A Systematic Review of Geophysical Studies at the Bosumtwi Impact Crater in Ghana

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Abstract

Meteorite impact craters are an essential process in how planetary bodies evolve, and a resurgence in space exploration has necessitated a renewed focus on such studies. But due to the non-uniqueness of the geological characteristics associated with impact craters, the science of geophysics plays an indispensable role in identifying them. The Bosumtwi Impact Crater in Ghana is one of the world's youngest well-preserved mid-sized impact craters. Here we explore the current state of geophysical research in the Bosumtwi Impact Crater, focusing on analysing what part has been played in this research by local researchers. We employed the PRISMA technique for data collection, which includes identifying the sources of data required for the analysis, screening and checking the eligibility of the data. We report that the peak number of articles (7) was published in 2006. Researchers affiliated with Ghanaian institutions are in third place, with 13 % of the articles. We also observe that only two articles report a funding source from Ghana, where the Bosumtwi Impact Crater is located. All the major geophysical methods applied in geophysical studies have been observed in the studies on the Bosumtwi Impact Crater. These studies confirm the presence of shock-metamorphosed rocks. Results from our review show that, while geophysical methods did not provide an unambiguous signature for the Bosumtwi Impact crater, they provided constraints for confirming the impact origins. Our findings are significant because they highlight the lack of local financial support for research in Ghana and African countries in general. A compelling consequence of the underrepresentation of Ghanaian geophysical researchers on studies in the Bosumtwi Impact Crater is the lack of studies on hazards which is very important due to the impact origins of the crater.

Keywords: Bosumtwi Impact Crater; Systematic Review, Geophysics; Ghana; funding research.

1.0 Introduction

Impact craters are important because they are responsible for massive extinctions, can serve as natural laboratories for studying broad geological processes and are associated with ore bodies and hydrocarbon deposits (*French, 2004; Grieve and Masaitis, 1994; Marvin, 1999*). Increasing interest in space exploration has compelled a renewed interest in understanding meteorite impact events. One major use of impact crater studies in space exploration is estimating the age of the surface of a solid planetary body (*Michel and Morbidelli, 2012*). Most solid planetary bodies and satellites have a history of accumulated impact craters on their surfaces. These craters come in many sizes. The age of a surface is related to the number of impacts it has endured, assuming a constant impact rate across time. The total number of craters may therefore be used to determine how old a surface is if it is feasible to estimate the rate of crater creation on that surface.

Compared with Mars, which has over 300,000 impact craters with at least 1 km diameter, only 188 have been identified on Earth so far (*Hergarten and Kenkmann, 2015*). The lower number of discovered craters is obviously due to the Earth's weathering process, which presents a challenge to identifying craters on Earth. But there has been an increasing amount of research dedicated to investigating impact craters worldwide. Progressive research has focused on distinguishing impact craters from their surroundings *(Glikson and Haines, 2005; Koeberl and Anderson, 1996; Koeberl and MacLeod, 2002*). Previous work has established that most of the geological characteristics associated with impact craters are not unique, e.g., their generally circular shape, circular deformation pattern, extensive fracturing and brecciation, circular gravity and magnetic anomalies, and the presence of sizable igneous rock units (*French and Koeberl, 2010*). Other conventional processes like tectonic deformation, salt-dome formation, volcanic eruption, or internal igneous activity can also generate such geological characteristics. Distinct identifying signatures are shock-metamorphic effects which are particular outcomes of an impact's shock waves*(Grieve, 1991; Stöffler and Langenhorst, 1994*). Continuous research in identifying formerly unrecognised impact craters and their evolution is critical. However, a cursory look at the literature shows that the distribution of research output and researchers participating in impact crater research is not uniformly distributed.

In Ghana, West Africa is one of the youngest well-preserved mid-sized Impact Craters known as the Bosumtwi Impact Crater. According to*Karp et al. (2002*), the Bosumtwi Impact Crater is "more comparable in form and impact to lunar and planetary craters than other terrestrial craters". This paper explores the current state of geophysical research in the Bosumtwi Impact Crater, focusing on analysing what part has been played in this research by local researchers. Specifically, this study will seek to answer the following questions concerning the Bosumtwi Impact Crater: what is the yearly distribution of publications on geophysical investigations; what is the country distribution of publications on geophysical investigations; what is the funding distribution of publications on geophysical investigations; which geophysical methods have been applied and how were they utilised? In this paper, our principal focus has been on understanding the contribution of researchers in-country to geophysical research in an obviously scientifically important place.

The study is organised into the following sections: Section 1 covers the study's introduction. Section 2 outlines the geophysical methods used in discovering impact craters. Section 3 provides information on the systematic review methodology used in this study. Section 4 outlines the results of this study, including publication distribution yearly, publication distribution on a country basis, publication distribution on a funding basis and the specific applications of geophysics in the Bosumtwi Impact Crater. Sections 5 and 6 discuss the findings and present the study's conclusions.

2.0 Geophysical Investigations in Impact Craters

Unlike Earth, impact craters can commonly be recognised from morphological characteristics on the Moon and other planetary bodies that lack an appreciable atmosphere. However, a large portion of the record of impact is modified and partially destroyed due to the extremely dynamic terrestrial geologic environment. The initial morphological components of terrestrial impact craters are swiftly destroyed by erosion, and over time, the geological and structural imprint is also lost. On the other hand, sedimentation obscures craters from view while protecting them. To identify impact craters, a simple workflow usually applied involves detecting crater morphology, geophysical anomalies, evidence for shock metamorphism and the presence of meteorites or geochemical evidence for traces of the meteoritic projectile. Geophysical anomalies are, therefore, an essential process for identifying impact craters (*Grieve and Pilkington, 1996*).

In 1992, *Pilkington and Grieve* attempted to compile the basic geophysical details of terrestrial impacts.

Further reviews on this subject can be found in *Grieve and Pilkington (1996*). The methods commonly used in impact crater investigations are gravity, magnetic, seismic, geoelectrical and Ground Penetrating Radar *(Karp et al., 2002; Pilkington and Grieve, 1992; Reimold and Koeberl, 2014*). The use of these methods depend on the fact that impact craters frequently have a distinct geophysical signature, and changes in the physical characteristics of the near-surface are effective indications of lithological changes.

Simple and complex structures are the two categories of impact structures' morphology. Positive and negative gravity anomalies represent higher and lower densities, respectively, compared to a baseline value, showing how sensitive gravity readings are to changes in near-surface density. Negative gravity anomalies are often circular and extend to or just beyond the crater rim and are linked to impact craters. Although low-density impact breccias and sedimentary infill may also contribute to the density loss, the target rocks' fracture and brecciation is the primary reason (*Grieve and Pilkington, 1996*). A magnetic anomaly near zero is a common feature of impact craters, which shows that the impact process has demagnetised the materials there (*Pilkington and Hildebrand, 2003; Plado et al., 2000*). The centre of larger craters may be affected by short-wavelength magnetic anomalies, and if the zone of central uplift is created from magnetic basement material, it will result in a longer-wavelength magnetic anomaly. Short-wavelength anomalies can be caused by various processes, including shock metamorphism, hydrothermal processes, post-impact cooling, melts, and impact breccias. As electric current flows more freely in the salty water that often fills the pore space and fissures, resistivity typically reduces with increased porosity. Thus, at impact craters, resistivity is often higher in deeper portions of the central uplift and lower in less fractured or brecciated rocks, allochthonous deposits, and porous sedimentary infill (*Aning et al., 2013*). Seismic reflection data have been used to image a variety of crater features, including faulted blocks of target rocks that are downthrown and/or rotated in the terrace or megablock zone, coherent reflections in targets rocks that become increasingly disturbed when tracked towards the crater center, and uplifted rocks in the crater center (*Karp et al., 2002*).

3.0 Systematic Review Methodology

We employed the PRISMA technique (*Liberati et al., 2009*) for data collection, including identifying the data sources required for the analysis, screening and checking data eligibility. In this study, we used a mixture of keywords to classify studies that utilised geophysical methods to investigate the Bosumtwi Impact Crater. Using three databases (SCOPUS, Google Scholar and Dimensions), we searched for articles in English related to geophysical studies in the Bosumtwi Impact crater from 2000 to date. We assume that these databases represent a wide range of scientific literature (*Gupta et al., 2018; Gusenbauer and Haddaway, 2020; Waddington et al., 2012*). The specific keywords used were "Geophysical" and "Bosumtwi" OR "Bosumtwe" and "Impact Crater". An additional list of words used in this study is "Seismic" and "Resistivity" and "Magnetic" and "Gravity" and "GPR" and "Remote Sensing" and "Electromagnetic". *Table 1* shows the breakdown of the number of items identified from the three databases. From this search a total of 278 articles; 28 from SCOPUS, 210 from Dimensions and 40 from Google Scholar were identified. After deleting duplicates, we were left with 117 publications (see *Figure 1*). The resultant studies found from the literature search were further manually screened by reading their titles and abstracts. Consequently, we exclude review articles, technical reports, books, conference papers, and theses. *Figure 1*shows a schematic workflow for the data screening process.

Table 1. Databases and the number of items identified from the databases.

Database	**Number of articles**
SCOPUS	28
Dimensions	210
Google Scholar	40
	278

After the screening phase, the remaining 42 articles were assessed by reading their full texts. We choose the full texts that fully meet our eligibility criteria for further analysis. To gauge the objectivity of this process, the selected articles were given to three other reviewers for assessment. The three reviewers assessed the full texts independently. The final number of articles with significant agreement among our reviewers for analysis was 23.

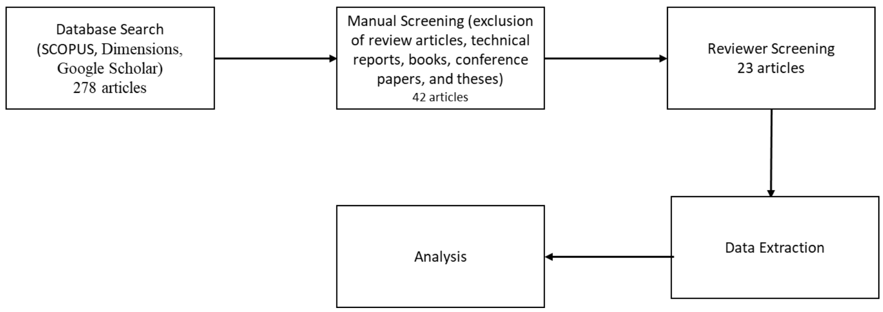

Figure 1. Schematic workflow for the data screening process.

Framework for Analysis

After the full-text assessment, there are 23 articles. We analyse the articles with a predefined data extraction framework. *Table 2*shows the data extraction framework used in this study.

Table 2. Data extraction framework used for analysis

	Information Extracted	**Description**
Bibliometric material	Year of Publication, Authors and their affiliations, number and type of institution.	Nationality of first/corresponding authors, the type of institution and the number of institutions.
Data and measurement	Geophysical method, purpose of the study, approach and analysis technique	Which methods were used? The aim of the study and the approach and technique used for the study.
Results	Major findings	What were the results obtained?
Funding	Funding Agencies	Were the funding agencies from Ghana, other African countries, or outside Africa?
Journal	Journal Name	Type of journal of publication

4. 0 Results

4.1 Overview of the Bosumtwi Impact Crater

The Bosumtwi Impact Crater is 1.07 Myr old and, therefore, one of the youngest moderately sized impact craters on Earth. The impact occurred in the 2.1 to 2.2 Gyr Proterozoic Birimian Supergroup, which is intruded by granitic and granodioritic bodies. The crater is classified as one of the best-preserved impact structures on Earth. The crater (06°30'N, 01°25'W) is 30 km southeast of Kumasi, the second-largest city in Ghana. It is a complex impact crater with three distinct rings. The 10.5 km diameter inner crater is filled with a lake 8 km in diameter and 75 m deep at its centre (*Boamah and Koeberl, 2007*). The inner rim of the crater rises 200 to 300 m above the lake level and is covered by ejecta blankets (*Theilen-Willige, 2021*). An outer rim also occurs 18-20 km from the centre of the structure. Also, in the centre of the Bosumtwi impact crater exists a central uplift with a diameter of 1.9 km (*Reimold and Koeberl, 2014*). The lake in the impact crater has no outlet and is mainly controlled by rainfall and the rate of evaporation from the surface

(*Turner et al., 1996*).

As far back as 1899, people wondered about the origins of the Bosumtwi Impact Crater after locals complained about a two-year cycle of sudden bubbling on the lake accompanied by a strong sulphurous smell (*Jones, 1985*). This phenomenon and the crater depression indicated volcanic origins to scientists at that time. Due to the lack of evidence of volcanic activity in the observed rocks, this theory was not generally accepted. The first suggestions of a meteorite impact origin were first promulgated in 1931 by *Maclaren* . He categorically ruled out volcanic origins since no evidence could be found to support such a claim. He then proposed meteorite impact as the cause of the crater. *Maclaren*(*1931*) also arguably conducted the first geophysical survey using a prismatic compass and dip compass to make magnetic observations. He observed fluctuations in inclination and magnetic intensity, implying the existence of a magnetic body. But volcanic origin theory remained an alternative theory until the second half of the 20^{th}century. In the 1960s, a series of expeditions to the Bosumtwi crater resulted in samples being sent to the United States for laboratory investigations (*Jones, 1985*).

In addition, a swarm of tektites were discovered in Cote D'Ivoire and associated with the Bosumtwi impact crater. The laboratory investigations were mainly based on comparing the ages and compositions of the tektites from Cote D'Ivoire to glass samples in tuffaceous rocks and other rock samples from Bosumtwi. Using techniques such as the K/Ar technique, fission track dating, Rb/Sr technique, and XRF analyses, the content of radioactive elements (U, Th, K), O^{18}/O^{16} ratio analysis large body of evidence was accumulated showing similarities between the Cote D'Ivoire tektites and the rocks samples from Bosumtwi. These data reinforced the impact crater theory based on the tektites being derived from ejecta originating from the Bosumtwi crater. With the meteorite impact crater theory now firmly established, subsequent research from the 1970s onwards (*Jones, 1985; JONES et al., 1981; Palme et al., 1978)*focused on identifying other characteristics reminiscent of impact craters.

4.2 Publication distribution on a yearly basis

Figure 2 shows the yearly distribution of articles from all the accessed databases from 2000 to 2021. The figure shows that the peak number of articles (7) was published in 2006. Four (4) articles followed this in 2007. In 2004, 2013 and 2018, two (2) articles each were published. In 2000, 2001, 2002, 2003 and 2019, only a single article each was published regarding geophysical studies in the Bosumtwi Impact Crater. No articles were published in 2005, 2008, 2009, 2010, 2011, 2012, 2014, 2015, 2016, 2017 and 2020. The cluster of articles from 2006 and 2007 is due to the multidisciplinary International Continental Drilling Program (ICDP), a project that took place in 2004. The project involved unravelling the 3D building blocks of the impact crater, delineating key lithological units, imaging fault patterns, and defining key alteration zones (*Koeberl et al., 2005*).

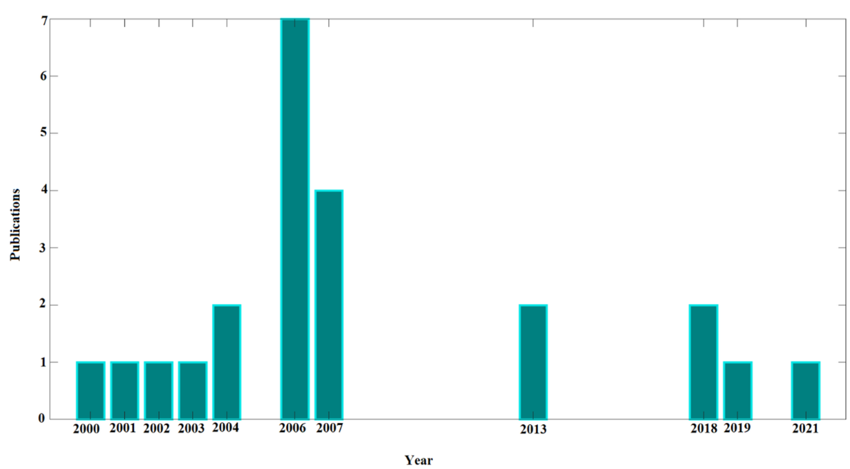

Figure 2. Total number of publications from 2000 to 2021.

4.3 Publication distribution on a country basis

To identify the publication distribution on a country basis, we used the first author and/or the corresponding authors to represent the country we tied the article to. Our primary interest was in the country in which their institution of affiliation was located. *Figure 3* shows the distribution of publications by country basis. Surprisingly, Canada and Germany have the highest number of publications on geophysical investigations in the Bosumtwi Impact Crater. Researchers associated with institutions in Canada have authored 25% of the articles, whereas authors affiliated with German institutions have 21% of the articles. Researchers affiliated with Ghanaian institutions come in third place with 13 % of the articles. Other countries represented are Rwanda, France, Finland, Austria, Russia, South Africa and Estonia. In*Figure 3b,* we observe that on a global scale, whereas only thirteen (13%) of the published studies on the Bosumtwi impact crater were authored by researchers from Ghana, eighty-seven percent (87%) of the geophysical studies on the Bosumtwi impact crater were authored by researchers affiliated to institutions from outside Ghana. Out of this, eighty-seven percent (87 %), eight (8 %) are by scientists from other African countries.

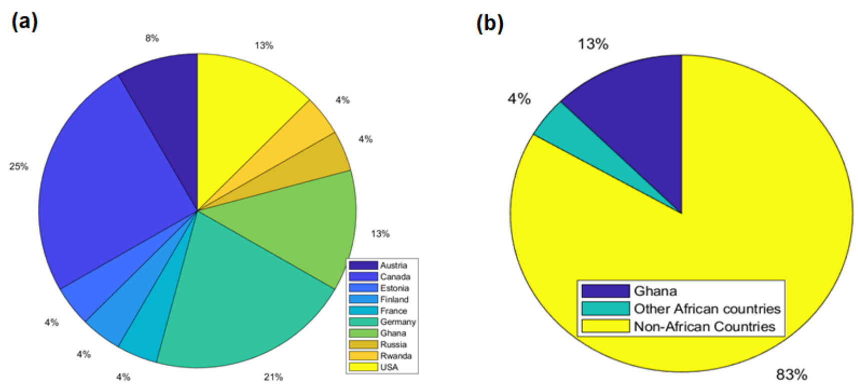

Figure 3. Pie chart illustrating the proportion of articles by country of affiliation. (a) Proportion by individual country (b) Proportion by African and non-African countries.

4.4 Publication distribution on a funding basis

The authors of 19 of the articles reported funding sources. *Table 3* shows the funding sources of the studies recovered in our studies. We observe that only two articles report a funding source from Ghana, where the Bosumtwi Impact Crater is located. These studies are *Aning et al. (2013*) and *Habimana et al. (2020*). *Habimana et al. (2020*) also reported support from the University of Rwanda. The predominant source of funding for the studies is from external funding agencies in countries such as Austria, Germany, Canada and USA.

Table 3. Sources of funding for geophysical studies in the Bosumtwi Impact Crater. ‘

Funding Agency
Austrian Fonds zur Forderung der wissenschaftlichen Forschung, project, Austria
Deutsche Forschungsgemeinschaft (DFG), operating grants and by the Deutsche Akademische Austauschdienst (DAAD), Ge
Geological Survey of Canada, Canada
University of Toronto, Canada
US National Science Foundation grant ATM-0117019, USA
NSERC SRO to Bernd Milkereit of the University of Toronto, Canada
International Continental Drilling Program (ICDP), the U.S. NSF-Earth System History Program under grant No. ATM-0
US National Science Foundation Earth System History program

German Research Foundation
Kwame Nkrumah University of Science and Technology (KNUST), Kumasi, and Laboratoire IDES- UMR 8148, Université
Institute of Earth and Environmental Sciences (Geology), Albert-Ludwigs-University Freiburg, Germany
National Program of Planetary Sciences, France(INSU) and the West African Exploration Initiative (WAXI)
University Rwanda-College of Science and Technology and KNUST, Ghana.

4.5 Application of Geophysics in the Bosumtwi Impact Crater

Geophysical methods play a significant role in exploring and studying impact craters. A compelling number of impact craters are usually buried underneath post-impact sediments and cannot be easily exposed without applying geophysical methods (*Pilkington and Grieve, 1992*).*Table 4* shows the geophysical methods applied to investigating the Bosumtwi Impact Crater from our review. The magnetic method has been utilised more than any other method. Nine (9) studies involve some form of the magnetic method. This method is followed by the seismic method, with seven (7) studies utilising this method. Petrophysical and gravity methods follow at five (5) each. Remote sensing methods were applied in two (2) studies, whereas resistivity and radiometric methods were only used in two (2) studies each. All the major geophysical methods applied in geophysical studies have been observed in the studies on the Bosumtwi Impact Crater.

Table 4. Geophysical Methods Applied to Investigating the Bosumtwi Impact Crater

Geophysical Method	Number of Articles	References
Geomagnetic methods	8	(*Plado et al., 2000*), (*Pilkington and Hildebrand, 2003*), (*Ugalde*
Seismic method	6	(*Karp et al., 2002*), (*Scholz et al., 2002*), (*Schmitt et al., 2007*)
Gravity method	3	(*Danuor and Menyeh, 2007*), *(Ugalde et al., 2007a*), (*Danuor et*
Electrical Resistivity	2	(*Aning et al., 2013*), (*Habimana et al., 2020*).
Radiometric method	2	(*Peck et al., 2004*), (*Baratoux et al., 2019a*).
Petrophysical measurement	6	(*Schell et al., 2007*), (*Peck et al., 2004*), *(Ugalde et al., 2007a*),
Remote Sensing	2	(*Wulf et al., 2019*), (*Theilen-Willige, 2021*)
Numerical Modelling	1	(*Artemieva et al., 2004*)

Geomagnetic Methods:

Geomagnetic methods have been in existence since the second century BC. They have been deployed in various applications such as locating buried pipes, drums and other objects, archaeological investigations, igneous dykes, and large-scale geological structures such as impact craters. Magnetic anomalies in impact craters are complex due to significant variations in the magnetic properties of rocks (*Pilkington and Grieve, 1992*). In this section on the geomagnetic methods used in the papers retrieved, we focus on both magnetic measurements of core samples, borehole measurements, and magnetic measurements over the crater either through airborne, marine or ground-based measurements.

Plado et al. (*2000*) proposed a magnetic model which showed a circular magnetic halo at the crater rim. Central negative and smaller positive anomalies were observed at the lake's central north, north and south. Together with weaker negative anomalies observed in the eastern and western parts of the lake, they envelop a central uplift. Their explanation of the magnetic anomalies suggested they were due to several relatively strongly remanently magnetised impact-melt rock or melt-rich suevite bodies. In the study, the magnetic survey was conducted at every ˜6.25 m along the flight lines with the survey positions determined using Global Positioning Systems. Data was recorded along 30 profiles with an average length of 22 km. The instrumentation used was a Scintrex CS-2 magnetometer at a resolution of 0.001 nT with a nominal flight altitude of 70 m, flight directions north-south, and line spacing of 500 m. The aeromagnetic survey was conducted in 1997.

Pilkington and Hildebrand (2003) used magnetic data to estimate the diameter of central uplift (D_{CU}), the diameter of melt (D_M) and the diameter of the innermost slump block (D_S). *Ugalde et al.* (*2007c*) reported new experimental methods for conducting magnetic surveys, which were trialled in the Bosumtwi Impact Crater. Due to the existence of previous airborne and marine magnetic surveys in the crater, they attempted to introduce an innovative way of conducting magnetic surveys. They acquired, processed, and interpreted 3-D vector magnetic data. Even though the Earth's magnetic field is a vector quantity with both amplitude and orientation, currently, magnetic surveys only record the amplitude, i.e., total magnetic intensity. Conducting magnetic surveys with the full magnetic vector provides many advantages for mapping anomalies in the subsurface.

Elbra et al. (*2007*) measured the paleomagnetic properties of drill cores from LB-07A and LB-08A in the Bosumtwi Impact Crater. The measured magnetic susceptibility, the intensity of natural remanent magnetisation (NRM) and the Koenigsberger ratio (Q ratio; representing the ratio of remanent to induced magnetisation) among other petrophysical properties. Measurements of magnetic susceptibility of the drill cores show mostly paramagnetic values (200–500 $\times$ 10^{-6} SI) throughout the core, except for a few metasediment samples, and correlate positively with natural remanent magnetisation (NRM) and Q values. They inferred that magnetic parameters are related to inhomogeneously distributed ferrimagnetic pyrrhotite. The paleomagnetic data show that NRM has shallow normal (and in some cases shallow reversed) polarity, which is consistent with the Lower Jaramillo N-polarity chron direction and is present in ferrimagnetic pyrrhotite.

Kontny et al. (2007) investigated the magnetic properties and mineralogy of drilled lithologies to understand and interpret magnetic anomaly patterns. The authors concluded that ferrimagnetic pyrrhotite is the most important carrier of remanent magnetisation. They observed somewhat surprisingly that the prediction of previous researchers of a strong magnetic impact melt body underneath Lake Bosumtwi interpreted from airborne magnetic data and numerical modelling were not confirmed in their study.

Danuor and Menyeh (*2007*) reported on the potential field measurements made in the Bosumtwi impact crater before the International Continental Drilling Program in 2004. Magnetic measurements were made on the lake with two proton precession magnetometers. The profile spacing on the lake was 800 m with station intervals of 10 m. The results revealed a large negative anomaly with a minimum value of 55 nT with less notable positive anomaly to the south. They also report other weaker negative anomalies in the southeast and southwest. The authors attributed the cause of the anomalies to magnetised bodies in the central northern area of the lake. Modelling suggested the most likely source of the anomaly as a body between 250 m and 61 0 m below the lake's surface.

In order to determine whether the strong magnetic anomalies observed within the Bosumtwi Impact Crater originate from strongly magnetic material in the form of impact melt *(Plado et al., 2000*) or weakly magnetic layers of impactite material overlying the crater floor with the larger magnetic anomalies being attributed to granites and other intrusives in the Proterozoic basement (*Ugalde et al., 2007c*), further investigations by *Morris et al. (2007*) focused on gathering additional rock property and borehole information. Magnetic susceptibility measurements were made with the Bartington MS-2 meter with an E probe attachment at ˜10 cm intervals on the core. They concluded that there is no evidence of a strongly magnetic impact melt within the layers of the derived sediments in the crater. *Danuor et al.* (*2013*) summarised the geophysical studies conducted in the Bosumtwi Impact Crater. In contrast, they report the presence of magnetised bodies between 250 m and 610 m below the lake.

Seismic Methods

The basic concept of seismic methods depends on the propagation of elastic waves in the Earth. The seismic signal strength and velocity depend on the elastic properties of the rocks. Even though seismic methods have been predominantly used in oil and gas exploration (*Mondol et al., 2007*), they are increasingly used for other applications. Recent developments in the computing industry have significantly affected the acquisition, processing and interpretation of seismic data. The seismic method has been utilised in detecting precursors of magma movement and eruption (*Chouet and Matoza, 2013*), in mineral exploration and mine planning (*Malehmir et al., 2012*), detection of cavities (*Grandjean and Leparoux, 2004*) and geotechnical investigations *(Signanini and Torrese, 2004*). In this section, we review the seismic studies in the Bosumtwi Impact Crater. In impact crater studies, the seismic method can provide information on the morphology and structure post-impact.

Karp et al. (*2002*) and *Scholz et al.* (*2002*) investigated the subsurface structure of the Bosumtwi impact crater by imaging the central uplift at the bottom of the lake and determining the thickness of the impact-related formations and the post-impact sediments. They acquired multi-channel seismic (MCS) reflection and wide-angle data using Ocean-Bottom-Hydrophones (OBH). Source signals were gotten by firing an airgun. The shots were fired every 25 m with an airgun at a depth of 2 m. The inverted 2D velocity model showed indications of a central uplift feature. They interpreted the central uplift to have a width of ˜1.8 km and a height of 120 m. 180 – 300 m thick of post-impact sediments cover the crater structure.

A vertical seismic profile was acquired in a borehole (LB-08A) to aid in interpreting seismic reflection and refraction surveys (*Schmitt et al., 2007*). *Schmitt et al.* (*2007*) reported two layers of post-impact sediments (between 73 m to 239 m depth) and hard rock (between 239 to 451 m) depth. The former has a P-wave velocity of 1520 m/s, whereas the latter's P-wave velocity increases by up to 30% to between 2600 to 3340 m/s. Their observations matched with inversion results from previous seismic surveys. They also suggested a decreasing density of fractures and microcracks with depth.*Scholz et al.* (*2007*) report a study using a marine seismic reflection survey to image the subsurface of the Bosumtwi crater lake. Multi-channel seismic surveys (MCS) were conducted over eight (8) profiles in a radial pattern in addition to two other high-resolution seismic reflection surveys. They observed a buried central uplift and a section of postimpact lacustrine sediments more than 300 m thick surrounding the central uplift. They observe a central uplift with a diameter of 1.9 km and a maximum height of 130 m.*Danuor et al.* (*2013*) summarised the geophysical characteristics gleaned over the years from seismic surveys. Their summary describes the inference of a three-layer model consisting of the water layer with a velocity of 1.45 km/s and a higher velocity of between 1.5 km/s to 1.65 km/s interpreted as post-impact sediments and the crater floor. *Habimana et al.* (*2020*) deployed seismic refraction methods to delineate the subsurface structure of the suevites to the north of the Bosumtwi Impact crater. The investigation aimed to determine the depth of the suevite body and the p-wave velocity, among other things. The p-wave velocities were observed to be between 3 to 3.9 km/s. The suevite deposits were found to be within 12 m depth.

Gravity Method

Gravity measurements are one of the most important techniques for identifying and confirming impact structures on Earth, unlike volcanic craters (*Pilkington and Grieve, 1992*). In 1960, the first gravity measurements in the Lake Bosumtwi area were taken. The findings primarily reflected regional gravity field patterns (*Jones, 1985*) and could not disclose anything about the impact-formed crater structure. However, 163 gravity measurements were taken around the Bosumtwi Crater complex in 1999 to ascertain the gravitational signature of the impact structure (*Danuor and Menyeh, 2007*). Before the Lake Bosumtwi Drilling Project in 2004, *Danuor and Menyeh (2007*) reported on the Bosumtwi Impact Crater from the results of potential field measurements. In order to determine the impact-related crater structure, the authors used gravity and magnetic measurements. A 2.5-D gravity model was created for a south-north profile across and through the lake's centre, with a half-strike length of 1 km and the profile assumed to be perpendicular to the strike. They observed that the central zone of the lower boundary of layer three (breccia) is uplifted at a depth of about 780 m, indicating the impact's depth extent.

Similarly, *Ugalde et al.* (*2007b*) constructed a 3-D gravity model from gravity data acquired over the lake and in its surroundings between 1999 and 2001. The model integrates gravity, petrophysics, and seismic data. The model's purpose was to determine the extent of fracturing due to the impact. *Danuor et al. (2013)* used the gravity method with magnetic and wide-angle seismic reflection and refraction studies to obtain information on the impact-related anomalies. Gravity measurements yielded a maximum negative anomaly of 18 mgal over the crater. This was interpreted to be caused by fractured and brecciated rocks in the rim area and below the crater floor, breccias within the crater, and sedimentary and water infilling of the lake. A central uplift was clearly shown. It was also observed that the central zone of the lower boundary of layer three at a depth of about 780 m is uplifted.

Resistivity Method

Electrical resistivity imaging is becoming increasingly popular due to the availability of automated data acquisition devices and user-friendly inversion software, which allows it to produce images of the subsurface quickly and efficiently. It has been used to look at areas with complicated geology, such as volcanic and geothermal zones, landslides, seismotectonic structures, hydro-geologic phenomena and environmental issues, and the deposition and flow of impact melt and breccias (*Colangelo et al., 2008; Lapenna et al., 2005; Steeples, 2001*). In this section, we focus on the application of the resistivity method in investigating the Bosumtwi impact crater.

Aning et al. (2013) used the multi-electrode gradient array to conduct a 2D electrical resistivity tomography (ERT) survey at several places around the crater. The authors discovered three formations with distinct resistivity signatures: low resistivity regions from the lake's shore to uphill with resistivities of 64 Ω.m representing lake sediments; moderately high resistivity regions with values between 128 Ω.m and 200 Ω.m interpreted as impact-related breccias such as dikes, allochthonous or parautochthonous depending on their geometries; and finally, the model clearly distinguished the resistive basement metamorphic formations. Using the ERT model, the authors were also able to determine faults and fractures and the thickness of post-impact lake sediments and breccias. Based on their findings, they concluded that the multi-core cable's take-outs could be changed to suit the needs of a specific survey, underlining the technique's applicability in impact cratering investigations and geo-electrical imaging studies in general.

Habimana et al. (*2020*) used electrical resistivity imaging in conjunction with seismic refraction methods to map the subsurface structure of the suevites north of the Bosumtwi impact crater in Ghana to establish their depth extent, in-situ resistivity, and P-wave velocity. According to the authors, the suevite deposits were discovered at a depth of 12 meters. The findings also revealed that the subsurface consists of two or three layers: unconsolidated topsoil, clayey soil, and fractured claystone.

Radiometric method

This section explains how the radiometric method, including radiocarbon dating, was used in the Bosumtwi impact crater. *Baratoux et al.*(*2019b*) used a radiometric survey combined with detailed topographic analysis, including roughness mapping, to map near-surface K, Th, and U concentrations and field observations. The Geological Survey of Ghana provided two airborne radiometric surveys for this investigation. One of them (Aerodat) was taken with a 200 m gridded line spacing. It was properly calibrated and delivered absolute readings for K (weight percent), Th (ppm), and U surface concentrations (ppm). Unfortunately, only half of the Bosumtwi impact crater was covered by this survey. The second survey covers the full impact structure and has a grid line spacing of 400 m, although it was not calibrated. The two airborne surveys were combined to create a gridded data collection of K, Th, and U concentrations with a 50 m/pixel resolution. The authors obtained evidence that the moat and outer ring are features inherited from the impact event and represent the partially eroded ejecta layer of the Bosumtwi impact structure.

Peck et al. (*2004*) used the results from the Accelerator Mass Spectrometer (AMS) radiocarbon dating process and produced an age model from a suite of 30 AMS 14C dates from cores 12P, 15P, and 19P. While a distinct downcore trend of older sediment ages exists in these data, there is a significant amount of scattering below 700 cm standardised depth. The calibrated age range is between 3321 years for the sample taken at 90.0 cm depth and 24,355 years for the sample taken at 844.1 cm depth.

Petrophysical Measurements

Petrophysical measurements refer to measuring rocks' physical and chemical properties in the subsurface in boreholes or cores. In impact crater studies, petrophysical measurements such as porosity, permeability, Young's modulus, and strength are used to model impact craters. Petrophysical measurements are also used in unravelling fluid flow within hydrothermal systems (*Abramov and Kring, 2007; Sanford, 2005*) to understand the physical and mechanical behaviour (*Meillieux et al., 2007*) and slope stability and landscape evolution assessments for impact craters (*Heap et al., 2020*).

Peck et al. (*2004*) analysed sedimentary cores from Lake Bosumtwi and reported the magnetic hysteresis results. Their results indicate five (5) distinct magnetic zones spanning the 11 m core section representing the last 26000 calendar years. The magnetic zones illustrate climatic variability on various scales indicated by the coercivity of magnetic minerals. Samples taken from drill cores from well LB-07A and LB-08A drilled into the central moat and uplift of the Bosumtwi Impact Crater were characterised for petrophysical investigations. *Schell et al.* (*2007*) report on the magnetic properties of samples determined in the laboratory. The shape and degree of magnetic anisotropy with magnetic susceptibility were correlated with lithological properties. They could distinguish between lithic breccia, suevite, shale component, and meta-graywacke lithologies.

Ugalde et al. (*2007b*) constructed a 3-D model using gravity and seismic data constrained by petrophysical data. Boreholes were drilled within the impact crater in six locations, and post-impact sediments' average density and thickness were measured. By interpreting wireline logs and televiewer images, *Hunze and Wonik*(*2007*) aimed to understand the subsurface structure of the crater fill of the Bosumtwi impact structure. They report that the physical properties of breccia, meta-graywackes and slate/phyllites, such as shallow resistivity, p-wave velocity, magnetic susceptibility, and borehole diameter, are useful in differentiating between the subsurface layers. The boreholes were drilled under the Lake Bosumtwi Drilling Project (BCDP) and were supported by the International Continental Scientific Drilling Program (ICDP). The boreholes were drilled with the Global Lake Drilling 800 m system, specifically designed to collect long continuous cores. Borehole geophysical logging, including natural gamma-ray spectrometry (potassium, thorium, and uranium), magnetic susceptibility, electrical resistivity (shallow penetration depth), p-wave velocity, and caliper (borehole diameter) is used to acquire continuous, fine-scale, in situ physical parameters within the borehole which provided continuous lithological and structural data on the impact rocks.

Furthermore, an acoustic televiewer tool was used to investigate fractures, supply information on borehole breakouts, and give information on lithological boundaries, textures, and sedimentary features. *Morris et al.* (*2007*) attempted to provide validated geophysical signatures of geological materials. Magnetic susceptibility and density measurements made on the BCDP cores show no proof that highly magnetic and dense impact-melt sheets might be the source of the observed magnetic anomalies.

Remote Sensing Methods

Remote sensing methods use satellites and cameras in aeroplanes (and recently on unmanned drones) to detect and monitor an area's physical characteristics with different wavelength spectrum segments. The methods have been applied in weather forecasting *(Alley et al., 2019*), monitoring forests (*Huete, 2012*), agriculture (*Bandyopadhyay et al., 2009*), land cover and land use studies (*Alqurashi and Kumar, 2013*), and impact crater investigations (*Koeberl, 2004*). *Wulf et al.* (*2019*) compared terrestrial impact craters with Martian impact craters using the Bosumtwi impact crater as a case study. They combined remote sensing and geomorphological analysis with landform evolution modelling. The authors realised that they could not explain the current morphology of the Bosumtwi impact crater using a model dependent on the erosion of lunar-like impact craters. On the other hand, similarities with Mars, like impact craters, exist.*Theilen-Willige*(*2021*) were able to derive further geomorphological and structural knowledge about the Bosumtwi impact crater, such as new morphometric maps to visualise concentric and radial drainage and valley pattern surrounding the impact crater.

Numerical Modelling

Artemieva et al. (*2004*) evaluated the cratering process within the Bosumtwi Impact crater by using sophisticated numerical models. The numerical modelling was crucial in determining drilling locations within the crater.

5.0 Discussion

In this study, geophysics played a significant role in recognising the Bosumtwi as a terrestrial impact crater.

Twenty-three (23) geophysical papers on the Bosumtwi impact crater were identified from various databases, and 47.8% of these publications were published in 2006 and 2007 attributable to the multidisciplinary International Continental Drilling Program (ICDP), a project that took place in 2004. We also found that 13% of these published scientific articles on the Bosumtwi Impact Crater were written by researchers affiliated with Ghanaian institutions, whereas 87% of the studies were conducted by scientists affiliated with non-Ghanaian institutions. Our findings are significant because they highlight the lack of local financial support for research in Ghana and African countries. The lack of funding for research on the Bosumtwi Impact Crater from Ghana also bears this out. One would have thought that with such a unique location located in the country, adequate funding would have been allocated for research to advance knowledge.

In addition to our main findings, we demonstrate that the geophysical techniques employed so far in studying the Bosumtwi Impact crater include magnetic, gravity, seismic, electrical resistivity, GPR, petrophysical, remote sensing and radiometric methods. A residual negative gravity anomaly is the most conspicuous geophysical signature over impact craters. Gravity measurements at the Bosumtwi impact crater yielded a maximum negative anomaly of 18 mgal over the crater. This was interpreted to be caused by fractured and brecciated rocks in the rim area and below the crater floor, breccias within the crater, and sedimentary and water infilling of the lake. Also, magnetic measurements of core samples, borehole measurements, and magnetic measurements over the crater reveal interesting anomalies. A magnetic low with an amplitude of tens to several hundred nanotesla (nT) is the dominant effect over impact. A large negative anomaly with a minimum value of 55 nT and a less notable positive anomaly to the south of the Bosumtwi impact crater was recorded.

In contrast, weaker negative anomalies were also observed in the southeast and southwest of the crater, which is attributed to magnetised bodies in the central northern area of the lake. Measurements of magnetic susceptibility of the drill cores show mostly paramagnetic values ($200–500 \times 10^{-6}$ SI) throughout the core, except for a few metasediment samples, and correlate positively with natural remanent magnetisation (NRM) and Q values. Seismic refraction and reflection surveys showed the velocity distribution in the Bosumtwi Impact Crater, which expressed how much the shock load has fractured the material. The methods revealed a three-layer model consisting of the water layer with a velocity of 1.45 km/s and a higher velocity of between 1.5 km/s to 1.65 km/s, interpreted as post-impact sediments and the crater floor. Resistivity measurement at the crater reveals three formations with distinct resistivity signatures: low resistivity regions from the lake's shore to uphill with resistivities of 64 Ω.m representing lake sediments; moderately high resistivity regions with values between 128 and 200 Ω.m interpreted as impact-related breccias such as dikes, allochthonous or parautochthonous depending on their geometries; and a resistive basement metamorphic formations. The resistivity models were able to determine faults and fractures, as well as the thickness of post-impact lake sediments and breccias.

It is clear from our study that geophysical studies in the Bosumtwi Impact crater have stalled after a high in 2006 and 2007 (i.e., the period immediately after the Lake Bosumtwi Drilling Project in 2004. The Lake Bosumtwi Drilling Project was funded by a consortium of the International Continental Scientific Drilling Program (ICDP), the US National Science Foundation, the Austrian National Science Foundation, the Austrian Academy of Sciences and the Canadian National Science Foundation. Local funding from the Government of Ghana seems to be nonexistent. This study reinforces the overwhelming evidence of chronic internal underfunding of science research in Ghana and Africa (*North et al., 2020; Sawyerr, 2004*).*North et al.* (*2020*) also identify government spending on research and development as a key reason for low research output from African countries such as Ghana. Over the years, the Government of Ghana has not dedicated resources to investigating the origin, understanding the evolution and encouraging the continuous monitoring of the Bosumtwi Impact Crater. An unintended consequence is that data from geophysical research conducted on the Bosumtwi Impact Crater is unavailable to Ghanaian researchers. For instance, the data gathered during the Lake Bosumtwi Drilling Project should have been in an accessible research repository to Ghanaian researchers, but this is not the case. Original plans to have a museum and research centre at Abonu, the main town in the Bosumtwi Impact Crater enclave, to host some of the petrophysical cores, rocks and results from research conducted have not materialised almost 20 years after the ICDP ended.

Although Ghanaian researchers are underrepresented in geophysical research on the Bosumtwi Impact Crater, we do not ascribe the cause to "parachute science" (*Harris, 2004; North et al., 2020*), as evidenced by 19 % of the scientists who worked on Bosumtwi Impact Crater being Ghanaian *(Koeberl et al., 2005*). If anything, the internal evils of lack of resources for research and publications, high teaching loads, and lack of institutional incentives are to blame for the under-representation of African geophysical researchers in studies in the Bosumtwi Impact Crater.

Another significant aspect of our review is the importance of geophysics in understanding impact craters. The geophysical techniques of magnetic, gravity, seismic, electrical resistivity, GPR, petrophysical, remote sensing and radiometric methods were all utilised in the various investigations of the Bosumtwi Impact Crater. Meteorite Impact Craters are pervasive in our solar system, and studying them is useful for understanding the geological processes of other planetary bodies in our solar system, such as Mars, especially in the context of ramped-up exploration of other planetary bodies in the solar system. They are often the most significant modifiers of planetary surfaces. However, our review makes it clear that while geophysical methods did not provide an unambiguous signature for the Bosumtwi Impact crater, they provided constraints for confirming the impact origins. Our review supports French and Koeberl's (2010) and Koeberl's (2004) findings.

In our view, a very compelling consequence of the underrepresentation of Ghanaian geophysical researchers in studies on the Bosumtwi Impact Crater is the lack of studies on hazards due to the impact origins of the impact crater. For instance, *Jones (1985*) reported that the earliest mention of Lake Bosumtwi was by a certain *Perregaux in 1899,* who described inhabitants of the Lake Bosumtwi enclave complaining of bubbles accompanied by sulphurous smell and loud noises in a two-year cycle. Scientists then concluded that this occurrence, along with the crater depression, indicated volcanic origins. Since this report by *Jones (1985*), we have not found any study investigating this phenomenon. This record should be of particular concern to scientists conducting future research since it could have health and safety implications for the inhabitants of the Lake Bosumtwi enclave.

Furthermore, beyond geophysical research for understanding the origin and evolution of the Bosumtwi Impact crater, future research should focus on geological hazards related to impact, which may put the lives and properties of inhabitants of the enclave at risk. In addition, the potential for contamination of the lake through fractured conduits should be investigated. The Bosumtwi enclave is a zone of high agricultural activities, especially cocoa and other crops such as maise, cassava and plantain. Some farmers involved in these agricultural activities use high amounts of pesticides and inorganic fertilisers. The potential for contamination of the lake due to seepage through the fractures is high. Finally, the rapid increase in tourist numbers visiting the lake and the construction of several tourist resorts in the enclave should engender geotechnical research using geophysical methods in the future.

6. 0 Conclusions

This paper is a systematic review of geophysical research conducted in the Bosumtwi Impact Crater from 2000 to the present. The trend shows that many articles were published around the periods when the internationally funded Bosumtwi Drilling Project was undertaken. The paper provides an overall understanding of the geophysical methods utilised in the Bosumtwi Impact Crater. The following geophysical techniques were essential in the identification and study of the Bosumtwi Impact Crater: magnetic, gravity, seismic, electrical resistivity, GPR, petrophysical, remote sensing and radiometric methods. The magnetic method was used more than any other method to confirm the circular nature of the impact crater. Beyond the circular geophysical anomalies, petrophysical studies and measurements on cores from boreholes drilled in the crater show the physical properties of breccia, meta-graywackes and slate/phyllites. These observations confirm the presence of shock-metamorphosed rocks.

The under-representation of Ghanaian geophysical researchers on the list of published articles on the Bousmtwi Impact Crater can be primarily blamed on the lack of funding by the Government of Ghana in science research. The direct consequence is that the situation has caused a lack of geophysical studies on areas such as geohazards within the Bosumtwi Impact Crater, which should be of primary interest moving forward. Furthermore, the paucity of research in this area could mean scant knowledge of potential disasters and loss of human lives and livelihood in the future.

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