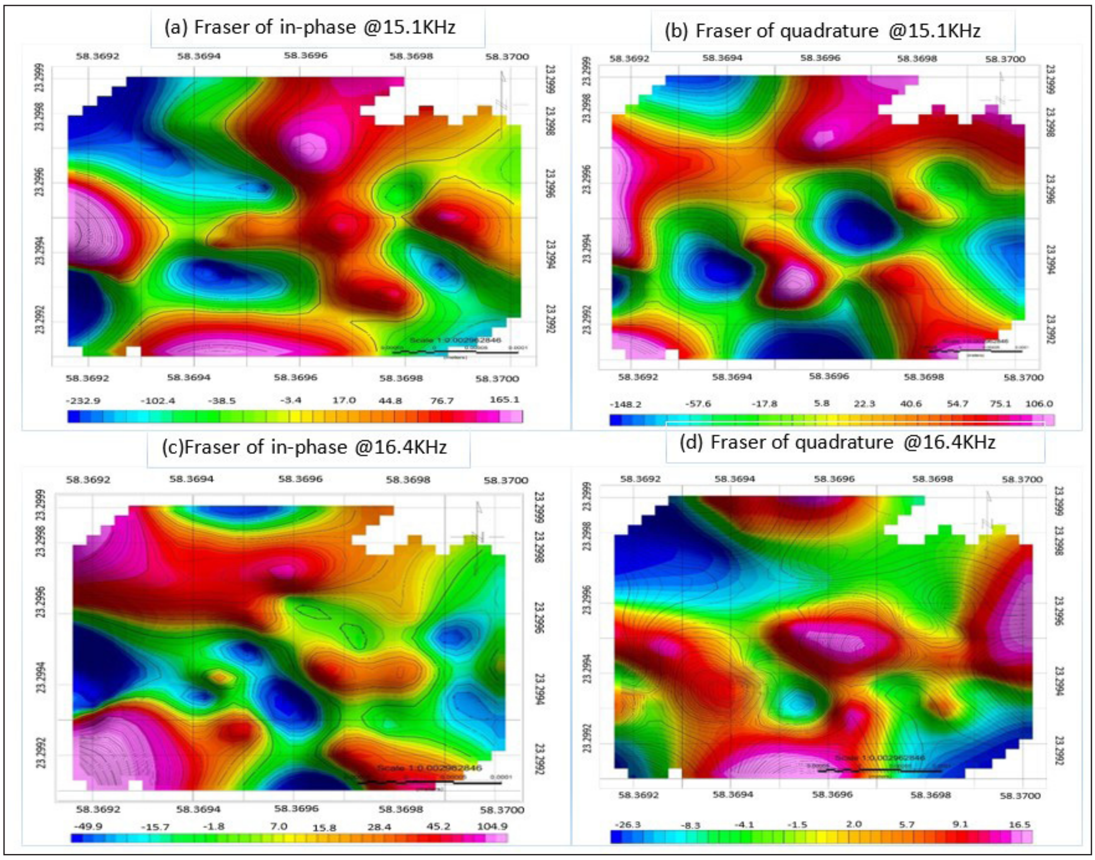

Figure 7. Contour map of Fraser filtered a) in phase and b) quadrature at transmitter frequency of 15.1 kHz, and c) in-phase and d) quadrature at transmitter frequency of 16.4 kHz.

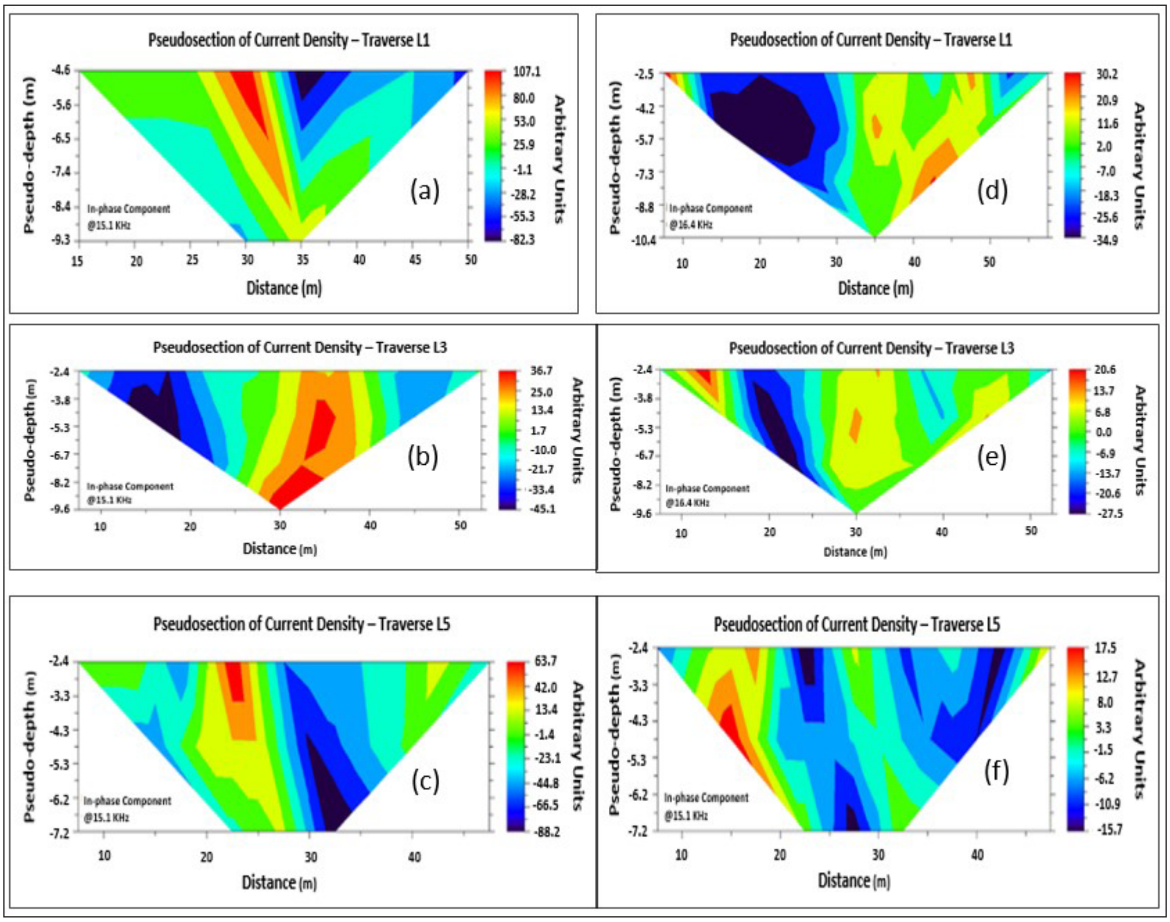

Figure 8. (a) Pseudosection of the current density of K-H filtering of traverses L1, L3, and L5 for transmitter frequencies of 15.1 kHz (a-c) and 16.4 kHz (d-f)

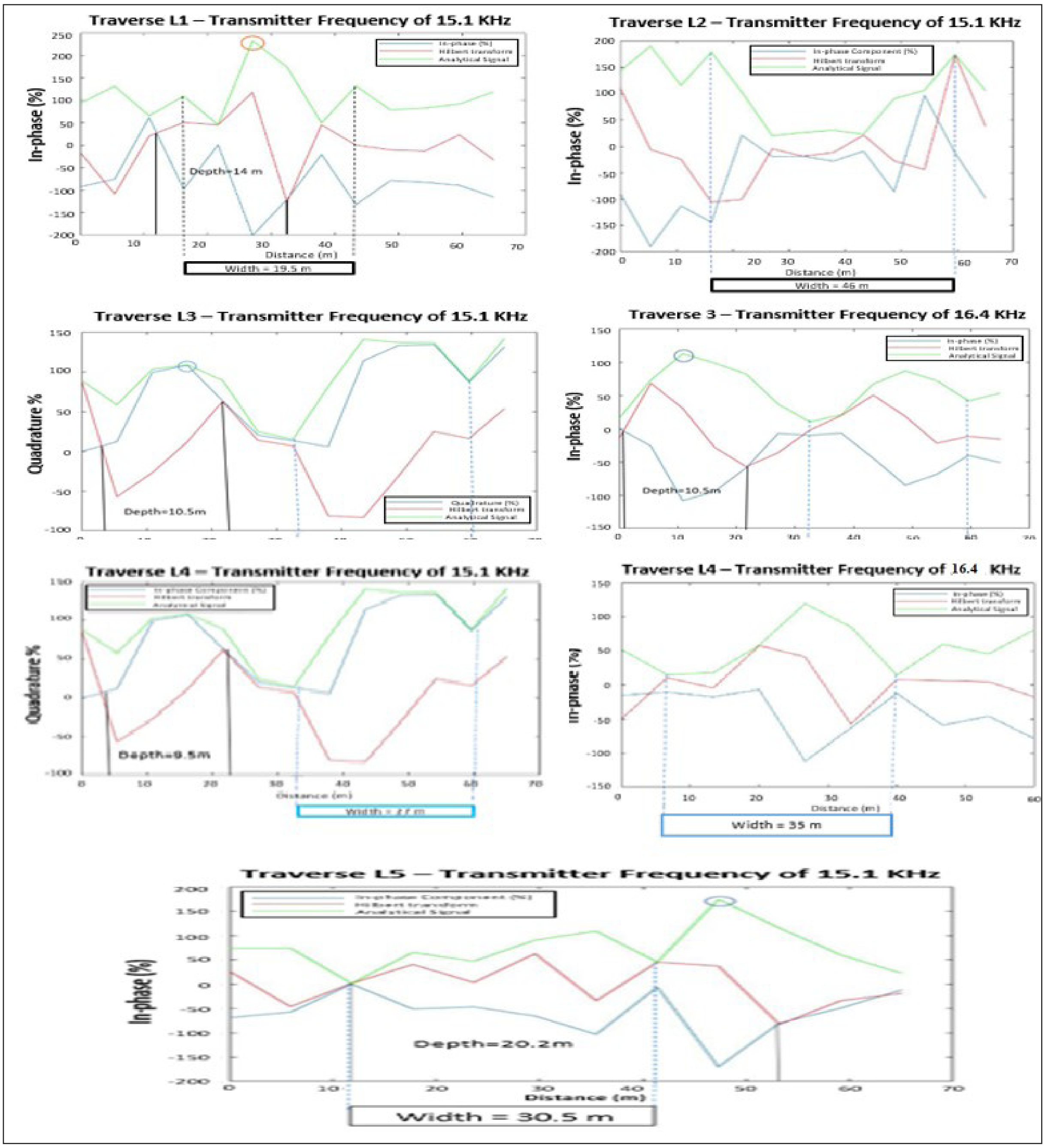

Figure 9. Hilbert transform (HT) analyses of VLF-EM signals of L1-L5 (a) HT of in-phase at a frequency of 15.1 kHz, (b) HT of in-phase of L2 at frequency 15.1 kHz, (c) HT of L3 at frequency 16.4 kHz, (d) HT of quadrature component of L3 at frequency 15.1 kHz, (e) HT of n-phase of L4 at frequency 15.1 kHz, (f) HT of quadrature component of L4 at frequency 15.1 kHz, and (g) HT of in-phase of L5 at frequency 15.1 kHz.

In general, KH (Karous-Hjelt) filtering is a forward modeling tool for depth determination either from measured in-phase (IP) or quadrature (OP) component of VLF-EM signal at a range of measurement intervals between measurement points (Karous and Hjelt, 1983, Sundararajan et al, 2007). Further, the interpretation is made simply based on a software VLF2DMF (A program for 2-D inversion of multifrequency VLF-EM data). On the other hand, depth from magnetics data is derived by a well-known method called Euler deconvolution (ED) using Geosoft. It is one of the elegant tools to estimate depth from potential field data, particularly magnetics on the horizontal location of an anomalous source, and requires the spatial location of the measurement points and structural index, a parameter to be assumed depending on the nature and shape of the anomaly (Thompson, 1982, Ebrahimi et. al, 2019).

In Fourier or Hartley spectral analysis (Fourier transform and Hartley transforms yield the same amplitude spectra), the log amplitude spectrum A(ω) of the total magnetic field results in a straight line, and the slope of such straight line yields the depth to source (Sundararajan et al, 2019). Further, the Hilbert transform of in-phase component of VLF-EM signal IP(x) can be computed using Matlab and then the amplitude of analytical signal can be obtained (Sundararaja and Srinivas, 2010, Ebrahimi et al 2019) as

$$A(x) = SQRT[\ IP(x)^2 + H(x)^2\ ]$$

where H(x) is the Hilbert transform of IP(x). The amplitude A(x) attains its maximum over the center of the subsurface target. If the width of the target is larger than the depth, the amplitude results in a minimum at the center of the target and two maxima on either side of the minimum. The distance between the two maxima gives the width of the target as shown in Figure 10. Further, the depth to the subsurface source can be determined as a function of abscissae of the point of intersection of IP(x) and its Hilbert transform wherein if there is a single point of intersection that corresponds directly to depth and in the case of two or more, the average yields the depth (Sundararajan and Srinivas, 2010).

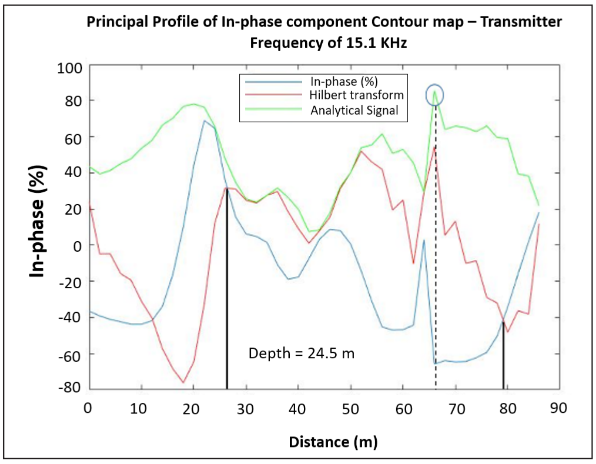

Figure 10. Hilbert transform analysis of an in-phase component of the principal profile.

5. Results and Discussion

Generally, the concentration of essential radioelements (Uranium, Thorium, and Potassium) expressively differs with the lithology of the study area and in the present study Figure, 2 reflects according to rock units such as metamorphic siliciclastic and placers. Also, the maximum variation of Uranium is seen in pink and red as shown in Figure 2a. Elevated Uranium and Thorium concentrations are more clearly shown in Figure 3, which corresponds to the values recorded along the principal profile (PP). The Uranium and Thorium concentrations along the principal profile (PP) are as high as 100 ppm and 900 ppm respectively.

The depth to the subsurface source obtained from magnetic anomalies by different methods such as radially average spectral analysis and Euler deconvolution agree well with each other. The estimated depth of subsurface structures ranges from 6-12 m by radially averaged power spectral analysis (Figure 5c) and 5-20 m by Euler Deconvolution (Figure 5d) respectively. On the other hand, the depth to source is obtained from the in-phase component of VLF-EM data by K-H filtering at two different transmitter frequencies viz. 15.1 kHz and 16.4 kHz range 7.2 m -10.4 m [Figure 8 (a-f)] and are presented in Table 1.

Further, the Hilbert transform analysis of the in-phase component of the VLF-EM signal has resulted in the depth as well as the width of the subsurface structure at both transmitter frequencies range 9.2 m -20.2 m [Figure 9 (a-g)] and 19.5m - 66.5 m. In addition, the principal profile yields the depth and width by HT analysis as 35 m and 24 m respectively at a transmitter frequency of 15.1 kHz which is somewhat close to the depth and width obtained from traverse L5 as shown in Table 2. It may be noted that the results obtained from spectral analysis(depth) and the Hilbert transform technique (depth and width) are more reliable as these techniques are analytical/quantitative methods in comparison with qualitative methods such as Euler deconvolution and K-H filtering.

6. Conclusions

The integrated geophysical strategy consisting of Gamma-ray spectroscopy, magnetic, and VLF-EM is a proven strategy elsewhere is employed in this study in the exploration of radioactive minerals. Gamma-ray spectroscopy recorded the occurrence of Uranium, however of low grade (<100 ppm) and Thorium moderately a high concentration of around 1000 ppm. The magnetics and the VLF-EM surveys have resulted in the depth of mineralized structures in the range of 5 – 24 m in addition to the width of 19.5 m-66.5m. The study area being small on a hilltop as well as uneven terrain, an extensive heliborne survey may be recommended for covering a wider area that will ensure a highly reliable outcome.

Acknowledgments

The authors wish to record their sincere thanks to Sultan Qaboos University for the strategic grants (SR/SCI/ETHS/12/02) provided to support this investigation.

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