

# Aeromagnetic Reconnaissance of Zagami Meteorite Impact Site, Katsina State, North-Western Nigeria for an Impact Crater

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**Abstract**— The fall of meteorite usually produces terrestrial impact crater and structural features around it. Zagami meteorite fall was witnessed and about 18 kg sample was recovered at Katsina Province, Nigeria. Surficial investigation of the impact site with Landsat images and SRTM data did not reveal an impact crater. This could have resulted from concealment overtime by erosion, post-cratering sediments and/or anthropogenic activities. In such a case, non-invasive geophysical method can be used for subsurface investigation, but it is not affirmative of an impact crater existence. This study enhanced aeromagnetic data of the impact site with 3-D Euler deconvolution and 2-D forward modelling techniques for subsurface investigation aimed at identifying and characterizing an impact crater. The results showed that an elliptical negative magnetic low underlain the spot where the meteorite sample was recovered. The elliptical magnetic low, configuration of surrounding structural features with depth range 16 m to 350 m, and 2-D depth image of the subsurface suggested possible formation of a concealed impact crater with edges at a depth between 120 m and 140 m, minimum diameter of 570 m, breccia thickness of 10 m and true depth of 180 m from the meteoric impact. The depth and diameter of the suspected impact crater are consistent with the crater scaling equation for simple impact craters, but they cannot ascertain whether the magnetic feature was formed pre-, post- or syn-impact. Hence, further study is required to confirm whether the magnetic feature was formed by the meteoric impact or another event.

**Keywords**—Aeromagnetic, Reconnaissance, Subsurface structure, Impact crater, Imaging, Modelling.

## I. INTRODUCTION

The curiosity of human beings has been the impetus to explore everything in their vicinity. This has been enhanced by creativity and resourcefulness at developing scientific methods and technological devices which have evolved over the years. The surface and subsurface of the Earth have earned recognition as part of the exploratory targets of human beings. These parts of the Earth contain landforms, structures and morphology which are consequential of geologic processes. One of the geologic processes is impact cratering proven by space programs to be momentous cause of impact craters. It is imperative to recognize that not all craters on Earth are impact craters because they may be caused by other geologic processes (McHone, 1986). The sequence of events of an impact cratering have been classified into three main stages: compression stage, excavation stage and modification stage

(Gault et al., 1968; Simonds et al., 1978; Melosh, 1989; Adepelumi et al., 2005).

The criteria for identifying a terrestrial impact crater are grouped into field criteria and laboratory criteria (McHone, 1986). The most important criterion for recognition of terrestrial impact craters is the occurrence of shock-metamorphic effects not their form (Grieve and Pilkington, 1996). Based on morphology, impact craters are categorized into simple craters and complex craters (Henkel and Reimold, 2002; Les, 2012; Reimold and Koeberl, 2014). Impact craters are being searched and studied for academic and economic values (Reimold and Koeberl, 2014), and they help scientists to gain insights into the past, present and future of impacts in all parts of our Solar System. Large scale impact events are known for producing significant environmental and natural consequences (Adepelumi et al., 2005; Reimold and Koeberl, 2014). The natural consequences include alteration of physical properties and mineralogical phase, and structural deformation of the subsurface rocks at a terrestrial impact site (Cisowski and Fuller, 1978; Zhang et al., 1988; Hart et al., 1995; Amir et al., 2002; Adepelumi et al., 2005). The significant and detectable contrast in the physical properties of rocks at an impact site justifies the application of geophysics to identifying and characterizing a terrestrial impact crater. However, geophysics or remote sensing is not self-sufficient in proving the existence of an impact crater. Ground-truthing and laboratory analysis of rock samples acquired from field work or drilling at an impact site are required in every instance (Reimold and Koeberl, 2014).

Twenty-one meteorites have been officially recognized from Nigeria over the years 1903 to 2019, and one of them was named Zagami (LPI, 2022). The record of the fall of Martian meteorite called Zagami and its sample recovered at a Global Positioning System (GPS) location 7° 5' E, 11° 44' N has been extensively documented (Graham et al., 1985; Haag, 1991; Meyer, 2012; Adigun, 2017), but no terrestrial impact crater has been associated with the Zagami meteoric fall. Remote sensed data and imagery are accessible these days through online digital repositories for crater discovery (Pourkhorsandi, 2013; Gottwald et al., 2017). Among the terrestrial impact craters that were initially discovered with Land Satellite (Landsat) Imagery are Serra da Cangalha crater (Dietz and French, 1973) and Sithylemenkat crater (Cannon, 1977). Landsat images and 30-metres resolution Shuttle Radar Topographic Mission (SRTM) elevation data of the Zagami meteorite impact site were downloaded from United States

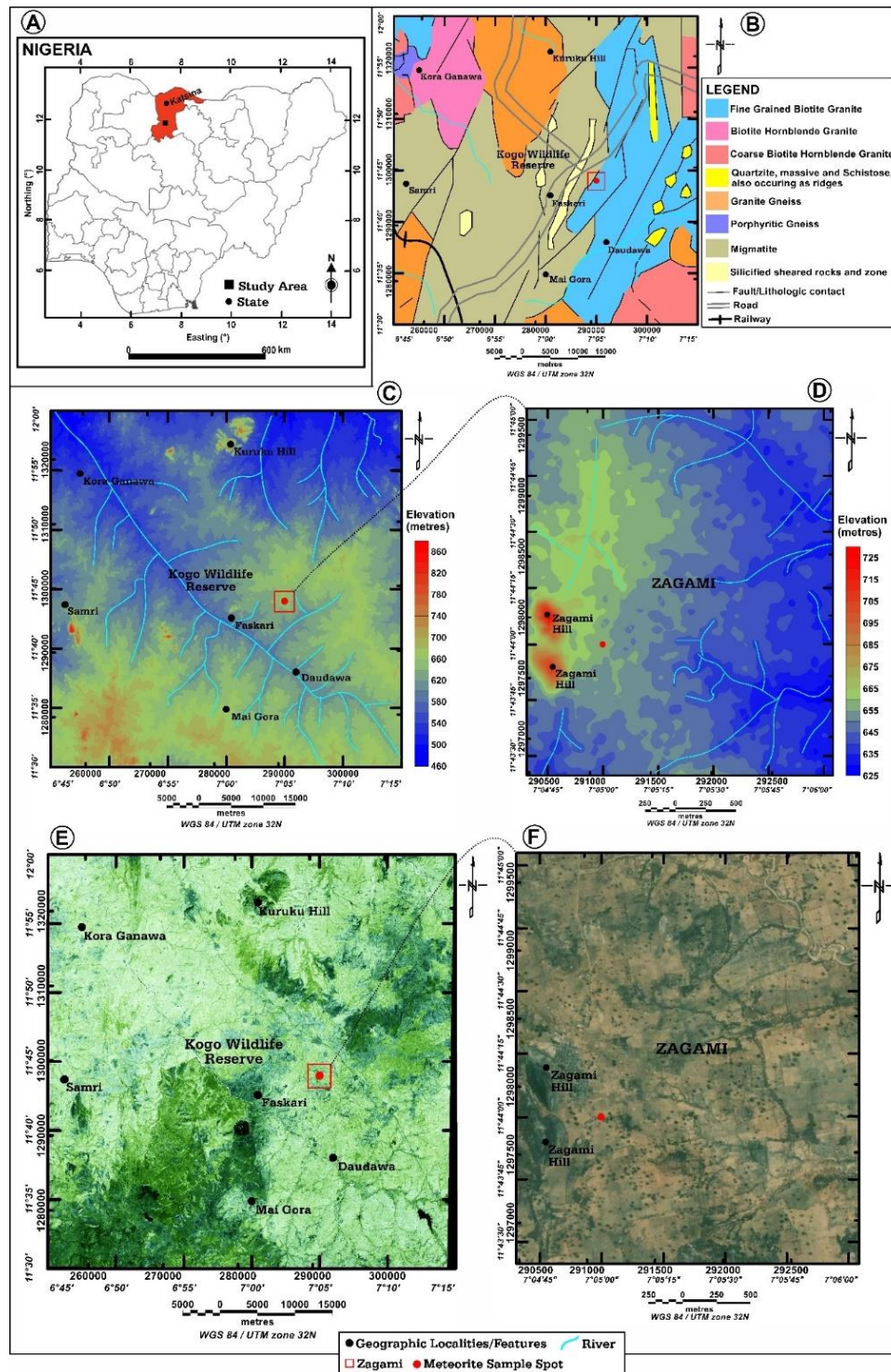


Fig. 1. (a) Location map (b) Geological map (after NGSA, 2006) (c) 30-metres resolution Shuttle Radar Topographic Mission (SRTM) elevation data (d) Narrow-scale 30-metres resolution SRTM elevation data (e) Land Satellite (Landsat) image (f) Narrow-scale Landsat image of the study area.

Geological Survey (USGS) website, processed and visually scanned at broad and narrow scales for an impact crater but none was found (Figs. 1c, 1d, 1e and 1f). The Landsat images and SRTM data gave only the surface view of the impact site. Hence, the subsurface image of the impact site is pivotal to probing further for the identification of a probably concealed impact crater from Zagami meteoric fall. The aim of this study is to identify and characterize a probable subsurface impact crater at the Zagami meteorite impact site. This will be achieved by carrying out 3-D Euler deconvolution and 2-D

forward modelling on the aeromagnetic data of the impact site to help delineate and estimate the depths to the structural features beneath the impact site, and help have an overview of the 2-D subsurface image of the probable impact crater.

### 1.1. Geographical and Geological settings of the study area

The total surface area of the study area is approximately 3,080 km<sup>2</sup>, and it lies within the Universal Transverse Mercator (UTM) Zone 32N coordinate Y (1272000 mN, 1328000 mN) and X (255000 mE, 310000 mE) (Fig. 1b) in the



southern part of Katsina State, North-Western Nigeria (Fig. 1a). It is easily accessible through a good network of roads, railway and footpaths (Fig. 1b). The terrain consists of gently undulating topography heavily dissected by rivers and streams (Figs. 1c and 1d), and steeply undulating topography of rock hills such as the Kuruku hill elongated in approximately northeast-southwest direction (Figs. 1c and 1e) and Zagami hill elongated in approximately north-south direction (Figs. 1d and 1f). The topographic elevation of the study area ranges from 460 m to 900 m above mean sea level (Fig. 1c). The drainage pattern is dendritic with the main river approximately 80 km curvilinear length running northwest-southeast within the study area (Figs. 1c and 1d). The study area falls within the tropical continental climate region, the period of rainfall is from May to November, and the vegetation consists of tall tussocky grasses of guinea affinities mixed up with fine-leaved species of thorny trees.

The study area is a part of the Precambrian Basement Complex terrain of Nigeria within the Pan-African mobile belt (Obaje, 2009). The local lithology in the study area are shown in Fig. 1b (NGSA, 2006). At least four major orogenic cycles (Liberian, Eburnean, Kibaran and Pan-African) of deformation, metamorphism, remobilization and migmatization (granitization and gneissification) are consensually accepted to have influenced the geological setting of the terrain (Burke and Dewey, 1972; Abaa, 1983; Gandu et al., 1986; Olayinka, 1992; Obaje, 2009).

The significance of the geographical setting is the likely occurrence of anthropogenic activities, surface weathering and erosion which are inimical to the preservation of surface expression of a probable impact crater and associated structural features within the study area. While the geological setting is favourable to the aeromagnetic reconnaissance of the study area for a probable concealed impact crater because most basement rocks are known to contain magnetic minerals, which are susceptible to the geomagnetic field of the Earth.

## II. MATERIALS AND METHOD

### II.I. Aeromagnetic Data and Processing

The aeromagnetic data used for this study was acquired by the Nigerian Geological Survey Agency (NGSA) with specification which met the requisites of high resolution aeromagnetic (HRAM) data as defined by Ferraccioli et al. (2002). The specification used for the acquisition of the aeromagnetic data is a nominal flight altitude of 80 m ground clearance, equally spaced flight traverses of 0.5 km interval and NW-SE orientation, and tie lines with 2 km interval flown in a NE-SW direction. The aeromagnetic data was processed with Geosoft software, Oasis Montaj TM version 8.3 which has been proven from several geophysical studies to be consistent at effective processing of aeromagnetic data and delivery of good results for over two decades (Oyeniya et al., 2016; Adepelumi and Falade, 2017). The preliminary data corrections, such as offsets, external time-varying field effects and Earth's core magnetic field were carried out by the data acquisition contractor, Fugro Airborne Surveys for the NGSA. This ensures that the magnetic variations represented by the aeromagnetic data are approximately from only sources within the Earth's crust (Telford et al., 1990).

The processing therefore proceeded with the use of upward continuation technique to filter noise from the aeromagnetic data. Upward continuation technique is capable of attenuating high amplitude and short wavelength which are associated with near-surface magnetic noise in an aeromagnetic data (Lidiak et al., 1985). After noise-filtering, the aeromagnetic data was reduced to the geomagnetic equator using the geomagnetic inclination and declination of  $0.283^\circ$  and  $-0.35^\circ$  respectively. Reduction to the geomagnetic equator is a reverse of reduction to geomagnetic pole required to symmetrize and centre the magnetic anomalies over the sources for easier interpretation at a low geomagnetic latitude (Silva, 1986; Hansen and Pawlowski, 1989; Keating and Zerbo, 1996; Rajagopalan, 2003). Finally, residualization was carried out on the reduced-to-equator aeromagnetic data. This retained the local magnetic response at the expense of regional magnetic response (Telford et al., 1990), and the resulting residual magnetic intensity data was presented as a colour shaded relief maps for interpretation.

### II.II. 3-D Euler Deconvolution Technique

Euler deconvolution has become a widely approved technique for quasi-automated estimation of the location and depth of sources of potential field anomalies with little prior knowledge about the source geometry and more importantly, without information about the magnetization vector in the case of magnetics (Thompson, 1982; Reid et al., 1990; Mushayandebvu et al., 2004; Adepelumi et al., 2005; Oyeniya et al., 2016). The technique has been applied to aeromagnetic and gravity data by several researchers for subsurface imaging of craters. Examples include Charlevoix, Canada (Keating, 1998), the Bangui anomaly, central Africa (Ravat et al., 2002a) and the Serra da Cangalha impact crater (Adepelumi et al., 2005). Euler deconvolution technique takes advantage of the fall-off in potential field strength with distance from an anomalous source to determine its depth and location from a potential field data such as magnetic data. (Thompson, 1982; Reid et al., 1990; Cooper, 2002; Keating and Pilkington, 2004). The measure of the fall-off rate is related to the geometry of an anomalous body, and it is the extremely important parameter known as structural index,  $\eta$  (Thompson, 1982; Barbosa et al., 1999) in finding the best solution to the mathematical expression of the technique (Reid et al., 1990):

$$x \frac{\partial T}{\partial x} + y \frac{\partial T}{\partial y} + z \frac{\partial T}{\partial z} + \eta T = x_0 \frac{\partial T}{\partial x} + y_0 \frac{\partial T}{\partial y} + z_0 \frac{\partial T}{\partial z} + \eta T \beta \quad (1)$$

where  $\beta$  is the regional value of the potential field and  $(x_0, y_0, z_0)$  is the position of the source, which produces the total potential field  $T$  measured at  $(x, y, z)$ . The admissible structural index values for magnetic data are within the range of 0 to 3 (Reid et al., 1990, 2003; Hsu, 2002). A wrong or poor choice of the structural index value is bound to bias the estimation of depth and diffuse the solutions of source locations (Hsu, 2002; Keating and Pilkington, 2004). A correct choice of structural index value will produce tightest clustering of Euler deconvolution solutions around an anomalous body (Thompson, 1982; Reid et al., 1990). The spray of solutions from tightest cluster on a source body could be spurious solutions arising from variety of causes (Reid et al., 2013) or diagnostic of a dipping source (Kuttikul, 1995).

Based partly on mathematical analysis and partly on experience, the rules that must be followed to avoid the abuse of application of Euler deconvolution to potential field data have been proposed and extensively discussed by Reid et al. (2013). The standard execution of Euler deconvolution solves an overestimated system of linear equations for each position of its fixed-size moving window to generate location and depth of the sources (Thompson, 1982; Reid et al., 1990). Euler deconvolution technique has its disadvantages and limitations as it is with every interpretation technique, but its usefulness outweighs them (Adepelumi et al., 2005). Several approaches have been found useful and effective at improving the solutions of Euler deconvolution technique. Some of the improvements include the located Euler deconvolution (Blakely and Simpson, 1986; Bainbridge et al., 2002), iterative Euler deconvolution (Cooper, 2020), weighted Euler deconvolution (Keating, 1998), application of the technique to the derivatives of potential field data (e.g. Ravat et al., 2002b; Hsu, 2002) and multi-source implementations (e.g. Hansen and Suci, 2002). In this study, the 3-D Euler deconvolution solutions were computed using the first vertical derivative of the residual magnetic intensity data. Euler deconvolution solutions for all plausible structural index values were obtained, but  $\eta = 3.0$  which gave the tightest clustering was presented for 3-D interpretation.

### II.III. 2-D Forward Modelling of the Subsurface

2-D forward modelling with magnetic data is applicable to investigating the subsurface structure of both confirmed and suspected impact crater (Armour et al., 2017). An apparent advantage of geophysical modelling is easy extraction of quantitative information of the subsurface from resulting image(s) through the structure under investigation. In geophysical modelling, a chosen geological model of the subsurface and its computed waveform are adjusted until there is a close-match between the computed data of the model and the field data. The degree of the match obtainable is dependent on the initial choice of subsurface geological model and the signal-to-noise ratio of the field data (Kearey et al., 2003, Fedi and Pilkington, 2012). In order to reduce the instability and non-uniqueness of the solution associated with forward

modelling, there must be geological and geophysical constraints.

The 2-D depth image of the suspected Zagami impact crater was produced with GM-SYS, a modelling package on Geosoft software, Oasis montaj, version 8.3. The modelling package used the algorithms of Wen and Bevis (1987) and the methods designed by Talwani et al. (1959), and Talwani and Heirtzler (1964). The subsurface model of a simple impact crater modified by Reimold and Koeberl (2014) after French (1998) was adopted for the forward modelling, and it was constrained with the results of the 3-D Euler deconvolution technique and geological information of the study area.

### III. RESULTS AND DISCUSSION

The residual magnetic intensity maps provide the aeromagnetic imaging of subsurface of the study area (Figs. 2a and 2b). It is characterized by magnetic variation between -36 nT to 32 nT classified into high, intermediate and low magnetic relief zones, which are designated by red/pink, green and blue tones respectively. The NE - SW and NW - SE trends of magnetic anomalies agrees with the prominent trends of lithology and geologic structures on the geologic map (Figs. 1b and 2a). This shows that the variation in magnetic intensity on the residual maps corresponds to the variation in lithology and geologic structures underlying the study area.

The visual examination of the residual magnetic map of the study area (Fig. 2a) does not reveal circular or ring-like magnetic anomaly of an impact crater expected at a low geomagnetic latitude (Les, 2012), but an elliptical negative magnetic low underlies the spot where Zagami meteorite was recovered (Fig. 2b). Magnetic anomaly may not necessarily be circular or ring-shaped over an impact crater (Henkel and Reimold, 2002; Reimold and Koeberl, 2014) as a result of flight height and line spacing in an aeromagnetic survey leading to attenuation and under-sampling of the magnetic anomaly of an impact crater, and the magnetic properties of the target rocks may be radically changed by several operative

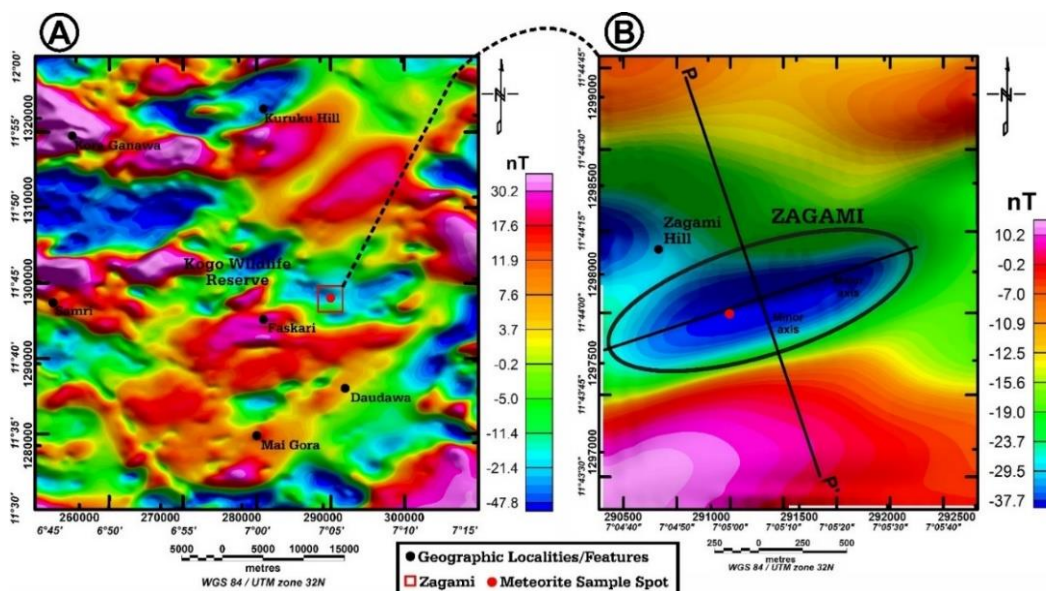


Fig. 2. (a) Residual magnetic intensity map of study area (b) Residual magnetic intensity map of the suspected Zagami impact crater magnetic anomaly, which shows its elliptical outline and profile PP' used for 2-D forward modelling.



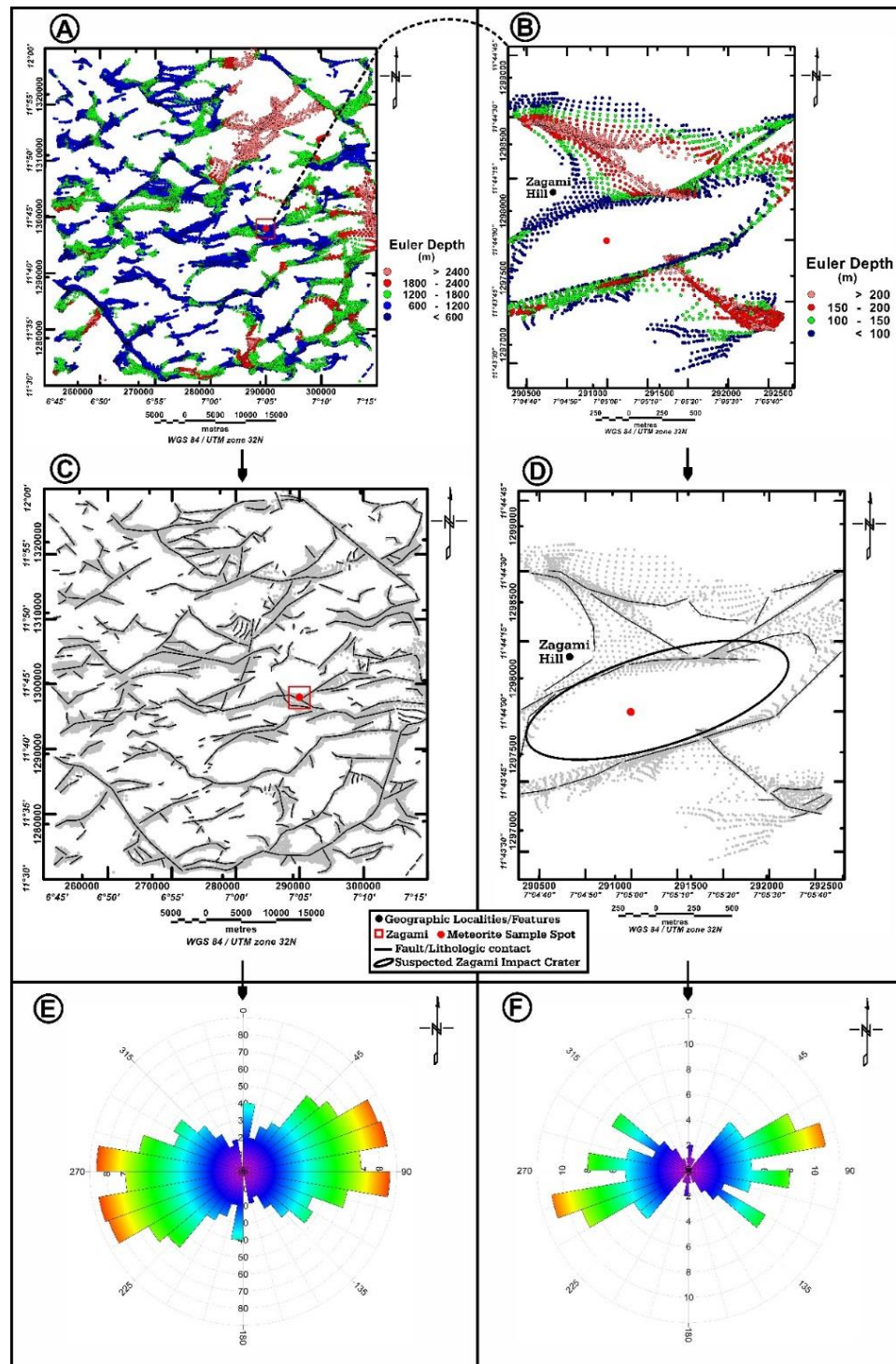


Fig. 3. (a) 3-D Euler deconvolution solutions of the study area for structural index,  $\eta = 3$ . (b) 3-D Euler deconvolution solutions of the suspected Zagami impact crater for structural index,  $\eta = 3$ . (c) Structural map superimposed on gray plot of Euler deconvolution solutions of the study area. (d) Structural map superimposed on gray plot of Euler deconvolution solutions of the suspected Zagami impact crater. (e) Rose diagram of estimated lineaments for the study area. (f) Rose diagram of estimated lineaments for the suspected Zagami impact crater.

mechanisms related to an impact process (Pilkington and Grieve, 1992; Grieve and Pilkington, 1996; Pilkington and Hildebrand, 2003). Also, the existence of impact craters with elliptical morphologies have been confirmed and documented (Kenkmann et al., 2022).

The NE – SW trend of the elliptical negative magnetic low is in stark contrast to the N – S trend of the Zagami hill (Figs. 1d, 1f and 2b), and the magnetic anomaly of the Zagami hill

might have interwoven with and distorted a circular anomaly into the elliptical anomaly due to overlapping effect. The elliptical negative magnetic low is therefore suspected to be from a subsurface impact crater formed by the fall of a large Martian meteorite, and the recovered Zagami meteorite is its fragment or remnant. It is suspected to be impact-related based on its form, and not its magnetic intensity (low or high). An impact crater could be characterized by either magnetic low or

magnetic high at any geomagnetic latitude depending on the magnetic susceptibility contrast between the impact crater and its host rock. For example, an impact crater characterized by magnetic low at the geomagnetic pole (low magnetic susceptibility) would still be characterized by magnetic low at the geomagnetic equator (high magnetic susceptibility) provided it was formed in a host rock with lower magnetic susceptibility. Therefore, neither magnetic high nor magnetic low is a diagnostic property for identifying an impact crater, but the form of the magnetic anomaly is one of the preliminary diagnostic properties for identifying an impact crater (Reimold and Koeberl, 2014). The strike length of the elliptical negative magnetic low is about 1.8 km, and the length of its minor axis is about 0.5 km (Fig. 2b). The suspected Zagami impact crater (based on magnetic anomaly form) is therefore characterized by central negative magnetic low having a relief of -38 nT and surrounded by higher magnetic anomalies (Fig. 2b).

The 3-D Euler deconvolution solutions obtained for the study area are presented as colour-range symbol maps to show the estimated depths and positions of magnetic sources (Figs. 3a and 3b). The accepted structural index solutions are based on percentage of error in depth and tightest clustering of solutions. The accepted maximum error in depth of Euler deconvolution solutions is 5.5 %. The Euler deconvolution solutions indicate magnetic source depths in the range 16 m to 5.8 km (Fig 3a) for the study area. The pattern of clustering of the Euler deconvolution solutions around the Zagami meteorite sample spot (Fig. 3b) mimics the elliptical negative magnetic low earlier suspected from residual magnetic intensity map (Fig. 2b) to be from a subsurface impact crater formed by the fall of a large Martian meteorite. The depth of the clustering around the Zagami meteorite sample spot within the range 16 m to 350 m (Fig. 3b) suggests that the suspected impact crater is shallowly buried. This confirms that the Euler deconvolution solutions are not artifacts, but are related to geological sources in the subsurface of the study area.

Figs. 3c and 3d represent the structural interpretation of the Euler deconvolution solutions in Fig. 3a and 3b respectively. The orientations or azimuthal directions of the lineaments on

the structural maps were measured and plotted on rose (azimuth-frequency) diagrams (Figs. 3e and Fig. 3f) using RockWorks16 software. The major trends of lineaments depicted by the rose diagram for the study area are ENE – WSW, WNW – ESE, NE – SW and NW – SE, with minor NNW – SSE and NNE – SSW trends (Fig. 3e). With the study area being a part of the Precambrian Basement Complex terrain of Nigeria (Obaje, 2009), these lineament trends suggest that structures delineated by the Euler deconvolution are most likely due to several tectonic deformations which affected the Nigerian basements (Burke and Dewey, 1972; Abaa, 1983; Gandu et al., 1986; Olayinka, 1992; Obaje, 2009). The rose diagram for the structural analysis of the lineaments around the Zagami meteorite sample spot (Fig. 3f) shows similar pattern of major and minor trends to the rose diagram of the structural analysis of the whole area (Fig. 3e). The lineaments delineated around the Zagami meteorite sample spot fall on the edge and within the elliptical outline of the suspected Zagami impact crater, while those outside are either directly or indirectly connected to the lineaments on the edge and within the elliptical outline of the suspected impact crater (Figs. 3b and 3d). While this configuration of the lineaments which are possibly fractures around the Zagami meteorite sample spot suggests that they could be due to the meteoric impact, it is not certain whether they were formed pre-, post- or syn-impact.

The resulting depth image from the 2-D forward magnetic modelling carried out along profile P – P' (Fig. 2b) for the suspected Zagami impact crater is shown in Fig. 4. It shows that the minimum diameter ( $D_m$ ) of the suspected impact crater is 570 m. The depth to the edges (rims) of the suspected impact crater is between 120 m and 140 m. The apparent source depth ( $d_a$ ) at the centre of the suspected impact crater is 170 m to the breccia unit, and the true source depth ( $d_t$ ) at the centre of the suspected impact crater is 180 m (Fig. 4). The true depth and minimum diameter of the suspected impact crater are consistent with the crater scaling equation for simple impact craters (Pilkington and Grieve, 1992) given as:

$$d_t = 0.28D^{1.02} \quad (2)$$

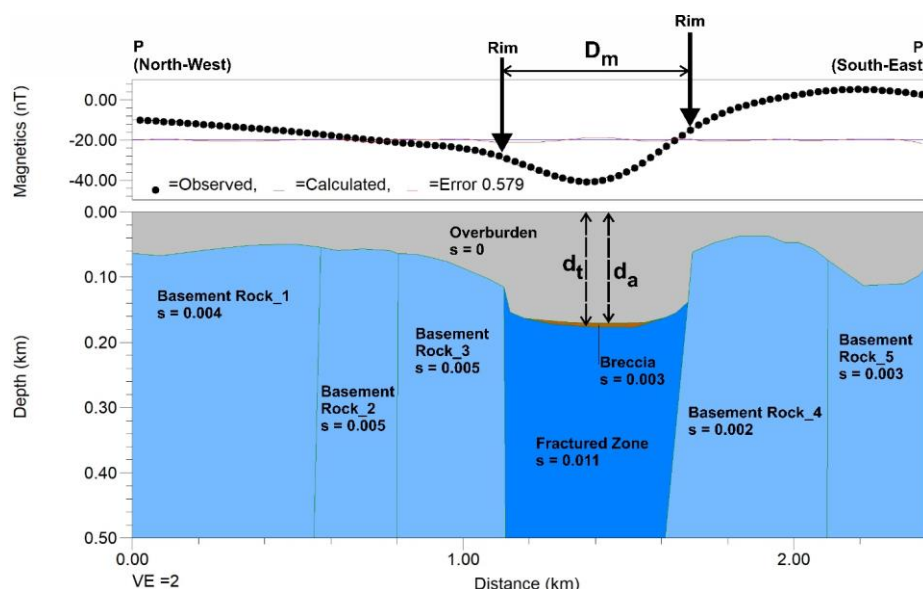


Fig. 4. 2-D depth image from forward modelling of the suspected Zagami impact crater. Where  $D_m$  is the minimum diameter,  $d_a$  is the apparent depth and  $d_t$  is the true depth of the suspected impact crater.

The 2-D depth image shows that the magnetic susceptibility of the basement rock under the suspected impact crater is significantly higher than the magnetic susceptibilities of adjacent basement rocks (Fig. 4). This is in conformity with the fact that a negative low magnetic anomaly is expected to have higher magnetic susceptibility at low geomagnetic latitudes (Oyeniyi et al., 2016), and it also adds to the credibility of the 2-D forward modelling of the suspected impact crater. This higher magnetic susceptibility is possibly due to fracturing and impact-related mechanisms that might have altered the magnetic property of the basement rock under the suspected impact crater.

#### IV. CONCLUSION

The geophysical reconnaissance of the Zagami meteorite impact site using aeromagnetic data was enhanced with 3-D Euler deconvolution and 2-D forward modelling techniques for identification and characterization of a subsurface impact crater that might have formed from the Zagami meteorite fall. An elliptical negative magnetic low which underlies the Zagami meteorite sample spot was revealed by the residual magnetic intensity map, and it was suspected to be from a concealed impact crater in the subsurface of the study area. The 3-D Euler deconvolution solutions and its structural interpretation maps reveal a configuration of lineaments with depth range 16 m to 350 m on the edge, inside and outside of the elliptical magnetic anomaly in a way which suggested that they could be due to the Zagami meteoric impact. The 2-D depth image from the forward modelling of the suspected elliptical impact crater shows its edges at a depth between 120 m and 140 m, and having breccia thickness of 10 m. The suspected impact crater minimum diameter of 570 m and true depth of 180 m are consistent with the crater scaling equation for simple impact craters. The basement rock below the suspected impact crater has a significantly higher magnetic susceptibility than adjacent basement rocks. The study concluded that the high magnetic susceptibility might be due to fracturing and alteration of the underlying basement rock by impact-related mechanisms. But aeromagnetic data cannot on its own ascertain whether the fractures were formed pre-, post- or syn-impact. The identified elliptical negative magnetic low from this geophysical reconnaissance study remains suspected to be from a subsurface impact crater underlying the spot where the Zagami meteorite sample was recovered, and it will take further study to confirm whether the elliptical negative magnetic low is due to the meteoric impact or another event.

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