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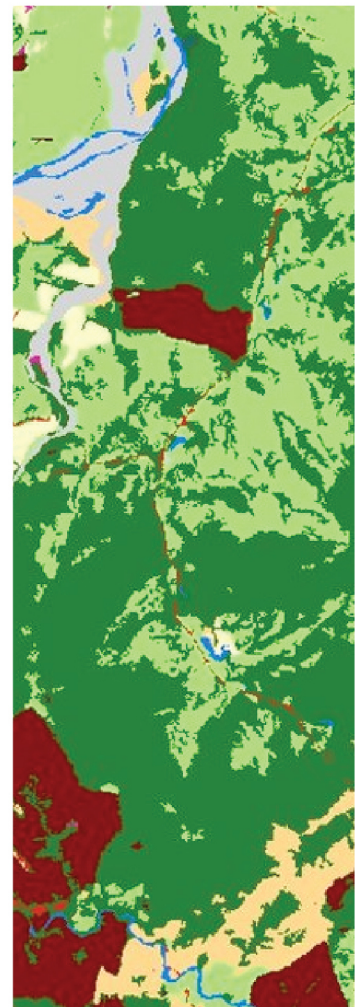
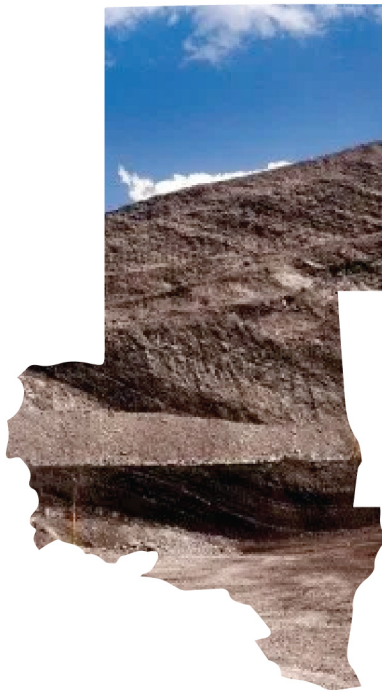
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STRUCTURAL CONTROL ON **GOLD MINERALISATION** REVEALED BY **REMOTE SENSING** AND **GIS TECHNIQUES** IN **CENTRAL NORTH DARFUR** **STATE, WEST SUDAN**



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Abstract

Purpose

This research is focused on the structural controls on gold mineralisation in the central North Darfur State, west Sudan. The region is rich in its mineral resources; nevertheless, it lacks detailed geological studies for better understanding its potentiality. In addition to some security problems, its accessibility difficulties make traditional field-based geological studies impossible. Accordingly, the main objectives of the present work are to utilise the means of remote sensing and GIS techniques, in addition to limited fieldwork, to determine structural controls on gold mineralisation through individual and integrated interpretations of multispectral data, and to develop a regional model of the structural geology and gold occurrences in the study area.

Methodology

The study area comprises various geological units ranging from a Precambrian metamorphic complex (which has been extensively weathered and eroded), to Pleistocene rift filling unconsolidated sediments, volcanics, and several base metal occurrences. Landsat 7 ETM+ images were used, digitally processed and enhanced to recognise the hydrothermal alteration zoning that constitutes a significant remote sensing guide to gold mineralisation.

Findings

Band ratio images disclosed the presence of several prospects that are now major gold deposits at Kassab, Umm Gussa, Hashaba, Alagab, Gabr Elghnam, Kulkul, Dabatuga and Ortow areas. The geophysical data have also proved to be a valuable tool to understand the surface and subsurface structures. The structural orientation analysis has revealed four dominant lineament orientations in the area: N-S, E-W, NW-SE and NE-SW, which are consistent with the regional tectonics. The control on gold was assessed in terms of lithological as well as in terms of structural elements. Most of the gold occurrences were found variably in shear zones and sutures. The prominent NE trending fault, identified from the satellite gravity data, has apparently controlled the distribution of gold occurrence of the study area. Furthermore, most of the gold occurrences of the study area have shown an intimate association with interpreted high gravity zones and quartz veins.

Practical implications

The results of the present work will have important implications for future gold exploration.

Keywords

*remote sensing, mineral exploration, gold mineralisation;
North Darfur State.*

Introduction

This paper focuses on structural controls on gold mineralisation in the central North Darfur State, west of Sudan. The acquisition of geological information has today been greatly assisted by remote sensing technology, as previous literature has documented. Analysis and integration of multi-disciplinary geoscientific information is becoming an advanced technique to ameliorate the geosciences knowledge. The North Darfur region is rich in its mineral resources; however, it lacks detailed geological studies for better understanding its potentiality. The accessibility difficulties, in addition to some security problems, make traditional field-based geological studies impossible.

Gold is one of the most important economic mineral ores available in the region. The main objectives of the present work are utilising the means of remote sensing and Geo-Information System (GIS) techniques, in addition to limited fieldwork, to document the structural geology and gold occurrences, and to define the distribution origins of and relationships between strain and gold mineralisation of the study area. It will also determine structural controls on gold mineralisation through individual and integrated interpretations of multispectral data, and develop a regional model of the structural geology and gold occurrences in the study area. Remote sensing is the science of acquiring, processing, and interpreting images and related data acquired from aircraft and satellites that record the interaction between matter and electromagnetic energy (Sabins, 1997). Remote sensing is best used for the discovery of rare, high-value commodities, such as diamonds and gold, which are becoming more and more difficult to locate (Sabins, 1999).

The study area is located in the northern part of the Darfur Region, west Sudan, between latitude 13.5°-14.5°N and longitude 24.5°-26°E. (Figure 1). This region comprises various geological units ranging from Pre-cambrian metamorphic complex (which has been extensively weathered and eroded), to Pleistocene rift filling unconsolidated sediments, volcanics, and several base metal occurrences (Vail,

1972; Vail, 1976; Vail, 1978; Gindy, 1984; David and Wilson, 1989; Salama, 1994; Ibrahim et al., 1996; Franz et al., 1999; Mohamed et al., 2001; Abdelsalam et al., 2002). The GIS has played a major role in integrating and overlaying the various geosciences data and then producing maps that could be taken to the field to assist field mapping and ground truthing. Reliable geoscientific information in the form of a structural map and a mineral potential map, could then be produced; these are vital for exploration and development of mineral resources.

In the study area, there are four main features of the physical geography. Many places are occupied by plains and low hills of sandy soils, known as goz, and sandstone hills. Dry goz may support rich pasture and arable land. To the north, the goz is overtaken by the desert sands of the Sahara. A second feature are the wadis; these range from seasonal watercourses that flood only occasionally during the wet season to large wadis that flood for most of the rains and flow to north, east and south, such as Wadi Elku, Wadi Sharak and Wadi Mellit. The third feature is the basement rocks that cover most of the study area. The fourth feature is the volcanic plugs created by a massif as Meidob Hills. Elevations of 1,000m above sea level and more are common in the study area; these are dominated by dendritic to parallel seasonal streams (wadis) flow in basement complex rocks. There are no drainage lines in the goz area that overlie the Nubian Formation. Darfur has low and variable rainfall, ranging from less than 50mm in the northern desert to approximately 200mm around El Fasher, 300-500mm in Geneina and Nyala, and up to 800mm or more in the south and in Jebal Mara. The rainy season generally starts in April with sporadic showers that gradually intensify towards June. These showers are followed by the main rains in July and August and by a period of declining intensity throughout September. However, rainfall amounts and predictability, as well as the length of the rainy season, increase significantly from north to south (Mukhtar, 1975; Hamid et al., 2008; Maniese, 2012).

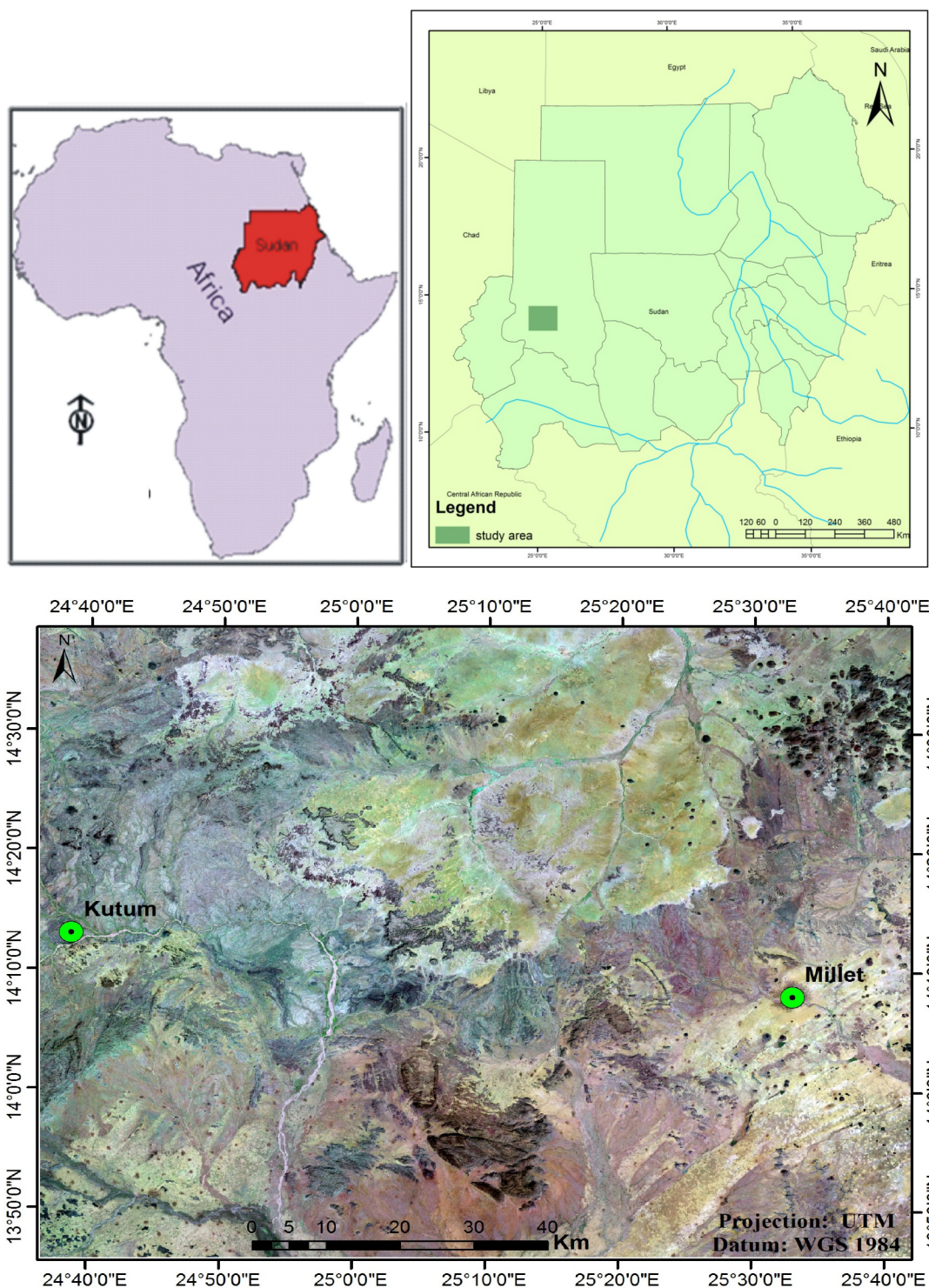


Figure 1: Location map and satellite image of the study area

Source: Produced by authors

Methodology

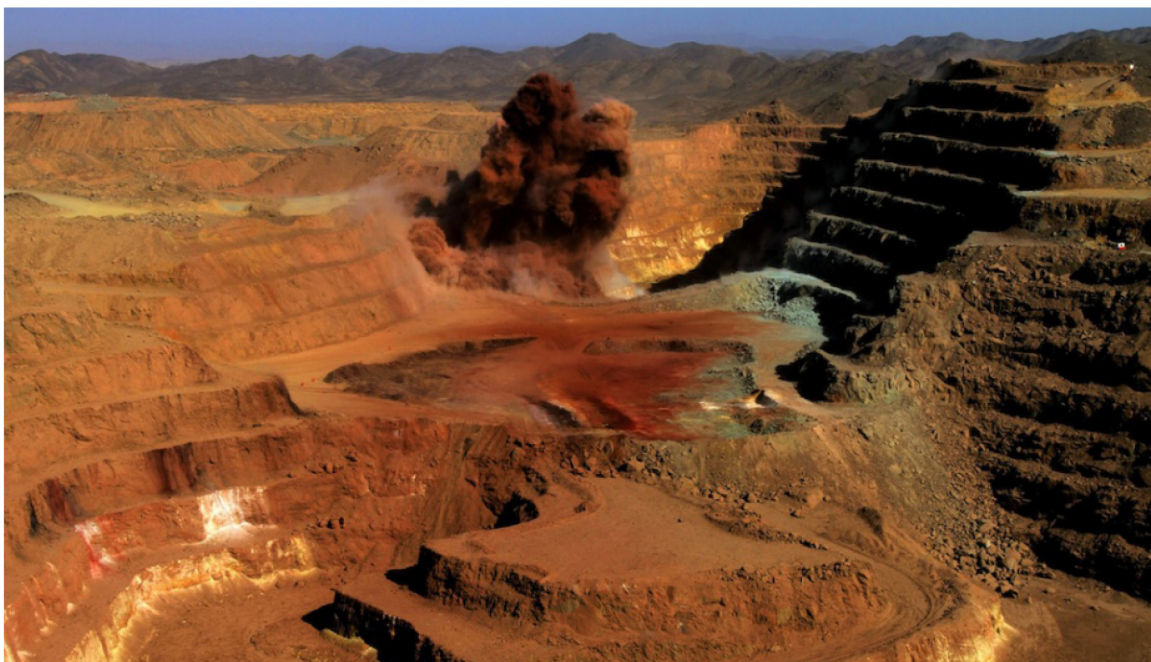
Data used

A geodatabase was created with all the different information available for the area, together with processed Satellite images, path 178, raw 50, acquired on 26 October 2011; these were obtained from The Global Land Cover Facility of the Maryland University, USA. The ETM+ images are of Landsat 7 and contain a total of eight bands; six in the Visible and Near-Infrared (VNIR), one in the Thermal Infrared Region (TIR), of the electromagnetic spectrum, and one panchromatic channel (band 8). Spatial resolution is 15m for the panchromatic band, 30m for VNIR bands, and 60m for the TIR bands, so that the samples for the mineral exploration can be taken with better criteria taking into account the many factors affecting the area.

Other ancillary data used in this study include State & County Boundaries, Existing Mines, Topographic maps (Kutum Sheet, 54-E) at a 1:250 000 scale (obtained from the National Survey Authority of Sudan), Geologic maps (Geological Map of the Sudan GRAS, 2004. 1:2000 000) (GRAS, 1988 and Robertson, 1988. 1:1 000 000 Geology Map of Sudan), and local maps from academic publications, e.g., Gindy (1984). DEMs, Google Earth Maps, Mining Claim Locations and Ownership Information, GPS data and Geologic Data (Structures, Alteration and Silicification).

Methods

The main methods of the study are remote sensing and GIS analysis. In addition, limited fieldwork was undertaken to design the geodatabase according to the required information. After the geodatabase design was finished, all the datasets were fed into the geodatabase. The raw datasets were put through the different Analysis Tools in ArcToolbox to obtain only the required derivatives. Also, several public databases were found that contained datasets that are updated every day. Hydrothermal alteration associated with gold mineralisation was mapped in the study. Landsat imageries were digitally processed and enhanced to gather more information about the study area concerning the lithological units and wall rock alteration. During the fieldwork, geological data, including rocks and structural measurements, were collected.





Mineral Potential of Sudan

Sudan has a long history and a large mining culture heritage that goes back 3,000 years when Nubians extracted gold and base metals and smelted iron to make water wells (Vail, 1978).

Mineral resources have not been fully explored as yet, but include petroleum, natural gas, gold, silver, chrome, asbestos, manganese, gypsum, mica, zinc, iron, lead, uranium, copper, kaolin, cobalt, granite, nickel and tin. The Pan-African terrains dominate the geology of the country. These terrains were found to host most of the economically valuable mineral deposits, especially gold, where huge mineral potentials are yet to be discovered and exploited (Elsamani, 2015).

The Arab Industrial Development and Mining Organization (AIDMO, 2014) confirmed that Sudan has large reserves of various minerals, such as

gold, chrome and manganese, underscoring that the mining sector has a promising future in the country's economy. The estimated mineral reserves in Sudan include 700,000 tonnes of chrome, 100,000 tonnes of manganese, 53 million tonnes of asbestos, 25 million tonnes of talc, 150 million tonnes of gypsum, 1.5 million tonnes of kaolin, and more than 15 million tonnes of magnesite.

In Sudan, the gold occurrences (Figure 2) (Elsamani, 2015) are located in five greenstone belts, namely the Red Sea Hills area in the north east, the Nubian Desert east of the River Nile and south of the border with Egypt, the Hofrat En Nahas area in the west (Darfur region), the Nuba Mountains area west of the White Nile, and the Blue Nile area in the south east.

According to the Ministry of Mining, traditional mining represents 90% of gold production in Sudan. The most important gold deposits of Sudan are located in the Ariab Mineral District (AMD) of the Red Sea Hills area. The lithological association of gold in this area has been linked to the presence of mafic-ultramafic sequences and associated volcano-sedimentary rocks (GRAS, 1995). Gold mineralisation in the region occurs in different geological environments and at least three types are present (Aloub and Elsamani, 1991):

- pre-metamorphic mineralisation associated with stratiform massive sulphides deposits: this type of gold occurrence is syngenetic and pre-dates the regional metamorphism that affected the gneissic and volcano-sedimentary formations throughout the Red Sea Hills;
- gold mineralisation related to the regional tectono-metamorphic episodes: occurrences of this type are lithologically controlled and assigned to particular gold-bearing horizons. Two varieties have been categorised: (a) gold collapse breccias, which occur in the form of auriferous units that are essentially composed of silica, barite, and iron oxides; this type was first recognised in the Ariab area and is referred to as silica barite rocks (Cottard et al., 1986); (b) the second category is that of gold in recrystallised host rocks close to sulphide minerals;
- gold mineralisation related to shear zones: this type of mineralisation is dominant in the region and is exclusively in the form of auriferous quartz veins that are always located along fracture zones; their emplacement appears to be structurally controlled.

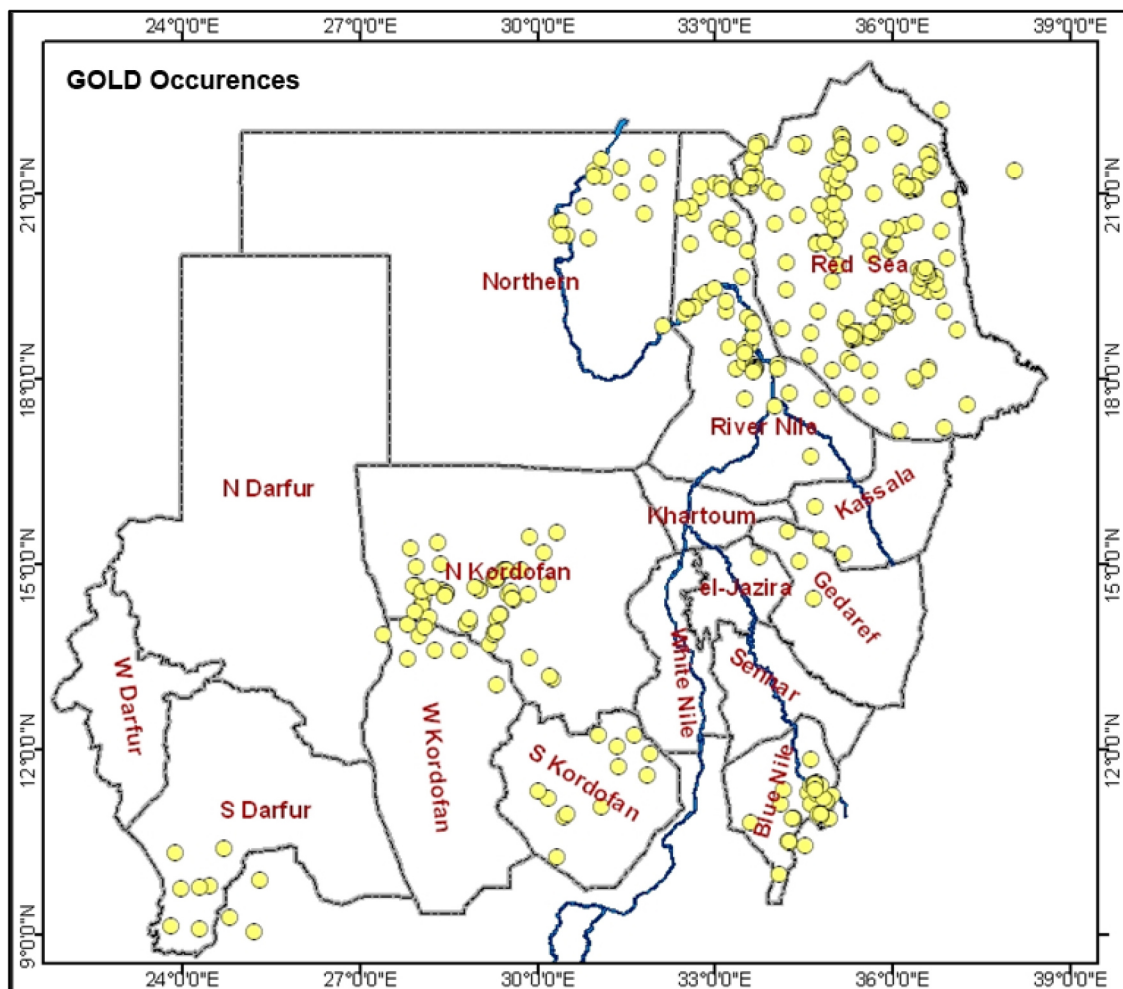


Figure 2: Gold occurrences in Sudan

Source: Elsamani, 2015

Geology of the North Darfur

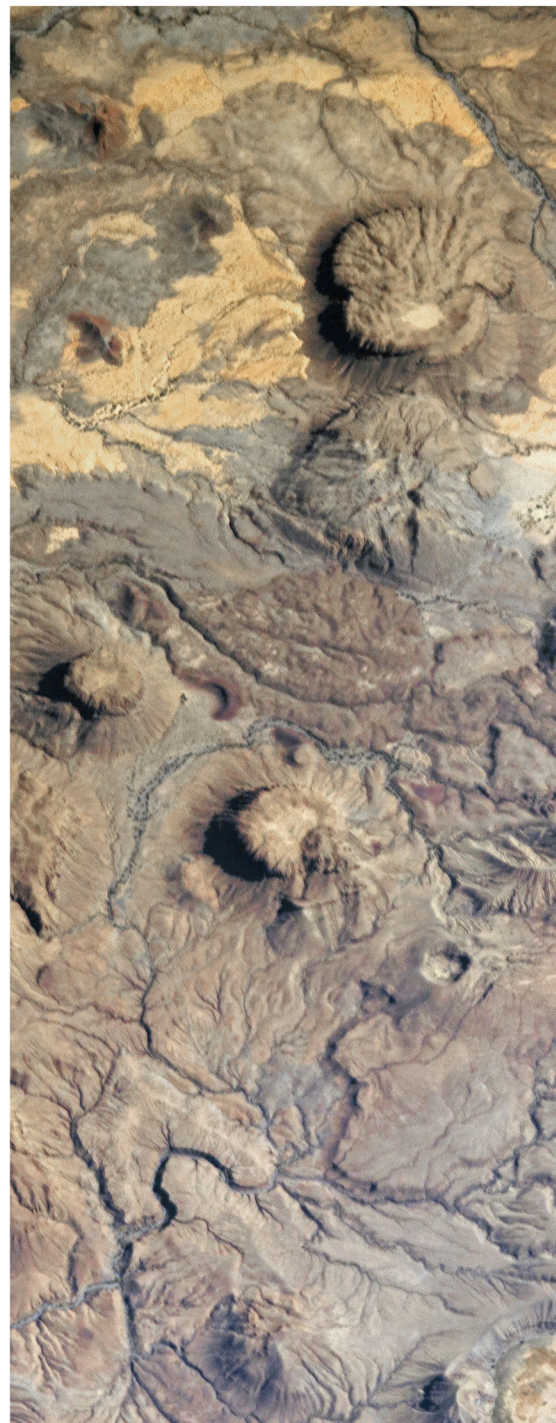
The first geology of the area was described by Delany (1952), Whiteman (1971), and Vail (1978). The general geology of the area includes the basement complex: these are Precambrian rocks of metamorphic rocks and younger intrusives. The metamorphic complex comprises undifferentiated gneisses and a sequence of supercrustal rocks that include mica schist, graphitic schist, and quartzite. These rocks are intruded by granitoids grouped as undifferentiated Precambrian granitic rocks. The fresh basement is sometimes covered by a zone of altered basement rocks of highly variable thickness. Quartz veins are widely distributed over the whole area.

The Nubian Formation is Jurassic, Cretaceous in age and consists of medium- to coarse-grained, cross-bedded sandstone, pebbly and siliceous sandstone, sandy mudstone, and conglomerate. The sub-Nubian topography is uneven and forms sub-basins, which are separated by basement ridges. The sediments of Nubian sandstone were deposited rapidly by the river system onto delta fans across flood plains (Vail, 1978).

Volcanic rocks of Paleogene-Neogene age, and probably Miocene, range from basalts to trachytes. These crop out in the Meidob Hills in the north east, in the Tgabo hills between Mellit and Malha, and in the Jebel Marra complex with its eastward directed lava outflows to the Shagera Basin. The Marra Mountains are located at the intersection of two transcontinental tectono-volcanic zones, ENE from Cameroon to the Red Sea, and SSE from Libya to Kenya (Vail, 1972). Trace element and isotope data indicate a mix of fractional crystallisation and an assimilation of crustal material and mantle material (Davidson and Wilson, 1989).

The superficial deposits are unconsolidated sediments deposited during the Pleistocene to recent time; they can be classified into windblown sands (qoz) and stream deposits (wadi fills). The windblown sands consist of quartz grains, while the stream deposits consist of gravels, sands

and sandy clay. The thickness of the superficial deposits ranges between 2-35m. These deposits are called Umm Ruwaba Formation in central, southern and northern Darfur.



Result and Discussions

Remote sensing and GIS

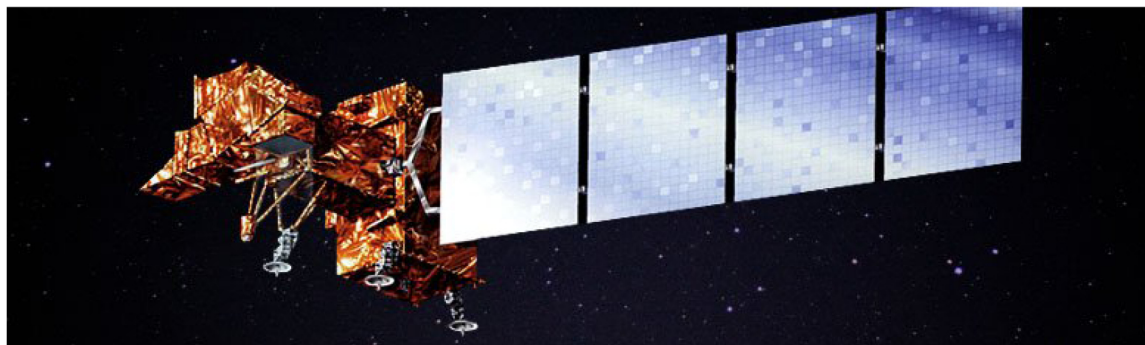
In developing countries such as Sudan, most geological, hydrogeological and mineral exploration works have been done with the absence of the application of remote sensing and Geographic Information System (GIS). Remote sensing, as a supplement to field lithologic and structural mapping, has played an important role in the study of mineralised areas since aerial photography became available in the early 1950s. Satellite imagery can be successfully used for mineral reconnaissance; it is simply a search for examination and evaluation of features that may indicate a mineral deposit. It is fairly general in scope, being followed in favourable areas by detailed mapping, sampling, assay and possible development. The features that indicate mineralisation are known as localisers, indicators or guides. If these indicators can be identified on satellite data/imagery, then the mineral explorations can be much faster with increased efficiency (Gupta, 1991, 2003).

Satellite imagery has proved valuable for mineral exploration in three ways (Sabins, 1997): mapping of regional and local fracture systems that controlled ore deposits, detection of surface alteration effects associated with ore deposits, and providing basic data for geologic mapping. In addition, topographic data in the form of Digital Elevation Models (DEM) can be combined with remotely sensed imagery to map geological features indicative of mineralisation of the type sought (Sarapirome et al., 2002). The analysis

of remotely sensed data is performed using a variety of image processing techniques, including analogue (visual) image interpretation of the hard copy data, and digital image processing algorithms applied on digital data that allow the analyst to perform scientific visualisation, define as visually exploring data and information in such a way as to gain understanding and insight into the data (Lillesand and Kiefer, 1994).

GIS can help in many aspects of the mineral exploration activities: data collection, management, analysis, and reporting. Information from the processed and interpreted satellite imageries, combined with geological fieldwork data, petrographical, structural and elevation data, were integrated in a GIS database system using GIS software packages; a geodatabase was then designed to extract only the information needed for each task. The outcomes of this step are the structural map, the delineation of the extension of the alteration zones, and other relevant maps.

In this study, multispectral remotely sensing dataset Landsat 7 Enhanced Thematic Mapper Plus (ETM+) was used; it was digitally processed and enhanced to recognise the geological and structural information of the study area. The applied enhancement techniques have been used, including colour compositing, band rationing, principal components analysis (PCA), edge enhancement and image classification properly separated the alteration zones from the unaltered rocks.



Structural elements in the investigated area

The distribution pattern of structural elements, such as fractures, shear zones and other geological lineaments were extracted from remote sensing data. For quality control, the results were compared with published and unpublished maps and ground checked during fieldwork. Structural information extracted from the lineaments analysis, together with the field check, was used to generate a 1:100,000 structural map of the study area (Figure 3).

The structural orientation analysis revealed four dominant lineament orientations that determine the tectonic terrain of the study area, N-S, NE-SW, NW-SE and E-W. These orientations were found to be consistent with the regional tectonics. Both ductile and brittle tectonic structures are present in the region and have NE major lineament frequency.

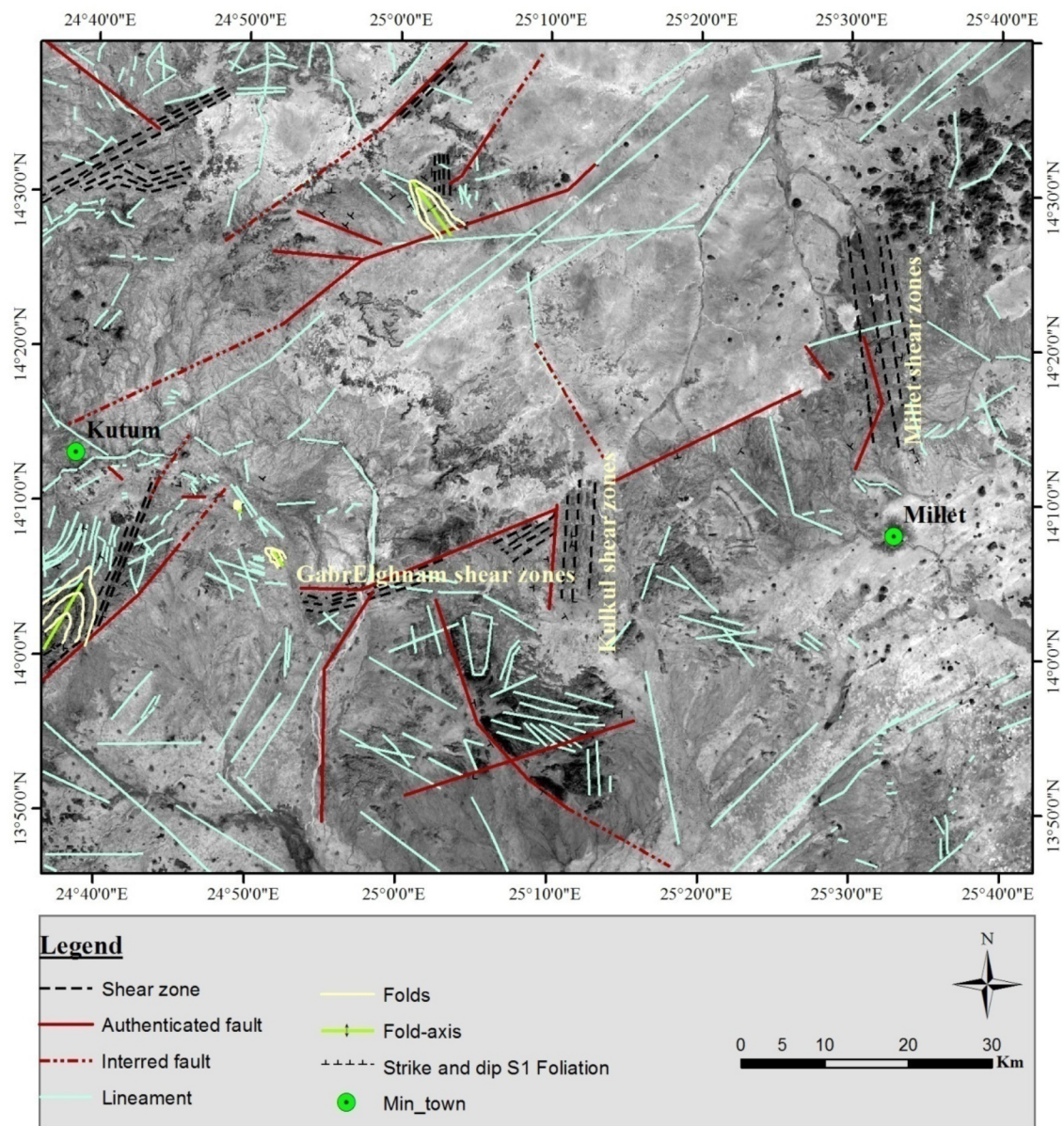


Figure 3: Various brittle and ductile structures in the study area

Source: Produced by authors

A total of 182 observation points were visited along geological traverses, starting from El Fasher, Mellit and Kutum. In the Kutum region, three traverses were undertaken south and as far north as Kassab, Umm Gussa and Hashaba, and as far southeast as Gabr Elghnam, Kulkul, Dabatuga and Ortow north Mellit. Observations were also made along the main road between El Fasher and Kutum and in both the Mellit regions (Figure 4).

Information and samples were collected from various rock units for microscopic and structural investigations, and for studying tectonic evolution. Attitudes of planar and linear fabrics were taken for structural analysis.

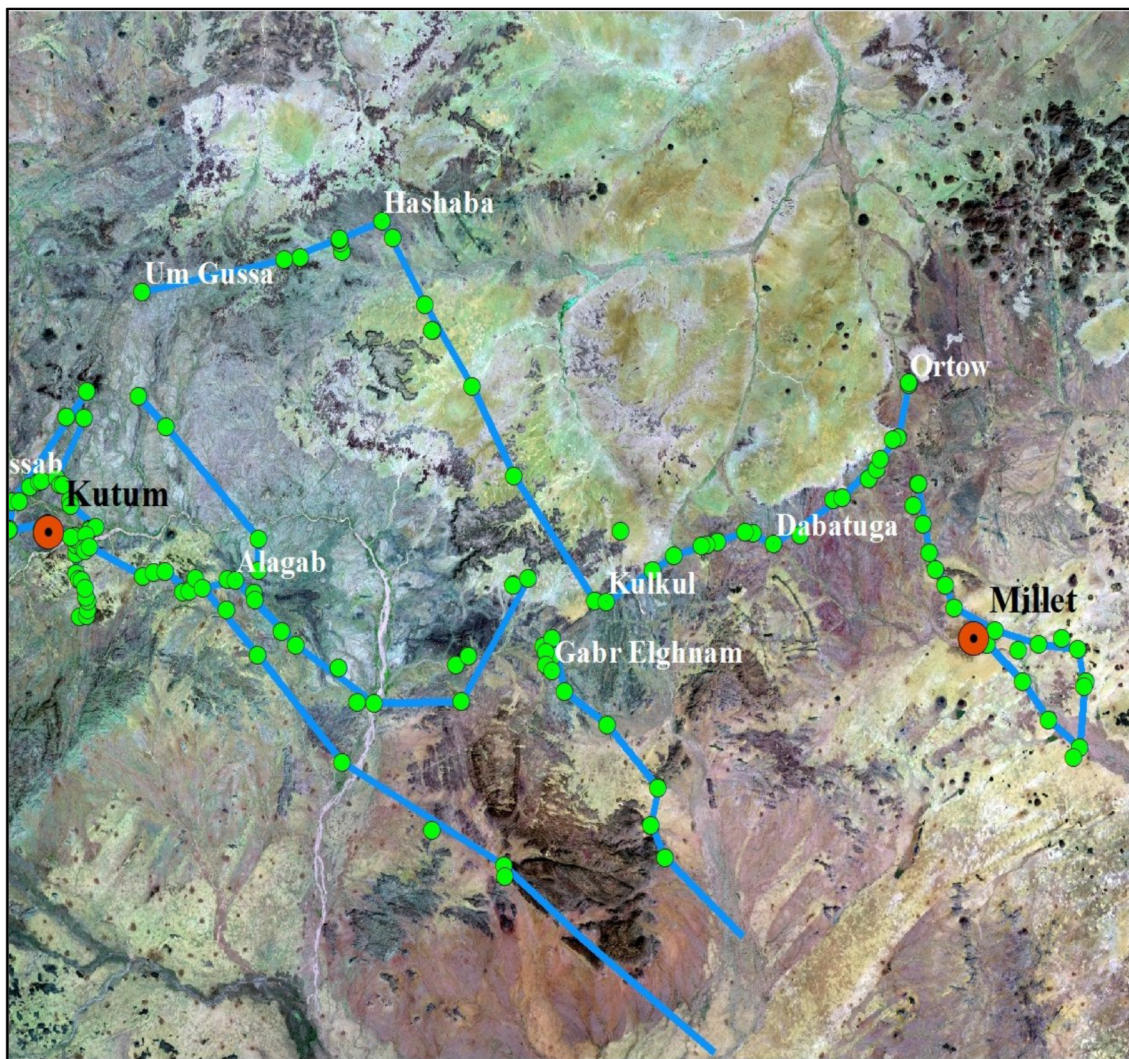


Figure 4: Satellite image showing field geological traverses and way points visited in the study area

Source: Produced by authors

Field investigations revealed that the strike slip faults are the most dominating brittle structural fabric in the study area. They are oriented in a N-S direction together with the shear zone, and in an E-W direction. The NE-SW trending lineaments are parallel to the regional Neoproterozoic fabric and are steeply dipping to the west. The N-S set of strike slip faults are of left lateral sense of movement.

Quartz veins in the investigated area

Two generations of gold bearing quartz veins were observed in the study area. The first generation are thin (~5-20cm across) (Photo 1A), occurring in the southern and western parts of the study area, mainly within the sericite graphitic quartz schist and sericite chlorite schist, trended E-W and occur in a relatively higher density in the shear zones. The second generation quartz veins are wide and long, their thickness ranges from 2-5m and their length ranges from 2-8km (Photo 1B), trended N-S, NE-SW and NW-SE occurring in the northern and eastern parts of the study area.



A



B

Photo 1: Field photo showing examples of the (A: left): Thin quartz veins occurring parallel to the foliation; (B: right): Large quartz veins up to 2m thick and up to 5km in length

Source: Produced by authors

Prospective areas for gold (Au) in the investigated area

Exploitation of remote sensing images in mineral prospecting can be understood by enhancing geological mapping, mapping the regional lineaments and structural trends, mapping local fractures and faults to delineate localised ore deposits, and recognising hydrothermally altered rocks by their spectral signatures (Sabins, 1997, 1999; Abrams et al., 1983; Lillesand and Kiefer, 1994; Jensen, 1996; Bennett et al., 1993; Lillesand and Kiefer, 2000; Zeinelabdein and Albiely, 2008; El Khidir and Babiker, 2013; Zeinelabdein, 2014).

Hydrothermal alteration zones were selected from the satellite images analysis results as a significant remote sensing guide to gold mineralisation. Band ratio images disclosed the presence of several potential targets in the study area. In addition, gold mineralisation was observed at eight locations in the study area; these are now major gold deposits at Kassab, UmGussa, Hashaba, Alagab, GabrElghnam, Kulkul, Dabatuga and Ortow areas (Figure 5) (Hassan and Zeinelabdein, 2016).

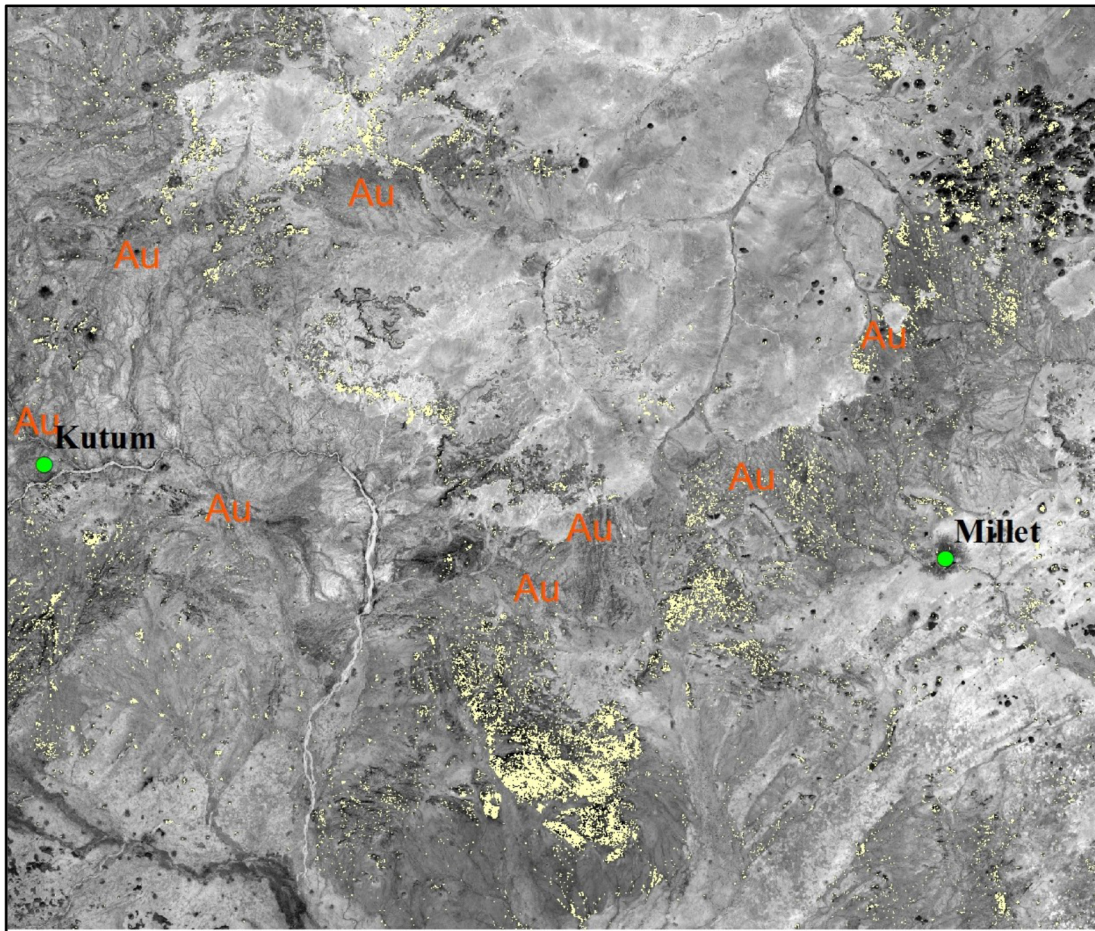


Figure 5: Alteration and gold occurrences (Au) overview map. Using Landsat ETM+ as background

Source: Produced by authors

Gold mineralisation controls

The controls on gold mineralisation were assessed in terms of lithological as well as in terms of structural elements. A regional model of the structural geology and gold occurrences in the study area was developed (Figure 6). Most of the gold occurrences were found in shear zones and quartz veins. The mineralising fluids were then transported upwards from deep regions through the shear zones.

Structural information extracted from the lineaments analysis, together with field checks, indicated that the E-W and NW-SE trending faults and fractures control the northeast and northwest trending quartz veins (Figure 7). Accordingly, the quartz veins carrying ore minerals in the study area are structurally controlled.

The sulphide mineralisation mainly occurred in the graphitic sericite quartz schist and sericite-chlorite quartz schists. The dykes/sills may contain sulphides in trace quantities. The mineralised zone is hosted in sheared Neoproterozoic metamorphosed sedimentary rocks and metavolcanics adjacent to monzogranite and lamprophyre dykes/sills, parallel and/or cutting the foliation D1 (Figure 8).

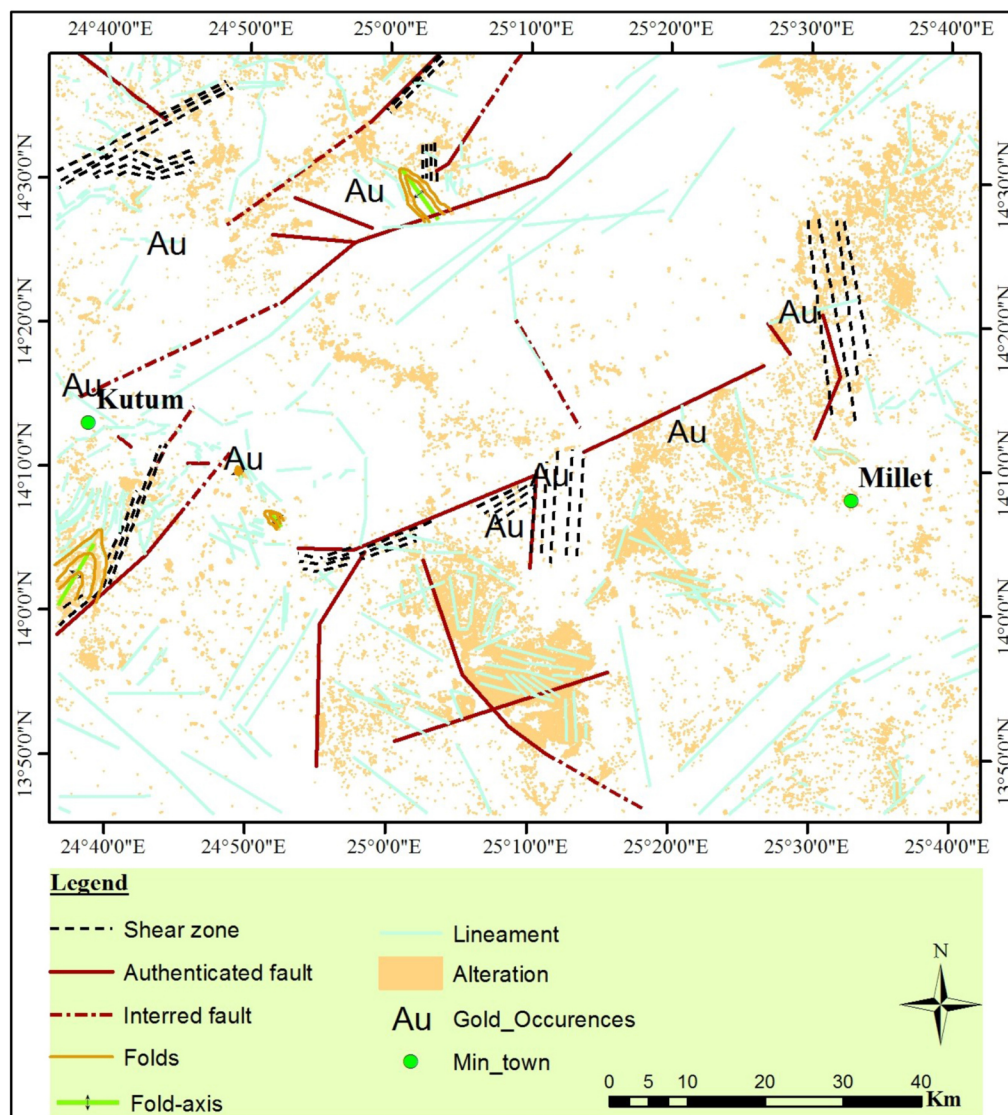


Figure 6: Alteration, gold occurrence and structures overview map

Source: Produced by authors

Field inspection revealed that the hydrothermal processes affecting the area are silicification, chloritisation, oxidisation and ferrugination. The metavolcano-sedimentary rocks are affected by at least two phases of ductile deformation (D2 and D3), and NW striking brittle faults post-date the ductile deformation.

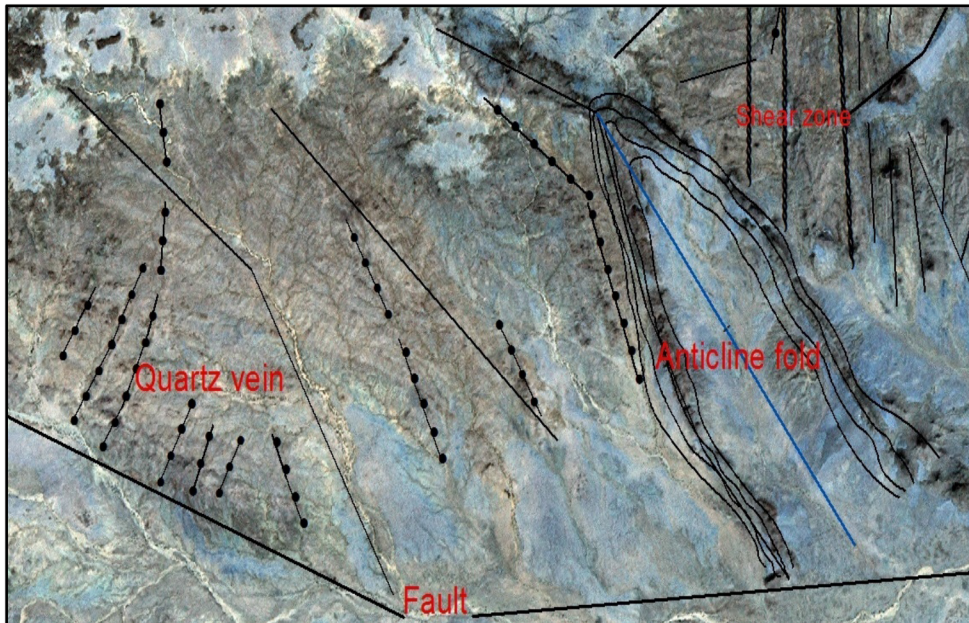


Figure 7: Quartz veins structurally controlled in the study area traces on the landsat image

Source: Produced by authors



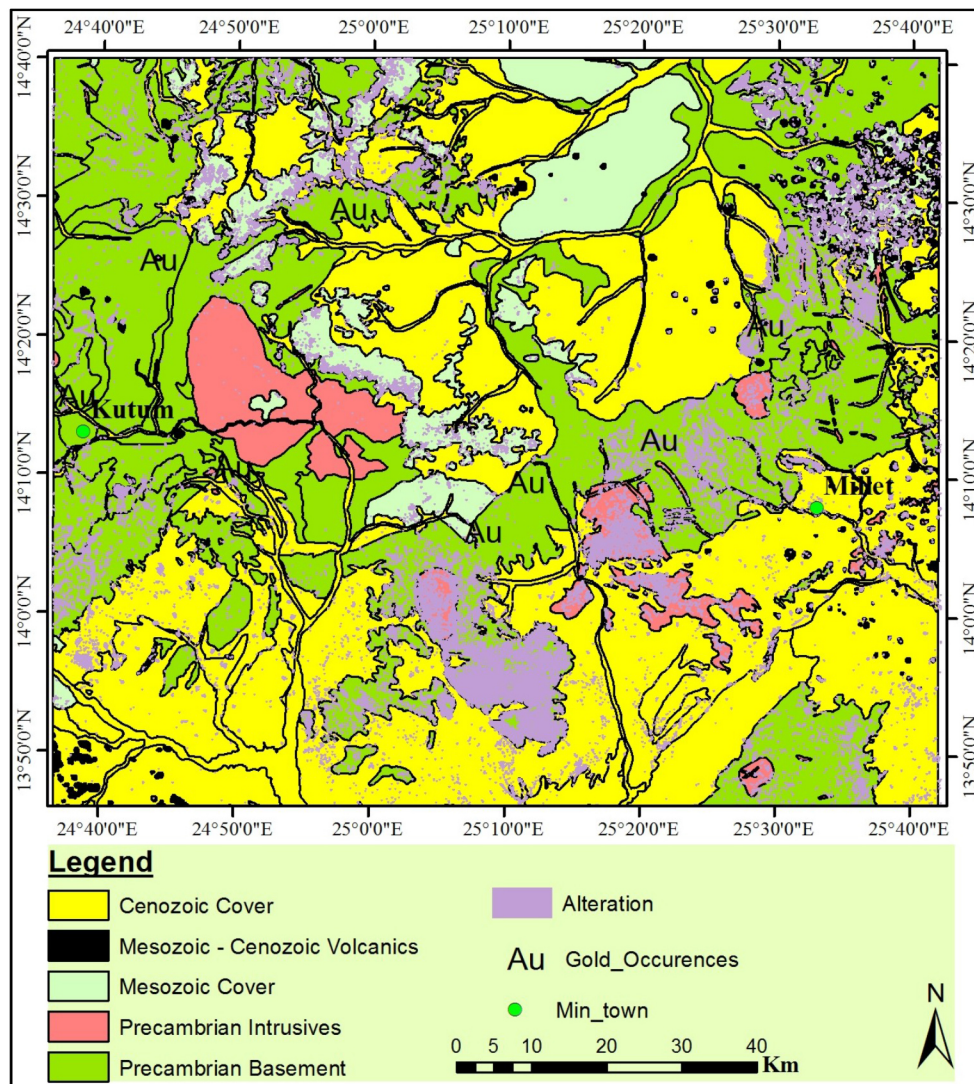


Figure 8: Lithological and alteration overview map

Source: Produced by authors



Conclusions and Recommendations

Huge arid areas such as the Darfur region that are characterised by hilly topography and a harsh environment, together with security problems, make conventional field surveys difficult if not impossible. In such cases the use of remote sensing must be considered as a major and efficient tool for the identification, detection and delineation of lithological rock units, hydrothermal alterations, and geologic structures associated with auriferous sulphides deposits. The study also aimed to assess the inter-relationships and to qualitatively assess structural control on gold mineralisation.

The lineament orientation analysis, together with structural field observations, revealed four dominant lineament orientations that determine the tectonic terrain of the study area, N-S, NE-SW, NW-SE and E-W. These orientations were found to be consistent with the regional tectonics. Both ductile and brittle tectonic structures are present in the region and have NE major lineament frequency. The strike slip faults are the most dominating structural fabric in the study area. They are oriented in a N-S direction with the shear zone and E-W. The NE-SW trending lineaments are parallel to the regional Neoproterozoic fabric and dip steeply to the west. The N-S set of strike slip faults are of left lateral movement. The structural pattern of the study area is dominated by regional scale, N35°E striking foliation, N-S striking shear zones with strong fabric and NW striking brittle faults. In addition, other types of structures, such as folds, joints, fractures and small shear zones, were observed in different localities of the study area.

The field inter-relationships were assessed and integrated with the alteration zones, rock samples and gold samples. The sulphide mineralisation mainly occurred in the graphitic sericite quartz schist and sericite-chlorite quartz schists. The dykes/sills may contain sulphides in trace quantities. The mineralised zone is hosted in sheared Neoproterozoic metamorphosed sedimentary rocks and metavolcanics adjacent to monzogranite and lamprophyre dykes/sills, parallel or cutting the foliation.

Two generations of gold bearing quartz veins were observed in the study area. The first generation

contains thin veins (~5-20cm thick), occurring in the southern and western parts of the study area. They are mainly within the graphitic sericite quartz schist and sericite chlorite schist, trended E-W and occur in higher density in the shear zones. The second generation quartz veins are wide and long; their thickness ranges from 2-5m and their length ranges from 2-8km, trending N-S, NE-SW and NW-SE, occurring in the northern and eastern parts of the study area. In addition, gold mineralisation was observed at eight locations in the study area that are now major gold deposits; these are at Kassab, Um Gussa, Hashaba, Alagab, GabrElghnam, Kulkul, Dabatuga and Ortow areas.

The control on gold was assessed in terms of lithological as well as in terms of structural elements; a regional model of the structural geology and gold occurrences in the study area was developed. Most of the gold occurrences were found in shear zones and quartz veins. Structural information extracted from the lineaments analysis, together with field checks, indicated that the E-W and NE-SW trending faults control the northeast trending quartz veins in Hashaba north. Therefore, the mineralised auriferous quartz veins in the study area are structurally controlled. The results of the present work will have important implications for future gold exploration in Darfur Region.

This study has better defined the lithological rock units, hydrothermal alterations and tectonic setting of the study area through an integrated analysis of remote sensing, surface and subsurface data. Therefore, similar approaches are recommended for other areas in the Darfur region in order to fully explore the region. The source of gold mineralisation in the study area is still not fully known. Therefore, a detailed geochemical investigation and high resolution geophysical data interpretation are recommended for better understanding of the source of gold mineralisation.

More detailed geological structural analysis (shear zone kinematics, lineament and fold structures), detailed geochemical investigation and geochronological analysis for the various rock units are recommended to contribute to the understanding of the tectonic evolution of the area.

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