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RESEARCH ARTICLE

Morphometric and Structural Evaluations of Satellite Data from the Bosumtwi Impact Structure and Adjacent Areas in Ashanti, Ghana

B. Theilen-Willige

ABSTRACT

The Bosumtwi impact crater in Ashanti, Ghana is one of the most thoroughly investigated impact structures in Africa. Nevertheless, by the evaluations of Sentinel 1 and 2, and Landsat data as well as by ALOS PALSAR, ASTER and SRTM digital elevation model (DEM) data further geomorphological and structural knowledge can be derived. Morphometric maps were used to visualize the concentric and radial drainage and valley pattern surrounding the impact crater. The larger valleys are arranged in a nearly concentric and radial pattern like the river Pra and its tributaries, the Ofin, Anum and Brim river, tracing the outer, southern border of the impact affected area. From the ASTER and SRTM DEM data the morphological drainage basin was calculated. The drainage basin-outline is nearly circular, discharging into the Pra river in the southern part. Structural evaluations of satellite radar and optical data reveal that linear and circum-linear features can be detected more than 80 km around the Bosumtwi impact crater. Small-scale/artisanal mining activities in this area are visible on satellite images and, thus, indirectly tracing ore deposits. As detailed mineral maps are not publicly available, the position and distributions of mining areas was used as indicator for the occurrence of mineral deposits, especially placer deposits. Their occurrence and the distribution of the mining areas follows the larger rivers. Weathering processes along the deformation pattern and erosion and sedimentation probably had an influence on placer deposit development.

Keywords: Bosumtwi impact structure, Ghana, GIS, remote sensing.

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I. Introduction

The Bosumtwi Crater is one of the youngest (1.07 Ma) and well-preserved impact structures in Africa [1]. It was formed by the impact of an object roughly 0.5 km in diameter [2].

The Bosumtwi impact structure has not only been investigated because of its high interest for impact crater research, but also because of known ore deposits in the wider region and gold exploration interest in the actual crater area [2]. Mineral deposits occur concentrated along larger rivers in this area, mainly as placer deposits [3]. The research has been concentrated so far on the central part of the impact structure. Less detailed structural / tectonic knowledge exists about the surrounding area. Therefore, this study is focused on this part. The question arises, how the impact shock of the meteoritic body and its rebound effects might have influenced the tectonic structure of the target area for example by the reactivation of existing fault zones or the creation of impact related deformation such as faults and folding?

How far this cosmic impact event and its post-impact deformation and overall development has been influencing the hydraulic permeability and groundwater conductivity and, thus, the mineralization processes?

II. Geomorphologic and Geologic Overview

The 1.07 Ma old Bosumtwi complex crater (centered at 06°30'N and 01°25'W) is situated in the Ashanti Region of Ghana, West Africa, about 30 km in the SE from Kumasi, the regional capital [1]. The complex impact structure that displays a pronounced steep rim at its center, is almost completely filled by the Lake Bosumtwi (Fig. 1 and 2). The crater rim rises about 250–300 m above the lake level (Fig. 2). The central crater with the lake has a rim-to-rim diameter of about 10.5 km [4]. The rime of the central crater area is covered by ejecta blankets. The characteristics of the outer ridge indicate that ejecta emplacement was not purely ballistic but requires ejecta fluidization and surface flow. The setting of Bosumtwi ejecta can therefore be considered as a terrestrial analog for rampart craters [5].

The crater itself is surrounded by a shallow, near-circular, but very slight depression at ca. 7 to 8,5 km from the

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structural center, also described as an annular moat, and a shallow outer topographic ring features at 18–20 km diameter [6]. The morphology of this impact structure is also characterized by a circular plateau extending beyond the rim and up to 9–10 km from the center of the crater.

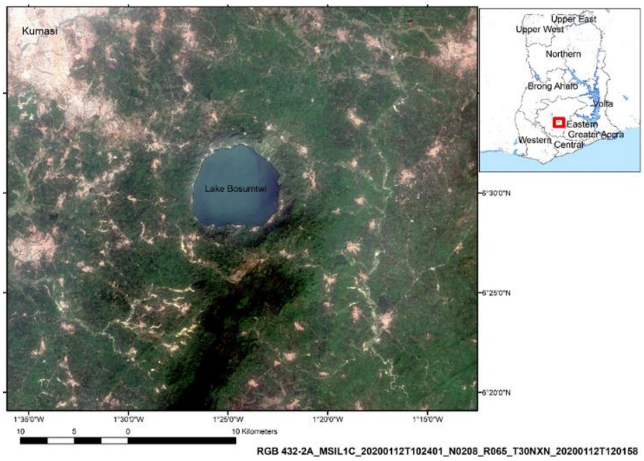

Fig. 1. Sentinel 2-scene of the water-filled Bosumtwi impact crater in the SE of the city of Kumasi, Ashanti, Ghana.

The southeastern sector of the structure within a few kilometers south of the Bosumtwi crater rim, is dominated by the Obuom hill range (visible in dark-green colors on Fig. 1), oriented in SW-NE direction, of up to about 720 m elevation (Fig. 2).

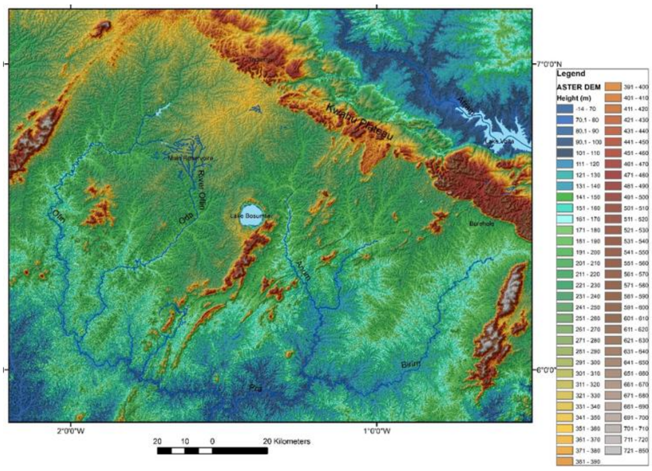

Fig. 2. Height level map based on ASTER DEM data (30 m spatial resolution) tracing the concentric arrangement of larger valleys of the Pra, Ofin and Brim rivers and the radial arrangement of the Odin and Anum rivers.

It appears that the pre-impact existence of this range could be a reason for the non-circular appearance of the southern part of the impact structure [4], [7]. The Obuom hill range may have forming a hindrance of the passage of impact-related shock waves and post deformation processes. Higher impedance, velocity, and density contrasts due to the differences of the lithologic units within the Obuom Hills (granitic dykes, dolerites and gabbros and other intrusive rocks) could be one of the reasons that the southeastern part of the Bosumtwi crater area shows less traces of crater deformation.

The Bosumtwi impact excavated into the 2.1–2.2 Gyr old Early Proterozoic Birimian Supergroup that can be divided into two contemporary units (volcanic belts and sedimentary deposits) aligned in multiple parallel structural features [8]. The main strike direction is oriented NE-NNE. The Birimian Supergroup is comprising interbedded phyllites, schists and quartzites and in lower greenschist facies metasediments quartz-feldspar schists and meta-tuffs, together with meta-graywackes, quartzitic graywackes, shales and slates. Birimian metavolcanic rocks (altered basic intrusive with some intercalated metasediments) occur to the southeast of the crater [8], [9].

Impact related shock features in the bedrocks such as shatter cones are described around the central crater [2], [8], largely overgrown by vegetation or covered by the lake. Tropical rainforest and shrubs largely cover the region around Bosumtwi.

The Bosumtwi crater in Ghana reveals a distinct central uplift [10]. The central uplift structure has a diameter of 1.9 km and a maximum height of 130 m above the annular moat inside the crater. Results of drilling within the crater's central uplift beneath the lake floor has provided an abundance of shocked materials. Geophysical data show the well-defined central uplift near the NW-central part of the lake, and a maximum lacustrine sediment thickness of ~310 m [10]. The target area has undergone faulting, probably during the latter stages of transient crater collapse and during the subsequent lacustrine phase of the structure [1].

The Kwahu plateau forming the northeastern and easter border of the Bosumtwi crater area is consisting mainly of sandstones, shales and siltstones belonging to the Kwahu Group of Late Mesoproterozoic to Early Neoproterozoic age [11], [12].

III. Materials and Methods

The interdisciplinary approach used in the scope of this research comprises remote sensing data, geological, geophysical, and topographic data and GIS methods. Satellite imageries and Digital Elevation Model (DEM) data were used for generating a GIS data base and combined with different geodata and other thematic maps. Satellite data such as Sentinel 1 – C-Band, Synthetic Aperture Radar (SAR) and optical Sentinel 2 images, Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) and Landsat optical data (Landsat TM and Landsat 8). Digital Elevation Model (DEM) data gained from the Shuttle Radar Topography Mission (SRTM), ASTER DEM data and Advanced Land Observing Satellite-1 (ALOS), Phased Array type L-band Synthetic Aperture Radar (PALSAR) mission / Japan Aerospace Exploration Agency (JAXA), were downloaded from open sources such as USGS / Earth Explorer [13], Sentinel Hub / ESA, [14], Alaska Satellite Facility (ASF) [15] and Google Earth. The data were processed using GeoInformation Systems (GIS) as ArcGIS from ESRI and QGIS. Shapefiles from Ghana were downloaded from the Geofabrik's download server [16].

For this research, remote sensing data and geographic information systems (GIS) are mainly used to obtain structural information.

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A. Digital Image Processing of Different Optical and Radar Satellite Data

ENVI software from Harris Geospatial Solutions and the Sentinel Application Platform (SNAP) provided by ESA were used for the digital image processing of the optical Landsat 5 and 8, Sentinel 2 and ASTER data. SNAP provided as well the tools for the processing of radar data. The evaluation of Sentinel 1 A and B radar images requires geometric correction and calibration. The different steps of digital image processing used in this research are described in the following text and Fig. 3. Digital image processing of LANDSAT 5 and 8 data was carried out by merging different Red Green Blue (RGB) band combinations with the panchromatic Band 8 to pan-sharpen the images (Fig. 3). The Red, Green, Blue (RGB)-Principle is reviewed briefly: Three images from different optical satellite bands to be used as end-members in a triplet are projected, one image through one primary color each, one image is coded in blue, the second in green and the third in red.

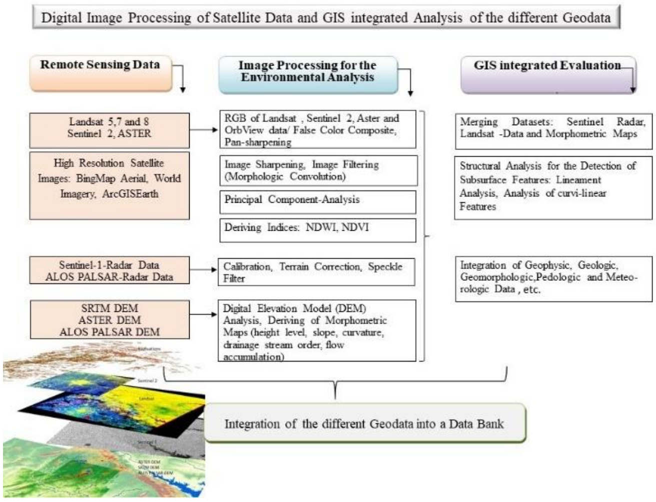


Fig. 3. Data mining and digital image and data processing.

B. Traces of the Structural-Tectonic Pattern

One purpose of this study is to investigate the feasibilities of visual lineament analysis in order to detect surface traces of fracture and fault zones and structural features visible on satellite images that might reflect traces of impact and post-impact deformation processes. Special attention was directed at distinct expressed linear features (tonal linear anomalies, geomorphologic linear features, drainage segments, etc.). In the scope of this study mainly 2 types of linear and curvi-linear features were mapped: lineaments (as a neutral term for linear features without knowing precisely their origin (probable fault zones), and structural features. Lineaments are often expressed as scarps, linear valleys, narrow depressions, linear zones of abundant watering, drainage network, linear vegetation occurrence, and geologic anomalies.

Tonal linear anomalies such as linear arrangement of pixels depicting the same color / gray tone were visually mapped as linear features or lineaments as well. Lineaments represent in many cases the surface expression of faults, fractures or lithologic discontinuities [17]. Lineament analysis can contribute to the detection of structural features that in the field are sometimes not visible or can be mapped only based on time and cost-intensive field investigations. Traces of structural features such as synclines or anticlines, bedding structures or traces of foliation in metamorphic rocks were digitized based on the different satellite images.

Structural features appear on satellite images often as dense, arc-shaped, parallel lines.

C. Evaluation of Digital Elevation Model (DEM) Data

The actual morphologic shape of the Bosumtwi structure at the surface is already the result of ongoing selective erosional processes. The geomorphologic pattern is closely related to the lithologic and structural setting. Digital elevation data help to identify and categorize the different geomorphologic units, their size and arrangement. SRTM, ASTER GDEM (30 m spatial resolution) and Advanced Land Observing Satellite-1 (ALOS), Phased Array type L-band Synthetic Aperture Radar (PALSAR) Digital Elevation Model (12,5 m resolution) were obtained from open sources (such as USGS, EarthExplorer [13] and Alaska Satellite Facility [15] used with GIS to evaluate terrain features. Terrain features can be described and categorized into simple topographic relief elements or units by parameterizing DEMs such as height levels, slope gradients, and terrain curvature. From DEM (Digital Elevation Model) data derived morphometric maps (slope gradient maps, drainage, etc.) were combined with lithologic information in a GIS data base.

The weighted overlay tool of the Spatial Analyst extension in ArcGIS was used to visualize the concentric and radial valley pattern in the investigation area. By extracting first morphometric factors like slope degrees below 10° from the slope gradient map, by deriving from the drop raster the areas with values below 50.000 units using the hydrology-tools in ArcGIS (flow direction), by extracting from curvature maps areas with terrain curvature = 0 and from the aspect map the flat areas (-1), the flattest areas are highlighted. In the weighted overlay procedure these selected morphometric data were summarized, merged with different percentages of influence and represented in a map, subdividing the resulting map into several classes from 0 to 7, thus, enhancing and accentuating the visibility of valleys.

IV. RESULTS

A. Evaluation of Optical Satellite Data

In the scope of these investigations the evaluations of older Landsat 5 images were more useful than the newest Landsat 8 data because of the growth of the urban area of Kumasi, covering a large area in the northwest of the central core. The spectral reflection differences might not only reflect the different lithologic units such as the ejecta layers surrounding Lake Bosumtwi, but also the different shock zones in the metasediments (Fig. 4 a). The crater rim area of the central core covered by ejecta such as suevites and polymict breccias is clearly visible on Fig. 4. Impact breccia, suevite, and unclassified breccia have been observed at several locations [4], [18], [19]. The ejecta material is clearly visible on Landsat images. Rock alterations due to shock metamorphism could cause different surface reflections as well and, thus, be visible on the optical satellite images such as known from other impact structures, for example from the Araguainha structure in Mato Grosso, Brazil [20], [21]. Arc-shaped, parallel lines are visible in the west of the crater rim, see arrows in Fig. 4. Their origin has still to be investigated.

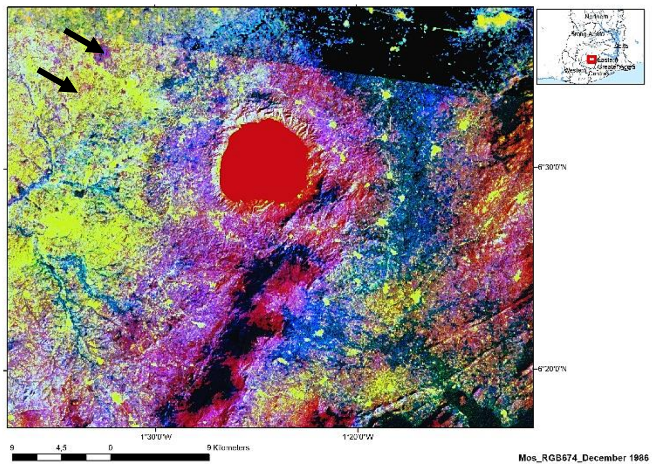


Fig. 4. Landsat 5-scene (RGB, Bands 6,7,4) of the Bosumtwi area acquired in December 1986 showing lithologic units, especially ejecta, due to their specific spectral reflectivity in the chosen RGB combinations.

B. *Evaluations of DEM Data*

From DEM-data derived morphometric maps (slope gradient maps, height level, drainage, etc.) were used for the detection of annular and radial terrain features. Height level maps support the morphologic description of the Bosumtwi impact structure. Striking feature of the structure is a shallow, near-circular, depression at 7-8.5 km from the crater center directly beyond the crater rim, followed by a shallow outer topographic ring feature at 18-20 km radial distance from the impact center. However, it is difficult to derive from remote sensing data, whether the ringed appearance of valleys and hill ranges is the result of selective erosion at the surface or the result of concentric faults, or of ring-grabens and ring-horsts in the subsurface or, both. The height level map reveals a concentric and radial arrangement of valley and hills, even in in a distance between 60 to 80 km from the impact center, whereby the larger valleys follow a more concentric pattern (Fig. 2). Slope gradient maps help to improve the visibility of structural features. The slope gradient map (Fig. 5) clearly shows the steep crater rim and the annular hill ranges.

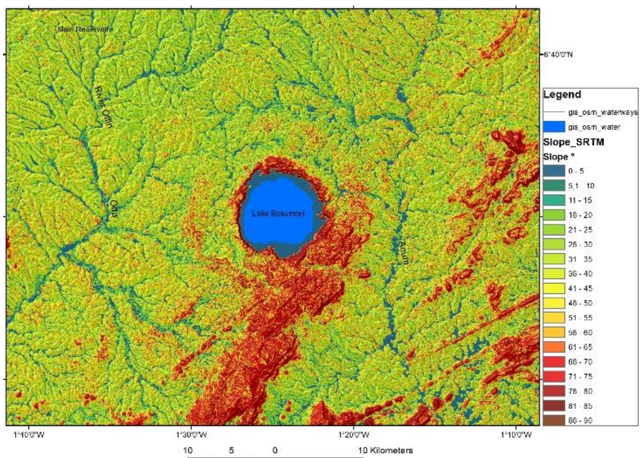
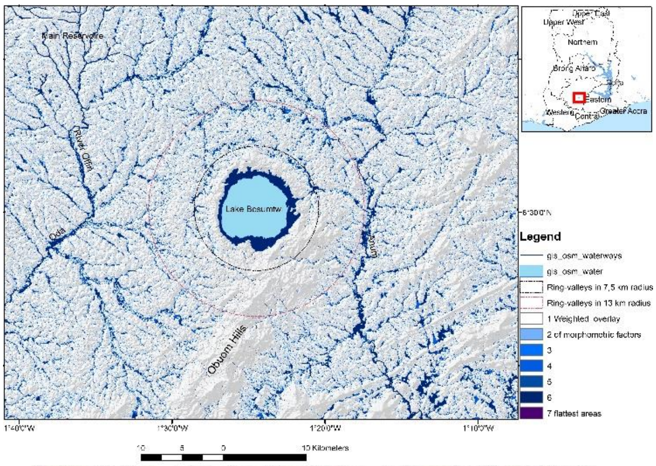


Fig. 5. Slope gradient map of the central part of the Bosumtwi structure created in ArcGIS 10.8 based on SRTM DEM data.

The analysis of the drainage pattern supports the detection of sub-surface structures. A distinct relationship between the surface-near tectonic setting, morphologic evolution and drainage pattern development can be observed. When calculating the stream order segments and flow accumulation, a concentric and radial drainage pattern becomes visible. Evaluating the different DEM data, it is evident that there is an influence of the impact related structures on the drainage development. The weighted overlay results visualize this drainage and valley pattern (Fig. 6). The course and contour of the larger rivers in this area as the Pra river and its tributaries like the Ofin, Anum and Brim trace the outer, southern border of the impact affected area what can be derived from their nearly concentric arrangement around the central Bosumtwi crater (Fig. 6, 7 and 8).



Morphometric Maps ➡ Extraction of Causal Factors ➡ Aggregation / Weighted Overlay

Height Level maps Slope Degree Curvature Aspect Dropraster	Local, lowest height levels lowest slope degrees < 10° curvature = 0 flattest areas (-1) dropraster < 50.000	Influence (%) varying according to seasonal changes calculated in this case with equal influence

Fig. 6. Concentric and radial valley and drainage pattern derived from ASTER DEM data outlining the impact center area visible on the weighted overly map (The circles underline the position of the annular drainage pattern.) Weighted overlay of morphometric factors: subdividing the resulting map into several classes. The flattest areas with lowest slope degrees and curvatures are classified by values from 6 to 7 accentuating the valleys.

From the ASTER and SRTM DEM data the morphological drainage basin was calculated. The drainage basin-outline (red line in Fig. 7) is nearly circular, discharging into the Pra river in the southern part.

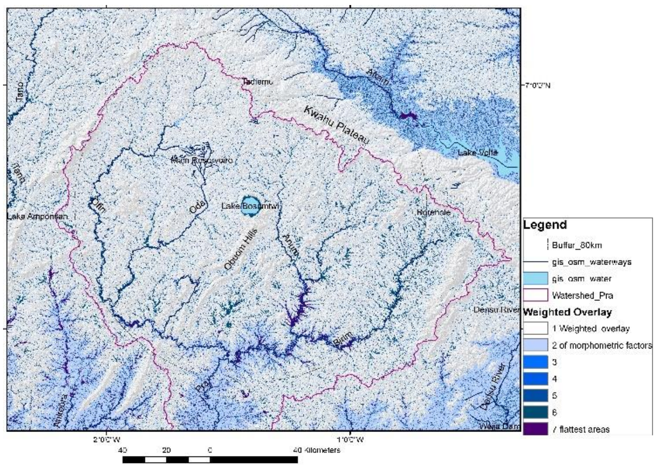


Fig. 7. Weighted overlay of morphometric factors in ArcGIS: slope < 10°, dropraster < 50.000, Curvature=0, Aspect=(-1) The circle representing the outline of a 80 radius from the Bosumtwi crater is included to visualize the annular pattern of the larger valleys and river beds.

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To be able to carry out statistical analysis of the drainage and valley orientations stream order calculations were carried out and the stream order raster converted to line-shapefiles. Based on these line-shapefiles the orientation distribution of the drainage segments could be calculated using the line direction histogram-tool in QGIS. The direction rose diagrams of the line segment directions is presented for three selected areas in the SW, S and NE of the area, see Figure 8. The spatial drainage segment distribution shows main orientation trends that are tracing a concentric pattern.

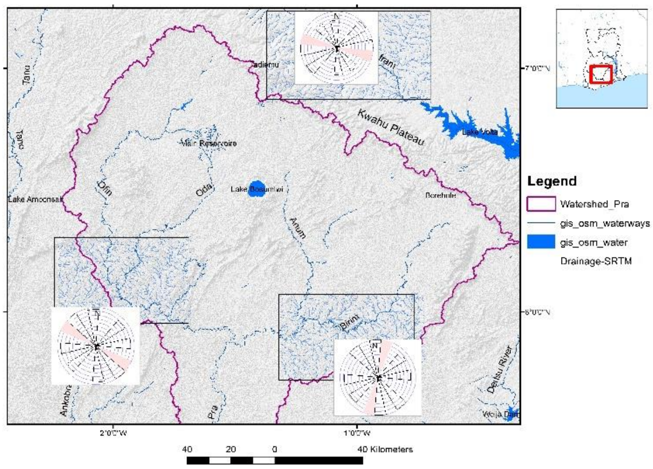

Fig. 8. Drainage basin and morphological watershed delineation and drainage orientation pattern analysis by line direction rose diagrams in three selected areas indicating the main trend of the drainage segment directions in rosa colors. The main trend in the drainage segment orientation follows the circular outline of the drainage basin area.

C. Structural Evaluations

The structural evaluation was carried out based on the different morphometric maps and satellite images, thus, taking advantage of each satellite properties and evaluation feasibilities. The evaluations contribute to the detection of fault and fracture zones, the impact related, curvi-linear features, the impact related features due to rebound processes and post-impact faults and fracture zones, cross-cutting the impact related features. The Bosumtwi area shows a complex structural pattern in the outer sections surrounding the impact crater in a distance between 60 to 80 km. This involves rim-parallel, radial, or oblique (with respect to the center), and tangential faulting.

Folding of strata, as a response to the dynamic and variably compressional or extensional forces involved with the different stages of impact deformation can be observed [19]. Whether the folds in the east and southeast of the central crater near the Kwahu-Plateau were pre-impact existing and modified because of the impact or were created during the crater formation, this has still to be investigated.

Concentric zones of structural deformation become visible on the morphometric maps and on Landsat and Sentinel 2 images. The annular hill ranges are obviously strongly fractured. This is visible on the different satellite images, especially on radar images, see Fig. 9 demonstrating the situation in the Obuom hills in the SE of the Bosumtwi crater area. WSW-ENE striking lineaments (see black arrow on Fig. 9) are clearly visible, tracing a larger fault zone. The fault character becomes visible due to the abrupt displacements of the lithologic and morphologic units. However, many linear features cannot be classified because of the limits of remote sensing. Complementary field research is needed to verify the mapped linear features based on satellite data.

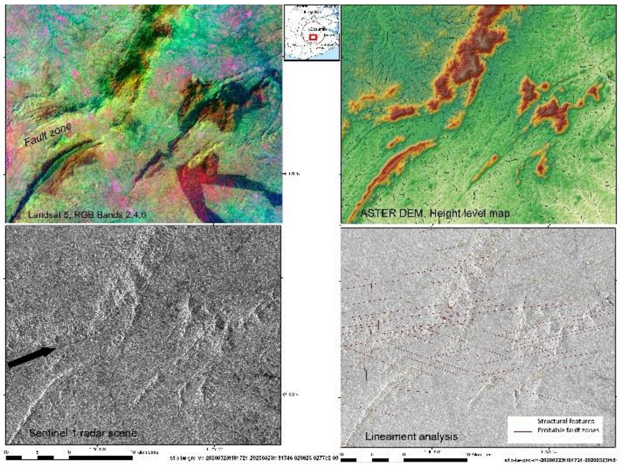

Fig. 9. Mapping of linear and curvi-linear features based on different satellite data from the Obuom hill range in the southern part of the Bosumtwi impact crater. The height level information can be derived from Fig. 2.

As many of the distinct visible lineaments are arranged circum-linear, arc shaped and parallel to the crater outline at the center, it is assumed that their origin is related to deformation processes of crater development.

Fig. 10 a and b presents the results of the structural evaluations. Line direction (rose) diagrams of the lineament orientation distribution are presented in Fig. 10 b from selected areas.

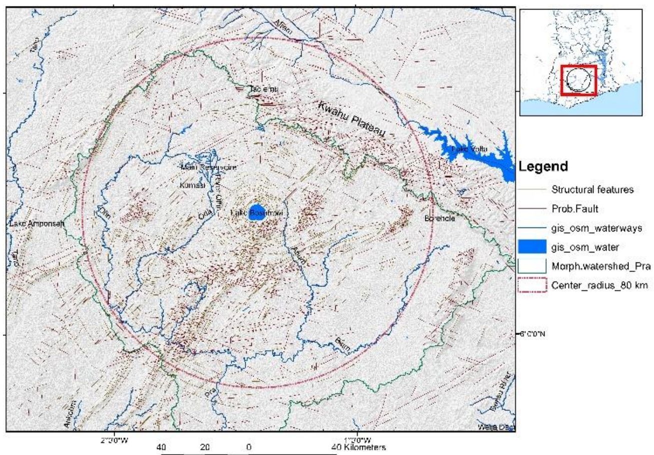

Fig. 10 a. Mapping of linear and curvi-linear features visible on satellite data. The red circle (80 km radius) provides an orientation of the concentric strike of the linear features within this radius.

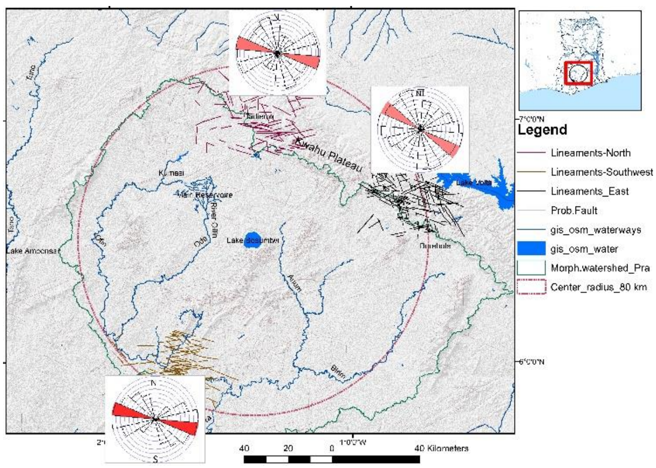

Fig. 10 b. Line direction diagrams for selected areas (red- main trend).

The main directions of the lineaments change according to their position towards the impact crater. Scenes of Sentinel 1 radar data visualize the changing orientation of structural features with respect to the crater center (Fig. 11) in an annular pattern. The dark-grey areas correspond to mining sites.

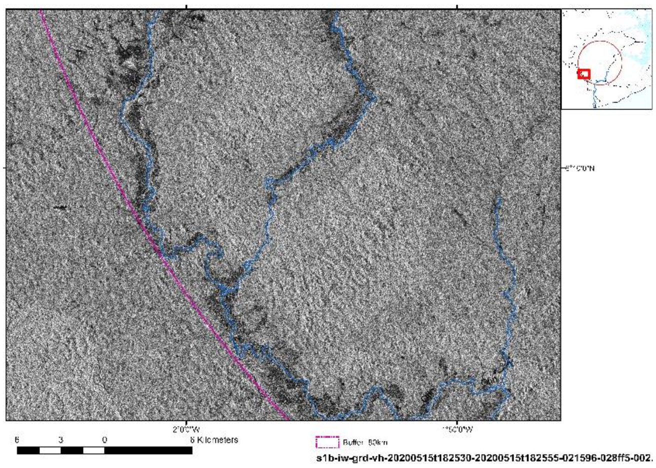

Fig. 11. Linear surface features with NW-SE orientation tracing the concentric structural pattern of the Bosumtwi area on the Sentinel 1 radar scene of the SW-border of the investigation area (The circle with 80 km radius helps to a better orientation of the scene position towards the Bosumtwi structure.)

D. Ore Deposits

In Ghana, artisanal and small-scale mining (ASM) has grown in size and significance. There are also large scale mining companies producing gold, diamonds, bauxite and manganese [22]. Its contribution to the economy makes it one of the nation's most important livelihood activities, employing an estimated one million people and supporting approximately 4.5 million more [23].

Recognized as Ashanti-type, gold deposits consist of multiple stages of quartz vein development with associated disseminated sulphides, occupying zones along the NE-NNE trending structural belts in the Birimian Mesoproterozoic basement. The host rocks are interbedded argillites, greywackes, and volcanoclastic units. The veins extend for large distances and may be discreet narrow structures or form as complex stockworks. There are significant gold occurrences associated with intermediate to felsic intrusives [11]. Igneous intrusions in the Precambrian rocks including ore deposits are one explanation for the gold occurrence. substantial amounts of gold eroded from the basement [11]. Alluvial gold mining is prevailing. This type of mining practice that can be observed on satellite images leads to the conclusion that mainly placer deposits are extracted.

When comparing the Landsat satellite images over the decades it becomes obvious that the mining activities have been increasing significantly during the last decade, especially in the western and southwestern part of the investigation area. The impact event might have contributed to the enrichment of ore deposits as well. Ore deposits that were formed as a direct result of an impact event are known as syngenetic deposits. Ore deposits in impact structures that already existed prior to the impact event are known as progenetic deposits. Post-impact epithermal/hydrothermal ore-forming processes are considered to lead to so-calledepigenetic ores that are known from many impact structures [2], [24]-[26]. The impact event in the Ashanti area has obviously made ore deposits more accessible to mining due to the impact related modifications and deformations. Erosional (enrichment in sediments) and weathering processes along the fault zones might have a further influence on ore occurrence. Due to the distance of most of the mining sites to the impact crater it can be assumed that weathering processes along infiltrating precipitation water and the higher groundwater permeability along the concentric and radial fault zones play an important role with regard to placer occurrence. Faults provide a favorable pathway for groundwater flow as they often serve as weakness zones with higher groundwater conductivity, generating a secondary porosity with higher permeability.

There are no detailed mineral maps of the investigation area public available. Therefore, the position of mining sites was used as indicator for the existence of mineralization of economic value, as otherwise the mining activities would not have spread over such large areas. The mining areas were digitized based on actual Sentinel 2 images of 2020 and BingMap Aerial /Microsoft, ArcGISEarth and WorldImagery / ESRI data (Fig. 12).

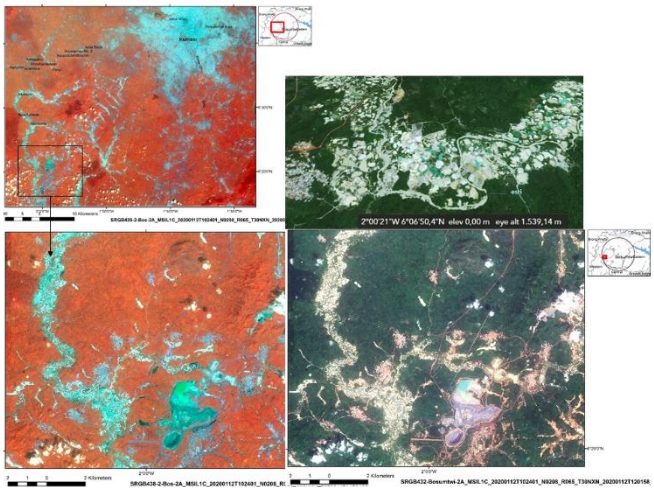

Fig. 12. Mining sites in the southwest of Lake Bosumtwi exploring placer deposits visible on Sentinel 2 images and ArcGISEarth / ESRI.

Artisanal and small-scale mining areas as well as the occurrence of industrial mining plants are located within a circular and partly radial pattern and trace the annular structure along the Pra river and its tributaries, the Ofin, Anum and Brim rivers in the south of the impact center. Most of the mining sites are concentrated in an almost concentric and radial arrangement within a distance between 60–80 km from the central part (Fig. 13). This concentric and radial pattern of ore deposit sites in the environment can be explained by deformation processes during and after the complex structural development of this area.

Whereas the ore deposits near the crater center within a radius of 20 km of Lake Bosumtwi might be related to hydrothermal activity related to the impact event, it can be assumed that weathering processes along infiltrating precipitation water and the higher groundwater permeability along the concentric and radial fault zones play an important role with regard to placer occurrence. Thus, the detailed inventory of structural features is important as well for the monitoring of groundwater pollution in this area due to the mining activities, increasing considerably during the last decade [3]. This is revealed by the comparative evaluations of older Landsat images since 1972 with recent satellite data.

The gold recovery with mercury releases a large amount of mercury into the environment [3]. Mercury contamination of surface water bodies and groundwater especially in the larger rivers as the Pra river, is forming a major health and environmental problem.

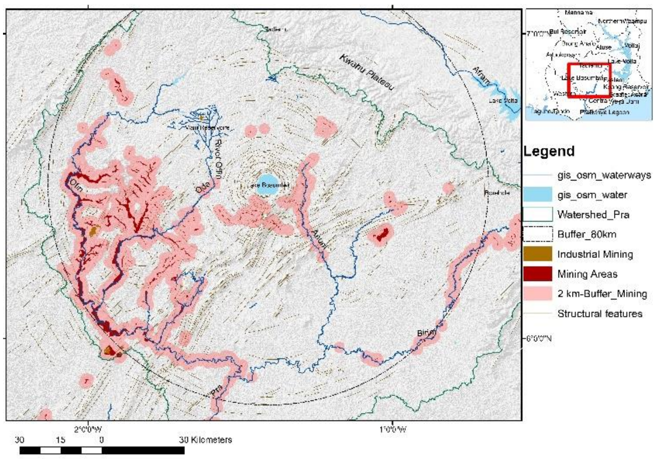

Fig. 13. Mapping of mining sites (dark red) in the area of the Bosumtwi impact structure (The 80 km radius is included to visualize the concentric pattern).

V. Conclusions

GIS embedded visual evaluations of digital processed and enhanced satellite data and of morphometric maps derived from digital elevation data support the detection of the structural pattern and the detailed morphometric analysis of the complex Bosumtwi impact structure and, thus, providing useful tools for its detailed investigation of the structural pattern and morphologic properties. The mapping of distinct expressed lineaments, obviously tracing fault zones, contributes to the inventory of the overall tectonic pattern. The evaluations of the different satellite data lead to the conclusion that the impact event had a larger influence on the tectonic pattern of the affected area than known so far. A circular and radial deformation pattern is visible on the different satellite data within a radius of about 80 km. This is traced as well by the radial and concentric drainage and valley pattern and the nearly circular drainage basin-outline.

The occurrence and distribution of mining sites (used as indicator for the existence of ore deposits) show an almost annular and radial arrangement, concentrated in a distance between 60 to 80 km from Lake Bosumtwi. It is assumed that weathering processes along the deformation pattern play an important role for the placer deposit development.

The evaluation results based on satellite data might help to plan and focus field research to learn more about the specific geologic structure and character of fault zones (dip, strike, type).

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