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## MINERAL EXPLORATION AND SUSTAINABLE DEVELOPMENT: A CASE STUDY IN THE REPUBLIC OF SOUTH SUDAN

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Dr. Edward Woolery, Director of Graduate Studies

MINERAL EXPLORATION AND SUSTAINABLE DEVELOPMENT:  
A CASE STUDY IN THE REPUBLIC OF SOUTH SUDAN

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DISSERTATION

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A dissertation submitted in partial fulfillment of the  
requirements for the degree of Doctor of Philosophy in the  
College of Arts and Sciences  
at the University of Kentucky

By

Cosmas Pitia Kujjo

Lexington, Kentucky

Director: Dr. Dhananjay Ravat, Professor of Geophysics

Lexington, Kentucky

2019

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## ABSTRACT OF DISSERTATION

### MINERAL EXPLORATION AND SUSTAINABLE DEVELOPMENT: A CASE STUDY IN THE REPUBLIC OF SOUTH SUDAN

South Sudan, a new country formed in 2011, has been planning to develop its mineral sector by allocating exploration licenses to investors. This decision requires preliminary knowledge of geology and mineral occurrences, both of which are unavailable because the country has been engaged in a civil war for more than 50 years. Exploration of mineral resources in South Sudan has lagged behind its petroleum industry, except for artisanal gold mining, which is practiced intermittently by local communities. Freely available satellite gravity and remote-sensing data were used to map the basement architecture as well as zones of hydrothermal alteration in the Didinga Hills; both basement architecture and hydrothermal alteration are of prime importance in exploration and development of mineral resources in the study area. Qualitative interpretation of gravity data is consistent with the known geology of petroleum fields and the Precambrian basement complex. Remote-sensing data and techniques—optimal band combination, band ratioing, and principal component analysis—have been effective in extracting information related to lithology, hydrothermal alteration, and geologic structures. The resulting basic information and methods have identified additional prospective exploration areas where more detailed gravity, magnetic, electromagnetic, and seismic surveys should be carried out; this will assist decision makers in matters related to land use, mineral titles, and exploration of natural resources, and lead to prosperity for the new nation of South Sudan.

KEYWORDS: Mineral Exploration, Sustainable Development, Remote Sensing, Geophysics, South Sudan.

Cosmas Pitia Kujjo

Date: March 20, 2019

MINERAL EXPLORATION AND SUSTAINABLE DEVELOPMENT:  
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## DEDICATION

*To my parents, Salvatore and Pukun, and to all peace-loving beings.*

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## **CHAPTER 1: INTRODUCTION**

### **Introduction**

South Sudan, a new country, is planning to develop its mineral resources by allocating exploration licenses to investors, a decision that requires preliminary knowledge of the geology and potential areas of mineral resources in the country. Although mineral exploration in the Republic of South Sudan has occurred for centuries, the sparse population and inhospitable climate have resulted in only sporadic prospecting (Kujjo, 2010). The most notable exploration period, by British enterprises, was between 1900 and 1954. Other attempts at artisanal mining, by locals, have been along the border with Ethiopia, Uganda, Central African Republic, and Democratic Republic of the Congo (Geological Research Authority of the Sudan, 1990).

### **Previous Studies**

There has been little geological survey of South Sudan because of political instability and civil wars that lasted for more than 50 years. Some mineral exploration in southern Sudan during stable times in the 1970s and '80s was conducted by Hunting Geology and Geophysics, Chevron Oil Company, and the Belgian Mission, however, as well as some academic research conducted by national and foreign educational and research institutions. All of these surveys demonstrated potential mineral resources, such as gold, silver, copper, zinc, nickel, manganese, bauxite, magnetite, and uranium, in addition to industrial and building materials (e.g., hard rock, marble, gravel, sand, clay, and gemstones (Geological Research Authority of the Sudan, 1990).

### **The Present Study**

Mineral exploration and sustainable development in the Republic of South Sudan is needed as the government plans to diversify its economy instead of being dependent on oil export only. South Sudan has been included in a World Bank report that identified five priority zones in Africa that are geologically underexplored but potentially prospective (Figure 1.1); the geologic conditions of these zones should be correlated with nongeological factors, including infrastructure (EI SourceBook, 2019).

The present study is aimed at determining how utilizing satellite gravity data and Landsat images could aid mapping of mineral resources and their sustainable development in the Republic of South Sudan, and hence fill in the gap in geodata mentioned in the World Bank report (EI SourceBook, 2019).

Remote predictive mapping can provide a base for geologic mapping, and it can be implemented cost-effectively by applying satellite remote-sensing techniques to Landsat imagery of the Didinga Hills, an area known for its artisanal and small-scale gold mining. Satellite gravity data that are publicly available at no cost have been used to study and map the basement architecture of the study area.

This introduction chapter gives an overview of previous studies and the present study in regard to diversifying the economy of the Republic of South Sudan. Additional studies could aid in mapping prospective mineral areas, which would be an effective contribution to the new nation.

Chapter 2 gives background information about the country's location and physiography, as well as its geologic and structural setting.

Chapter 3 discusses mapping the geology and minerals of the study area using satellite imagery. Landsat 8 imagery of the study area was processed and analyzed to map hydrothermal alteration zones in the Didinga Hills of the Eastern Equatoria region of South Sudan.

Chapter 4 describes processing and interpretation of satellite gravity data using Geosoft software to map the basement architecture and relate major geologic structures to potential mineralization, which is helpful for designing mineral title blocks or concessions in the country.

Chapter 5 details how South Sudan is adapting several regional and international legal frameworks to sustainably develop its mineral resources in order to effectively contribute to the national economy and help lessen the country's dependence on oil revenues, which amounts to about 98 percent of the country's gross domestic product. This chapter concentrates on adequate management, good governance, transparency, best practices in environmental protection, and community development by all stakeholders, including government, companies, and society.

Chapter 6 presents the major conclusions of this study and makes recommendations that will further the goal of mapping the mineral potential of the Republic of South Sudan, as well as sustainably developing these minerals for the prosperity of the nation.

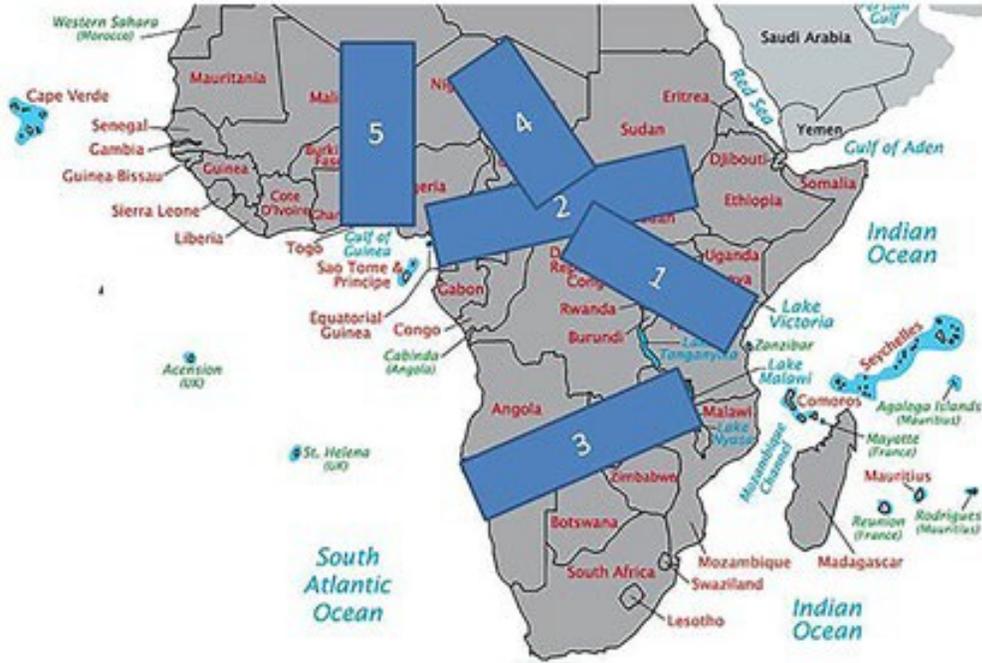


Figure 1.1. Five priority zones for mineral exploration in Africa selected by the World Bank; these areas are also without significant geodata (EI SourceBook, 2012).

## **CHAPTER 2: COUNTRY AND GEOLOGIC BACKGROUND**

### **Country Background**

The Republic of South Sudan seceded from the Republic of Sudan in July 2011 to become a sovereign state. Its capital city of Juba was already a regional capital for the autonomous southern Sudan government. The Republic of South Sudan joined the African Union as the 54th member and the United Nations as the 193rd member. The country has an approximate area of 644,329 km<sup>2</sup> and an estimated population of about 8.26 million representing a diversity of more than 60 different major ethnic groups (tribes), the majority of which follow Christianity and traditional religions ([www.globalreligiousfutures.org/countries/south-sudan](http://www.globalreligiousfutures.org/countries/south-sudan)).

South Sudan is located in northeastern Africa (Figure 2.1) and bordered by Sudan to the north, Ethiopia to the east, Kenya to the southeast, Uganda to the south, the Democratic Republic of the Congo to the southwest, and the Central African Republic to the west. The country constitutes the part of the Nile Valley that includes the “Sudd,” which is the largest tropical wetland in the world, formed by the White Nile (Sutcliffe and Parks, 1999).

#### *Physiogeography*

South Sudan lies between latitudes 3° and 13°N and longitudes 24° and 36°E. Its central part is covered by the swampy plain the Sudd, mentioned above, and is surrounded by mountainous highlands comprising massif plateaus containing drainage patterns that are the result of many streams flowing down the mountains in different directions. The most well-defined watercourse, the White Nile, flows through the capital city of Juba (Figure 2.2).

#### *Regional Geology*

The geology of east and central Africa is characterized by rift systems consisting of a network of tectonic structures originating at different geologic times (Kampunzu and Popoff, 1991). Stable cratons are associated with these rifts (Figure 2.3).

The East African Rift System, extending across central Africa up to the Atlantic Ocean to the west, has been considered by some to be part of a much larger, continent-wide system linking the Red Sea and Gulf of Aden (Kampunzu and Popoff, 1991). The East African Rift System (indicated in yellow in Figure 2.3 and labeled as Cenozoic rifts) extends from the Red Sea, where it forms a triple junction at Afar in Ethiopia and extends southward to the African Great Lakes region and continues to Mozambique, where it joins the Indian Ocean (Park, 1988).

Little is known about the pre-rift history of the area, partly because Cenozoic basalts cover much of this region. Tectonostratigraphic classification suggests a lower complex of presumably Archean rocks, a middle complex of Paleozoic and Mesoproterozoic rocks, and an upper complex of Neoproterozoic rocks, however (Davidson and Rex, 1980).

The Precambrian basement rocks are largely amphibolites and some rare granulites and have apparently been affected by the Pan-African Orogeny (Davidson and Rex, 1980). The broad plateaus in Ethiopia and Kenya have been cited as evidence for one or more mantle plumes (Ebinger and Sleep, 1998). Bosworth and Morley (1994) noted that at least part of the depression between the east African plateaus (Figure 2.4) was affected by rifting in the Mesozoic, producing northwest- and north-northwest-trending structures.

Episodes of rifting with little volcanism during the Jurassic and Cretaceous have been revealed by seismic-reflection and well data from South Sudan and northern Kenya near the Turkana Depression (Ebinger et al., 2000). An east-west lineament associated with a strike-slip fault is thought to link rift basins in South Sudan to the Anza Graben in Kenya (Bosworth, 1992; Ebinger and Ibrahim, 1994).

The structural architecture of the East African Rift System has been affected by regional stress regimes (Gani et al., 2009), including:

1. Northeast-southwest tensile stress related to the break-up of Gondwana and subsequent formation of northwest-trending rift basins that extend from the Anza Graben through the Turkana Depression (Kenya) and up to the Muglad Basin (South Sudan), finally terminating against the Central African Shear Zone.

2. Northwest-southeast tensile stresses associated with the opening of the orthogonally oriented Main Ethiopian Rift.
3. Shifting of the Main Ethiopian Rift's position from orthogonal to oblique relative to the eastern branch of the East African Rift System, facilitated by the existence of a Quaternary east–west-directed tensile stress.
4. A series of events associated with the opening of the Red Sea and the Gulf of Aden, as well as the subsequent progression of a spreading axis toward the Afar triple junction attributed to The eastward migration of the eastern branch of the East African Rift System from its initial Quaternary north-northeast to south-southwest tensile stresses.
5. Rifting near Lake Turkana, and the progressive deflection coupled with propagation to the north along the axis of the Main Ethiopian Rift, which has been considered to be an indication of plume processes beneath the East African Rift System.

### **Geologic and Tectonic Setting of South Sudan**

The study area constitutes part of the East African Orogenic Belt, comprising the Arabian-Nubian Shield in the north and the Mozambique Belt in the south, which resulted from the collision between east and west Gondwana (Stern, 1994). The Neoproterozoic Arabian-Nubian Shield crust is characterized by the occurrence of arc assemblages associated with ophiolites and granitoids, rejuvenated older crustal terranes, accumulation of sediments and volcanic rocks in aulacogens or tectonic basins, which subsequently were metamorphosed and deformed (Stern, 1994). The Arabian-Nubian Shield contains fragments of an intra-oceanic island arc/back arc basin and microcontinents welded together along suture zones.

The regional structural setting indicates northeast-southwest lithospheric extension that formed the northwest–southeast-trending Mesozoic rift basins in the Sudanese region—e.g., the Muglad and Melut Basins (Binks and Fairhead, 1992). These rift basins terminate abruptly against the Central African Shear Zone, which is a major dextral strike-slip shear fault related to the opening of the South Atlantic Ocean (McHargue et al., 1992). Another major geologic lineament is the northwest–southeast-

trending Aswa Fault Zone that links the northern tip of the western branch of the East African Rift System with the southern end of the rift system (Gaulon et al., 1992).

Generally, the geology of South Sudan (Figure 2.5), as deduced from a review of the available literature (Whiteman, 1965; Ahmed, 1975; Vail, 1978; Omer, 1983; Almond, 1984; Kröner, 1985; Abdelsalam and Dawoud, 1991; and Kujjo, 2010) is composed of the following rock units.

#### *Precambrian Basement Complex*

The Sudan (North and South) is considered one of the world's last large Precambrian terrains to be prospected in detail. Geologic environments that host large mineral deposits elsewhere in the world are found in the Sudan. The expectation that large mineral deposits occur in the Sudan is not based on theoretical grounds but is supported by recent finds of gold-bearing polymetallic deposits in the Ariab-Arbaat Belt of the Red Sea Hills (Ahmed, 1998).

The basement complex consists of a metamorphosed volcano-sedimentary series of rocks into which dismembered ophiolites were occasionally emplaced (Stern, 1994). The rocks of this unit belong to the Precambrian, and have been thoroughly deformed, metamorphosed, and granitized during the Pan-African thermo-tectonic event (Kröner, 1985).

The metamorphic rocks were later intruded by granitoids and related dikes. This intrusion was followed by several periods of erosion interrupted by periods of further deformation of the basement complex, which was formed by accretion of older microcontinents (Whiteman, 1970). The last event in the history of the basement is represented by the post-orogenic igneous rocks, which include granites, syenites, felsites, and rhyolites (Ahmed, 1975).

#### *Mesozoic Nubian Supergroup*

The Nubian Sandstone Formation (Paleozoic) covers much of South Sudan and rests unconformably on the Precambrian Basement Complex, and consists of conglomerates, sandstones, sandy mudstones, and mudstones (Omer, 1983). This formation covers most of South Sudan where the sedimentary basins are located and so constitutes the main oil reservoir rock. The sandstone formation has lately been

subdivided into various formations, which are collectively renamed as the Nubian Supergroup (Klitzsch and Squyres, 1990).

#### *Quaternary Surficial Deposits*

The surficial deposits generally include alluvial soil fans, valley wash (Whiteman, 1965; Kujjo, 2010), gravel terraces, and lacustrine deposits covering the ground in depressions. There was widespread volcanism in the eastern part of South Sudan in the vicinity of the Nubian Supergroup (Schlüter, 2008).

#### *Structural Setting*

The study area is a tectonically active region and is characterized by a series of continental rifts, widespread magmatic activity, strong deformation, and frequent earthquakes (Furman et al., 2004). Thus, affected by extensional stress fields operating in the Nubian Supergroup, the upper crust underwent brittle deformation and produced a series of extensional faults, grabens, and crustal thinning in South Sudan and Kenya (Binks and Fairhead, 1992).

South Sudan constitutes part of the East African Orogenic Belt, comprising the Arabian-Nubian Shield in the north and the Mozambique Belt in the south, which resulted from the collision between east and west Gondwana (Stern, 1994). The Neoproterozoic crust of the Arabian-Nubian Shield is characterized by arc assemblages associated with ophiolites and granitoids, rejuvenated older crustal terranes, accumulation of sediments, and volcanic rocks in aulacogens or tectonic basins, which subsequently were metamorphosed and deformed (Stern, 1994). The Arabian-Nubian Shield contains fragments of an intra-oceanic island arc/back arc basin and microcontinents welded together along suture zones.

The regional structural setting indicates northeast-southwest lithospheric extension formed the northwest–southeast-trending Mesozoic rift basins in the Sudanese region—e.g., the Muglad, Melut, and the Blue Nile—whereas in Kenya it is represented by the Anza Graben (Binks and Fairhead, 1992). These rift basins terminate abruptly against the Central African Shear Zone, which is a major dextral strike-slip shear fault related to the opening of the South Atlantic Ocean (McHargue et al., 1992).

Another major lineament is the northwest–southeast-trending Aswa Fault Zone, which extends through the northern end of the western branch of the Nubian Supergroup, as well as through the southern end of the eastern branch of the Nubian Supergroup (Gaulon et al., 1992).

#### *Mineral Potential of the Study Area*

The following information about the mineral potential has been extracted from South Sudan Ministry of Mining reports (Hunting Geology and Geophysics Ltd., 1980).

The mineral potential of South Sudan has been underexplored, but a few geological surveys have been conducted to locate minerals in some areas. Most of the information pertaining to mineralization was obtained during artisanal mining, which has been widely practiced in the country for generations.

The mineral potential in the study area includes:

1. Gold

Gold mineralization occurs in a variety of Precambrian basement rocks, in structurally controlled environments (e.g., shear zones) such as greenstone belts, auriferous pebbles-quartz conglomerates, tourmaline-rich quartzite, porphyry granites, extensive zones of quartz veins, and marble belts.

2. Silver

There has been no separate mining for silver in the region, but it occurs mostly in association with gold mineralization.

3. Copper, Lead, and Zinc

These minerals occur as strata-bound mineralization at the Hofrat El Nahas area, which is a continuation of a greenstone belt extending from the Central African Republic. Copper mining by natives started earlier in Sudan, and its production was controlled by the Turkish rulers of Egypt and Sudan in the 19th century. Copper, zinc, and lead also occur in other parts of South Sudan (Figure 2.6).

4. Aluminum

Aluminum ore was deposited in the form of bauxite along a variety of Precambrian, Paleozoic, and Mesozoic rocks during an extensive period of

Mesozoic and Cenozoic peneplanation and laterization of the stable massif areas of the Congo and Central African Republic.

5. Iron Ore

Iron ore formations occur extensively along the Precambrian Basement Complex (Figure 2.4) and have been exploited by natives for their livelihood.

6. Manganese

Manganese occurs in a variety of rocks and environments such as in the upper zone of a kaolinized granite in the greater Bahr El Gazal region. Manganese beds as thick as 100 to 150 m have been encountered in wells drilled in the Cretaceous basins of central South Sudan.

7. Diamond/Gemstones

Limited activities target gemstones in areas bordering the Democratic Republic of the Congo, Uganda, and Kenya. Indicators for diamond occurrence were identified in the above-mentioned countries, but no follow-up work was conducted.

8. Uranium

In cooperation with international communities in the 1970s, the government conducted exploration for uranium, which led to the discovery of the ore in areas of Hofrat El Nahas in the northwestern region of South Sudan. The New Kush Exploration and Mining Company, a South African mining company, recently explored for and discovered ore deposits in the southeastern part of the country.

9. Industrial Materials

Extensive occurrence of marble/limestone was studied in the 1970s, to exploit the ore in the establishment of a cement industry in South Sudan. Those efforts were hindered by the subsequent liberation wars in the region. Marble rocks near Kapoeta are associated with gold mineralization.

Recently, detailed investigations were conducted on limestone occurring near Kajo keji town to exploit it in the establishment of a cement factory in the area. Other occurrences of industrial materials in the study area include graphite, mica, feldspar, silica sand, kaolin, talc, and gypsum. Much work is required to

fully investigate further occurrences of mineralization in the study area, however.

Several hard rocks are being crushed into aggregate for the construction of the country's new infrastructure, as well as repairing structures that were damaged during the liberation wars.

#### 10. Rare Earth Elements

There is potential for this resource, especially in areas occupied by carbonatite and pegmatite rocks, which occur widely as intrusions into the Precambrian Basement Complex. Indicators were obtained from limited samples that were analyzed in South Africa and at the University of Kentucky (Kentucky Geological Survey). More sampling is needed, however, to fully investigate the occurrence of these rare earth elements.



Figure 2.1. Location of the Republic of South Sudan.

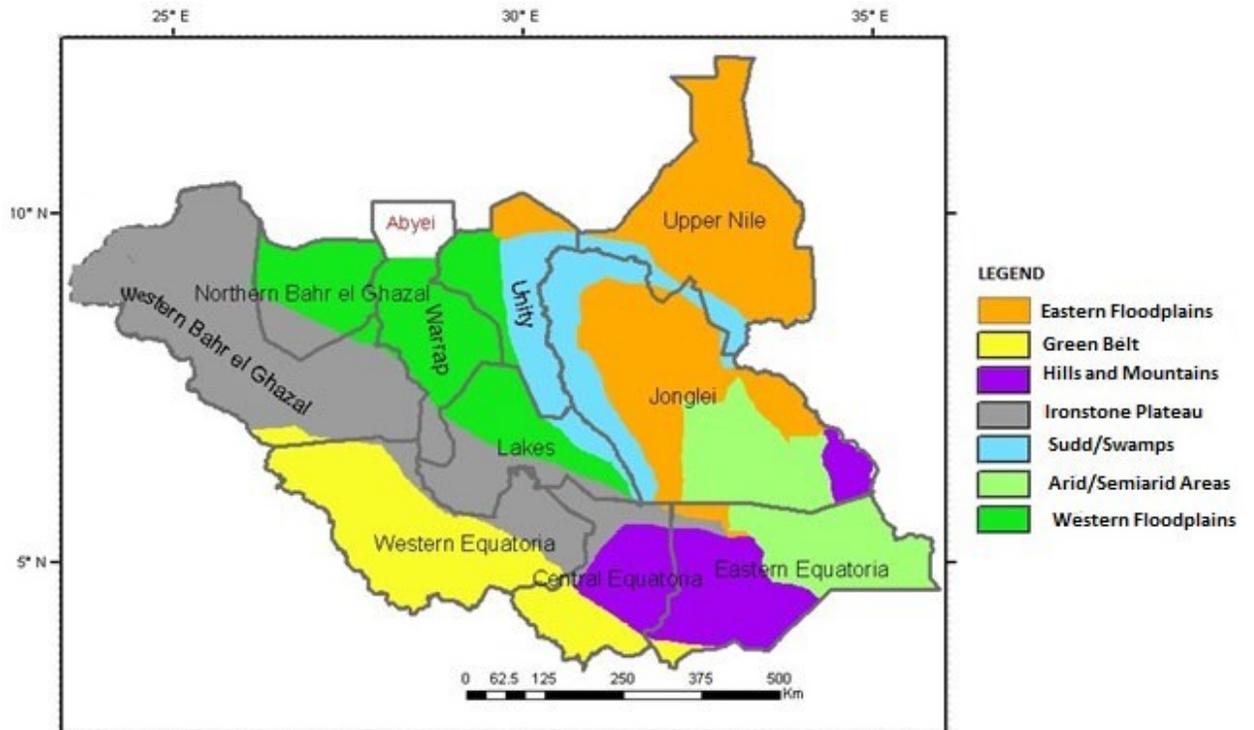


Figure 2.2. South Sudan physiographic zones (Diao et al., 2012).

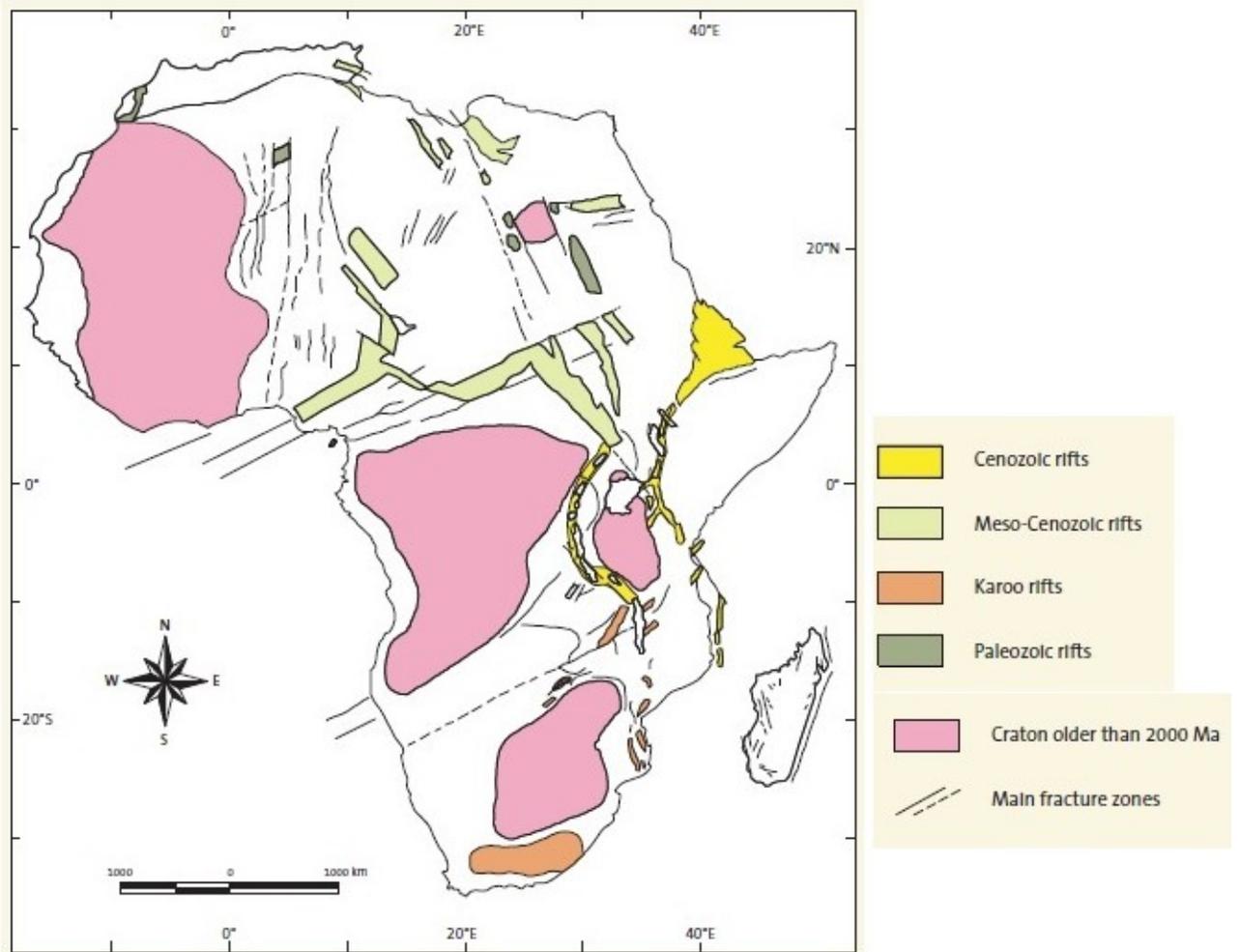


Figure 2.3. Main rift structures in Africa (after Kampunzu and Popoff, 1991).

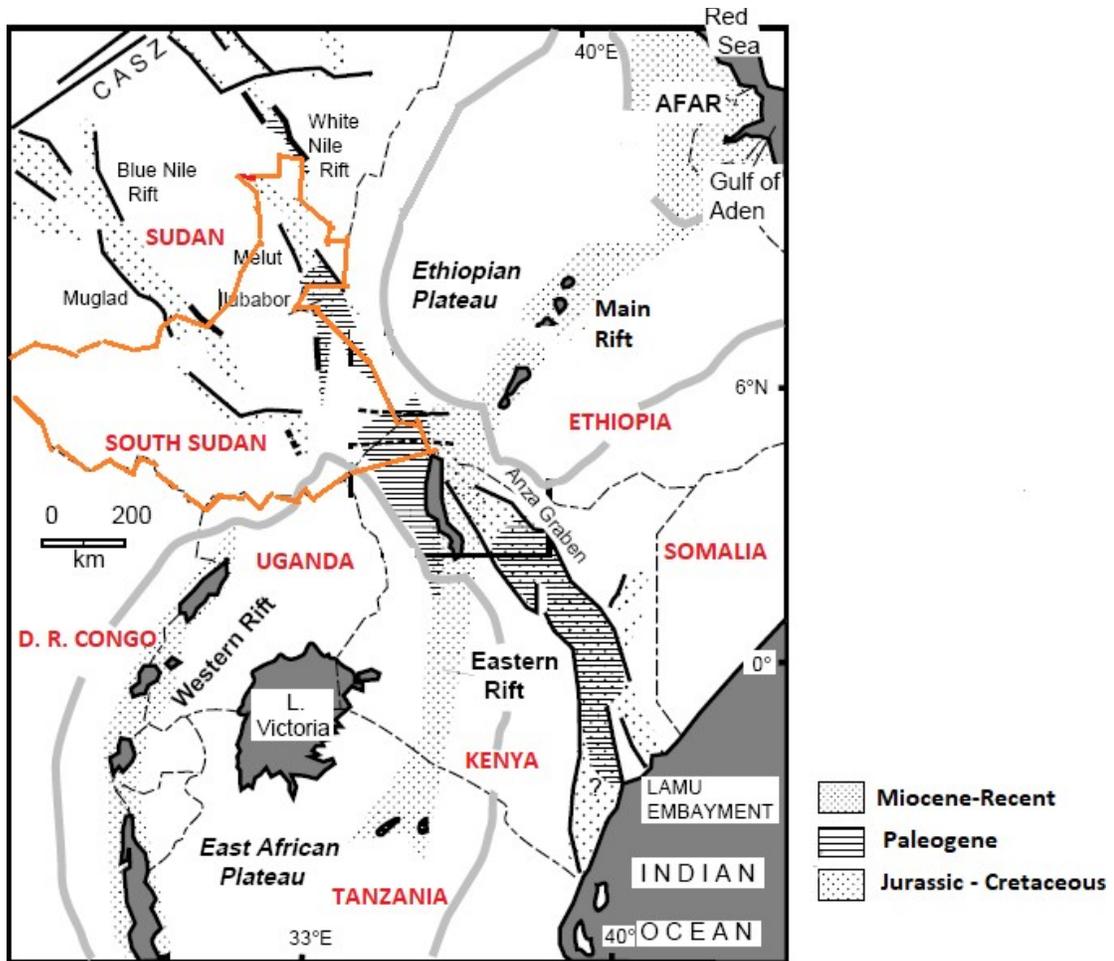


Figure 2.4. Location of the study area relative to the East African Rift System (after Gani et al., 2009).

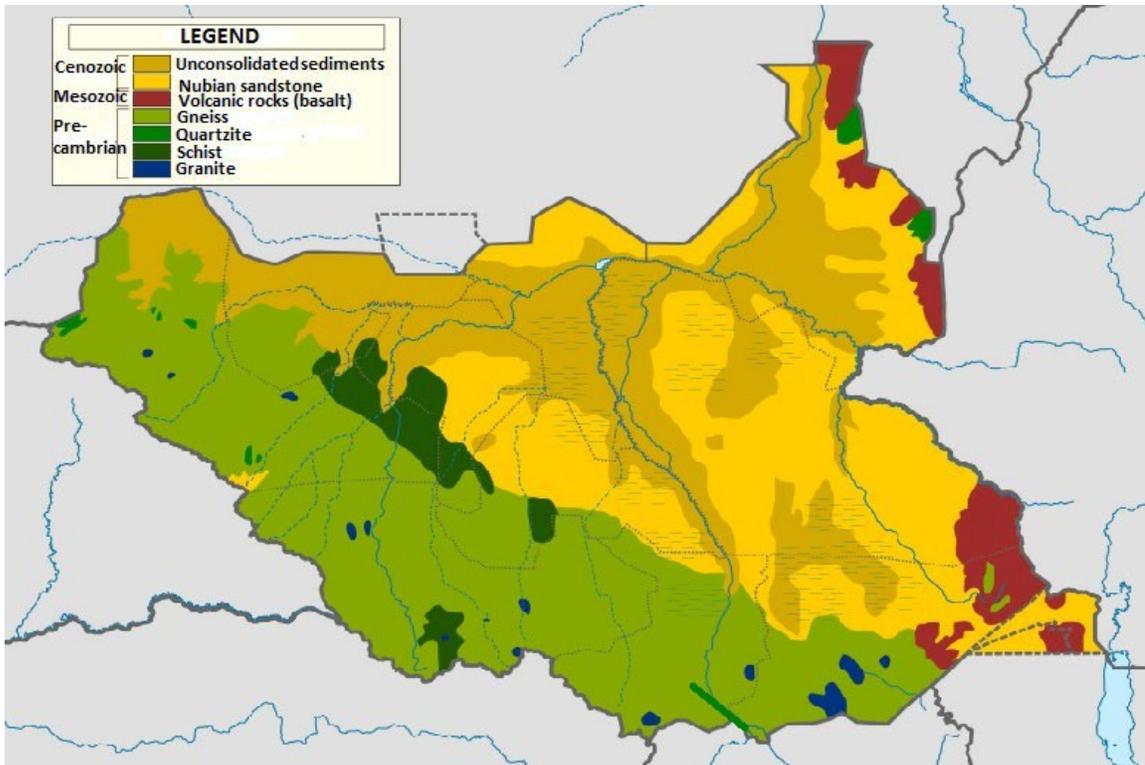


Figure 2.5. Simplified geology of South Sudan (after Geological Research Authority of the Sudan, 1981).

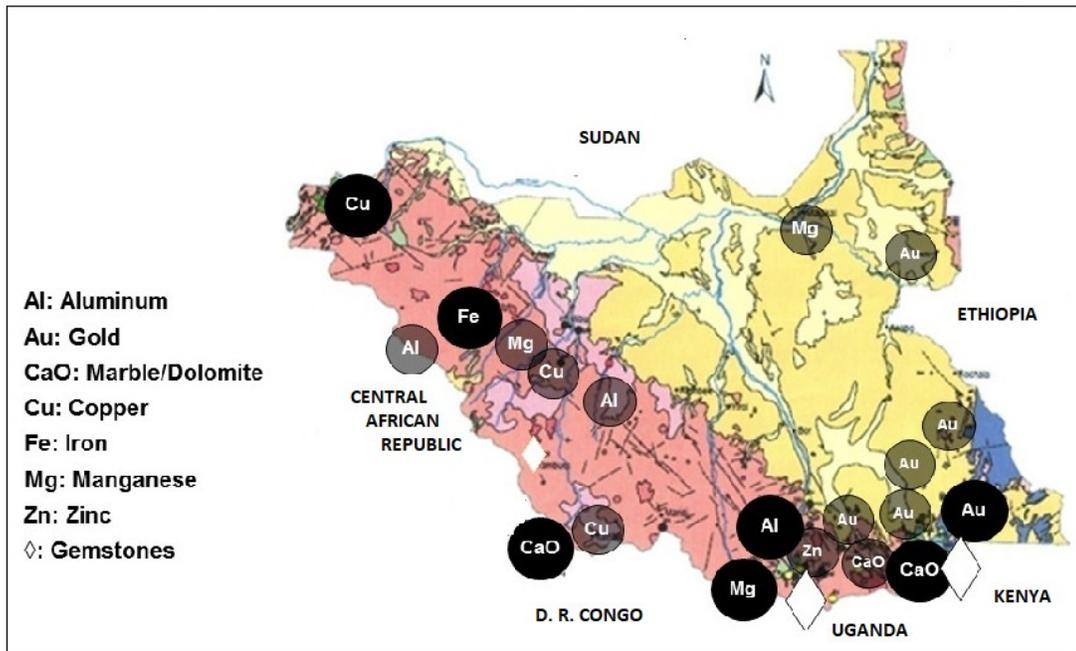


Figure 2.6. Mineral potential of South Sudan (Republic of South Sudan, Ministry of Mining, 2008).

## **CHAPTER 3:**

### **MAPPING GEOLOGY AND MINERALS IN THE STUDY AREA**

This chapter was published in *International Journal of Remote Sensing and Geoscience* (Kujjo et al., 2018). The contribution of the authors is as follows: Kujjo—75 percent (conducted the research and constructed the manuscript), Liang—15 percent (suggested ways of improving the analysis, reviewed the manuscript, and suggested improvements to the manuscript), Ravat—10 percent (suggested ways of improving the analysis, reviewed the manuscript, and suggested improvements to the manuscript).

#### **Introduction**

Geologic mapping through *in situ* field surveying is tedious, time-consuming, expensive, and sometimes impractical, especially in areas of remote and rugged terrain and regions affected by war. Such limitations could be mitigated by using satellite remote sensing, which is not restricted by natural and social barriers on the ground.

Geologic mapping is widely used in planning exploration strategies, such as the selection of regions to explore and extract certain types of ore deposits (Brimhall et al., 2006). Mapping of hydrothermal alteration zones, ore minerals, igneous rocks hosting ores, and oxidized and leached rocks that commonly occur at the surface above sulfide-bearing ores can be used in conjunction with geophysical and geochemical data to delineate zonation patterns and define prospective corridors of exotic mineralization (Brimhall et al., 2006). Likewise, regional mapping of major faults or contacts bounding shear zones that coincide with a map-scale transition of regional metamorphism from green schist to amphibolite facies that are spatially associated with major gold deposits in Archean greenstone belts can indicate areas of enhanced exploration potential (Anderson, 2005; Brimhall et al., 2006).

South Sudan is planning to allocate exploration licenses to investors, a decision that requires preliminary knowledge of locations of mineral resources. Construction of the country's major infrastructure (e.g., capital city, dams, roads, and bridges) also requires geologic information about sites, hazards, and building materials. The objective of this study is to apply remote-sensing techniques to map hydrothermal alteration zones of the Didinga Hills region of South Sudan and to use this mapping to facilitate allocation of mineral titles through the South Sudan Mining Cadastre System.

The Didinga Hills are in the southeastern part of the country and border Uganda, Kenya, and Ethiopia (Figure 3.1), an area that is not easily accessible because of rugged terrain, poor roads, and the remnants of wars (e.g., unexploded land mines). Didinga Hills was selected as the study area because of the region's diverse geology, aridity, and bedrock surface exposure relative to other parts of the country that are occupied by rain forest. The region is also ideal for this project because it is known for exploration of alluvial gold. Although the bedrock source of the alluvial gold has not been established, the presence of alluvial gold workings in the study area is clearly associated with the background geology of metasediments, schists, marble, and younger post-tectonic granitic intrusions known to cause contact metamorphism and alteration (Hunting Geology and Geophysics Ltd., 1980).

Remote sensing offers a synoptic view on a regional scale, hence providing a complementary perspective to ground observations. In 2002, Ariki et al. carried out reconnaissance field work (funded by the U.S. Agency for International Development) in the area, but only 60 km<sup>2</sup> was mapped in several months. Consequently, this study will use remote sensing to map the hydrothermal alteration zones of the Didinga Hills region in order to obtain better coverage and accuracy, with significantly reduced time and cost.

Hydrothermally altered rocks are characterized by an unusually colorful appearance. The variously colored rocks are the host rocks of mineral deposits, and the colors represent the results of chemical interaction with the surrounding hydrothermal fluids (Guilbert and Park, 1986). The hydrothermal fluid processes altering the mineralogy and chemistry of the host rocks can produce distinctive mineral assemblages, which vary according to the location, degree, and duration of those alteration processes. When the alteration products are exposed at the surface, they can be mapped as a zonal pattern, theoretically concentric around a core of highest-grade alteration and greatest economic interest (Yetkin et al., 2004).

Although gold cannot be detected directly by any remote-sensing method, the presence of minerals such as iron oxides and clay minerals, whose diagnostic spectral signatures (in the visible/shortwave infrared portion of the electromagnetic spectrum) could be used as indicators for hydrothermal alteration zones, which are associated with gold occurrence (Kujjo, 2010; Vincent, 1997). Hence, knowledge of these mineral

occurrences facilitates the licensing process, which is of prime importance in the exploitation of the country's mineral resources.

### **Regional Geologic Setting**

The area is part of the Precambrian East African Orogeny, consisting of the Arabian-Nubian Shield in the north and the Mozambique Belt in the south (Abdelsalam and Stern, 1996), and is dominated by volcano-sedimentary rocks, dismembered ophiolites, and syn- and post-tectonic granitoids. There are occurrences of many rejuvenated older crustal terranes and accumulations of sediments and volcanic rocks in aulacogens or basins, which subsequently were metamorphosed and deformed. The final accretion of different island arcs resulted in strong tectonic deformation during the Pan-African Orogeny in the Neoproterozoic.

Archean cratonic rocks of high-grade metamorphism (granulites; e.g., the Imatong Mountains), Proterozoic granitoids, and meta-sedimentary and meta-volcanic rocks occur in the area (Figure 3.2). The metamorphic basement is poorly surveyed and so is shown as undifferentiated (i.e., not separately identified or distinguished) basement on existing maps. Likewise, there are insufficient structural studies or modern age determinations for the basement rocks to allow a viable subdivision into major tectonic units or terranes (Vail, 1978, 1990).

Overlying the basement rocks are effusive volcanic rocks (mainly basalts) that occupy the eastern border areas with Kenya and Ethiopia. These volcanic rocks are related to the East African Rift System. These in turn are overlain by Tertiary to Quaternary unconsolidated sediments (Umm Ruwaba Formation), which are mainly sands, gravels, clay sands, and clay (Hunting Geology and Geophysics Ltd., 1980; Whiteman, 1970). The altitude varies between 440 and 3,100 m. Hence, many seasonal streams flow down the hills, causing remarkable erosion that leads to widespread deposition of placer gold, along with eluvial and alluvial stream sediments.

Artisanal gold mining by natives has taken place at widespread sites for decades (Figure 3.3).

### **Methodology**

Multispectral imagery for the target area consists of one frame of Landsat 8 data (P171/R057), collected on January 10, 2015. The visible and shortwave infrared bands 1 to 7 and 9, in addition to the thermal infrared bands 10 and 11, of Landsat 8 were stacked and used in this study. The thermal infrared bands were resampled to 30 m spatial resolution. The shortwave infrared bands are useful in rock and mineral discrimination, whereas thermal infrared bands are useful in recognizing silicate minerals. Table 3.1 lists both Landsat 7 and Landsat 8 bands and their wavelength coverage and pixel size. Digital processing of the multispectral images for the study area was performed using ERDAS Imagine and ER Mapper software (Hexagon AB).

Over the past two decades, the development of spectral remote-sensing technologies has significantly advanced capabilities for mapping mineral system-related alteration, particularly with the application of hyperspectral remote-sensing data (Rowan et al., 2000). A longstanding problem in remote sensing has been the trade-off between the ability to map complex scenes and the expense of developing sensors with high signal-to-noise ratio and spatial/spectral resolution, however (Hubbard and Crowley, 2005). Currently, operational hyperspectral remote-sensing data (e.g., AVIRIS, HyMap, Hyperion) are difficult to apply to a wide area because of the relatively narrow swath compared to Landsat ETM (Zadeh et al., 2014).

Hydrothermal alteration minerals with diagnostic spectral absorption properties in the visible and near-infrared through the shortwave infrared wavelengths can be identified using multispectral and hyperspectral remote-sensing data (Zhang et al., 2016).

A key concept in exploration geology is that remote-sensing techniques are applied to rocks, minerals, and structures associated with a particular ore, and not the ore itself. This is because the ore is not always exposed at the surface, and it is often not spectrally unique or as widely disseminated as the minerals and rocks associated with the ore body (Vincent, 1997).

The multispectral image processing techniques selected and applied in this research were:

1. Optimal color composite with selection of optimal band combinations based on the optimum index factor, developed by Chavez et al. (1982)
2. Spectral ratio (Vincent, 1997)

### 3. Principal component analysis described by Crosta and Moore (1989)

These techniques are discussed further below.

#### **Optimal Color Composite Images**

A composite image is generated by blending information from three selected bands based on their relation to known spectral properties of rocks and alteration minerals (Vincent, 1997; Jensen, 2005). For instance, in Landsat 7, the shortwave infrared band 7 is useful for rock and mineral discrimination (Vincent, 1997; Sabine, 1999; Jensen, 2005).

Spectral analysis of remote-sensing imagery exploits variation in color intensity values within color composite images to interpret them in terms of lithologic variations or rock alterations, or both; thus, the choice of which bands to use to generate a composite image is site dependent. The best combinations of spectral bands for lithologic discrimination were determined using the optimum index factor (Chavez et al., 1982):

$$OIF = \frac{\sum_{i=1}^3 S_i}{\sum_{i \neq j, j=1}^3 |R_{ij}|}, \quad (1)$$

where  $S_i$  is the standard deviation for band  $i$ , and  $R_{ij}$  is the correlation coefficient between bands  $i$  and  $j$  of the three bands being evaluated. The optimal index factor values are then ranked in a table in descending order. The relative order of the three bands into red, green, and blue colors has no effect on the value of the optimal index factor (Chavez et al., 1982).

The computation of optimal index factor simplifies the complex and tedious process of selecting three appropriate bands to combine for optimum interpretation. The technique is scene-dependent, however, and has the disadvantage of the images not being uniform because the assignment of colors is determined by the analyst (Ren and Abdelsalam, 2001).

#### **Band Ratioing**

Band ratioing is a technique used for the effective display of spectral variations (Vincent and Thomson, 1972; Goetz, 1989) and hence enhances compositional information while suppressing other types of information about the Earth's surface (e.g., terrain slope and grain-size differences) (Vincent, 1997). Band ratioing divides the pixel

values in one spectral band by the corresponding pixel values in a second band. There are two reasons for doing this. First, the differences between the spectral reflectance of certain surface types can be highlighted or emphasized. Second, the technique removes the variation caused by differences in illumination, and consequently radiance, which may affect interpretation. Consequently, the ratio between differentially illuminated areas of the same surface type will be homogenized (Vincent, 1997; Jensen, 2005). Overall, this process enhances the contrast between materials by dividing the brightness values (digital numbers) of two selected bands (Sabin, 1997; Vincent, 1997), because shadows are regions of greatly reduced radiance in all spectral bands.

Choice of band ratio depends on the purpose of the application, spectral reflectance, and positions of the absorption bands of the mineral being mapped. For discrimination of alteration of clay minerals (e.g., aluminum hydroxyl), Landsat 8 ratio B6/B7 is generally preferred, whereas for iron oxide minerals (e.g., goethite, limonite, and hematite), the Landsat 8 ratio B4/B2, which characteristically displays bright signatures for iron oxides, is preferred. The Landsat 8 ratio B5/B6 emphasizes ferrous minerals (Abrams et al., 1977).

Different alteration assemblages create outcrops of different morphology. For instance, silica-pyrite alteration produces resistant cliff outcrops, whereas clay-rich alteration assemblages result in extensive colluvium (Han and Nelson, 2015). The band ratio technique addresses well the influence of topography on spectral response, which qualifies it as an effective method for mapping hydrothermally altered rocks.

### **Principal Component Analysis Transformation**

Image transformation based on principal component analysis is an image enhancement technique for displaying the maximum contrast from multiple spectral bands with just three primary composite bands (Vincent, 1997). PCA is a multivariate statistical technique used to reduce data redundancy by transforming the original data into new orthogonal principal component axes, producing uncorrelated images. Such an image set has much higher contrast than the original bands.

The number of output principal component bands is equal to the input spectral bands, with the first principal component, PC1, containing most of the data variability (Jensen, 2005). Each subsequent PC contains the next highest amount of variance, which

becomes smaller as the order of the PC increases (Vincent, 1997). The last PC bands contain the least variance and represent the most unusual, most distinctive pixels in the scene. Some of those distinctive pixels are noise, which often can be recognized as such by their distinctive spatial patterns. The remaining distinctive pixels are the rarest minerals in the frame or scene, although we cannot identify the mineral composition by PC images alone.

The PCA technique applied for this study was introduced by Crosta and Moore (1989) and is essentially based on the examination of PCA eigenvectors to determine which PC images concentrate information directly related to the theoretical spectral signatures of specific targets. The relevant PC images could then show targeted surface types (rock, soil, and vegetation) by highlighting them as bright or dark pixels, depending on their respective eigenvector magnitudes and signs (positive/negative). The Crosta and Moore (1989) technique can thus be implemented to delineate hydrothermal alteration zones (Loughlin, 1991).

This study used a variation of PCA, called feature-oriented principal component selection, to process Landsat 8 imagery to extract hydrothermal alteration zones. The technique uses the generalized reflectance curve of the feature of interest, such as hydrothermal alteration, in which band ratios are considered in the choice of the best principal component, based on the ratio of the bands' respective eigenvector values (Kujjo, 2010). The technique uses four selected operational land imager bands to highlight the spectral response of iron-oxide minerals (absorption in visible band 2, and higher reflection in visible band 4, in the case of Landsat 8) and hydroxyl-bearing (clay) minerals (absorption in shortwave infrared band 7, and higher reflectance in shortwave infrared band 6). For instance, which PC best represents iron-bearing minerals depends on the eigenvector values of bands 4 and 2 in a Landsat 8 dataset. Likewise, the representation of clay minerals is controlled by the eigenvectors of bands 6 and 7 referenced to their generalized reflectance spectra curves in the U.S. Geological Survey's Library of Minerals (Loughlin, 1991).

Whether the eigenvector values are positive or negative was considered in the ratioing process, because this determines which feature of interest (iron oxide or clay) would be represented as bright or dark pixels in an image. When selecting the optimum

principal component, the two eigenvector values should always be of different signs. Consequently, the numerator being positive implies that bright pixels represent the feature of interest, whereas a negative numerator implies that dark pixels represent the feature of interest (Crosta and Moore, 1989; Loughlin, 1991; Crosta and Rabelo, 1993).

## **Results and Interpretations**

Using the optimal index factor in selecting the best spectral bands, based on their contrast, was effective. The true color image with the combination of bands 4, 3, and 2 in RGB (Figure 3.4) is among the images with the least contrast, whereas the false color combination of bands 4, 7, and 5 in RGB (Figure 3.5) exhibits greater contrast and hence indicates more variety of lithologies, in accordance with the respective optimal index factor.

The band combination FCC 432 RGB is as close to true color as one can get with a Landsat operational land image. One unfortunate drawback with this band combination is that these bands tend to be susceptible to atmospheric interference, so they sometimes appear hazy, as in the “smoke” trending northwest in the lowest corner of Figure 3.4.

Band ratio image OLI B4/B2 highlights rocks that have been subjected to oxidation of iron-bearing sulfides (e.g., pyrite and chalcopyrite). This is because altered rocks are more reflective in band 4 and less reflective in band 2—the latter because of iron absorption (Abrams et al., 1977; Vincent, 1997; Harris et al., 1998; Jensen, 2005). Likewise, the ratio for the clay alteration in B6/B7 revealed brighter pixels over rock exposures, mostly of the undifferentiated Precambrian basement. The intensity of alteration gradually changes for the gray images from darker (fewer) to brighter (more) tones.

In color composite images, the variation depends on the color assignment. In the ratio image (Figure 3.6), the red color has been assigned to the ratio B4/B2, the green to B6/B5, and the blue to B6/B7, respectively. The result is that the areas of hydrothermal alteration appear as bright yellow.

For feature-oriented principal component selection, statistical calculations of a Landsat 8 image for the Didinga Hills region produced the required parameters for data input, which were then used to determine the targeted alteration type and the relative PC

number, and whether it would be represented as a bright or dark pixel in the resulting image. The selected bands are shown in Tables 3.2 and 3.3, respectively.

The highlighted values in Tables 3.2 and 3.3 show that iron alterations appear as bright-toned pixels in PC4 (Figure 3.7) because eigenvector values are positive for band 4 and negative for band 2. Thus, the iron alteration ratio  $B4/B2$  will appear as bright. In contrast, the eigenvector values are negative for band 6 and positive for band 7, which means that the clay alteration ratio  $B6/B7$  will be represented in PC4 by dark pixels (Figure 3.8).

The enhancements to the clay (hydroxyl-bearing) alteration minerals were obtained after their respective PC4 was made positive (digital number multiplied by  $-1$ ), so that these alteration minerals would be mapped in brighter and distinguishable tones (Figure 3.9). The clay minerals cover a wide geographic area, occurring especially on low-lying plains in the southern part of the study area. Those areas do not necessarily represent potential mineral prospect locations, but instead represent only the accumulation of muds deposited by flash floods.

The selection of alteration zones by the feature-oriented principal component method (Figures 3.7 and 3.9) has revealed almost the same locations (see Figure 3.9) as those identified by the band ratio images (Figure 3.6). Consequently, those locations could be considered potential sites for mineral exploration. There is also a strong correspondence between these inferred alteration zones and known old artisanal gold mining locations in the study areas (Figure 3.3).

The spatial distribution of the hydrothermal alteration zones in the study area (Figure 3.10) is a result of the iron oxide minerals (seen as red) and the clay minerals (seen as white). Both iron and clay alteration zones (extracted from Figure 3.6) have been overlain on an FCC image (bands 7, 11, and 10 RGB) representing silicates in yellow. Solidification, which is an important indicator of hydrothermal alteration, is not recognizable on visible and shortwave infrared bands, but variations in silica content are recognizable in multispectral thermal infrared images (Vincent, 1997).

The distribution of the alteration zones corresponds well with seven of the artisanal mining works in the study area, except for two sites (Maji and Vaka), which are not associated with alluvial gold deposits.

The geologic features of prime interest for potential mineral prospecting are near structures such as fold axes and fault/shear zones. The results of this study have shown a clear association of the detected hydrothermal alteration zones with areas of contact metamorphism. For instance, the contact BB (Figure 3.11) between the extrusive volcanic (Px) and the schist along which artisanal mining sites (Anak-nak, Napotpot, and Lolim) are located southeast of Kapoeta and extending to the area southwest of Narus is a clear indication of such association (Figures 3.10, 3.11).

Other alteration zones are in the vicinity of the shear zone containing artisanal mining sites at Nakishot, Vaka, and Maji. Those associated with faults are in the proximity of the Chukudum Shear Zone (Figure 3.11).

## **Discussion**

The presence of zones of hydrothermal alteration is reflected by the higher values of operational land imager band ratios, illustrated by lighter-toned pixels in the Landsat 8 imagery shown in Figures 3.6, 3.7, and 3.9. Most of these same areas of greater alteration coincide well with areas characterized by significant silicification—quartz veins sometimes associated with sericite and pyrite (Hunting Geology and Geophysics Ltd., 1980). For instance, the areas to the east and southeast of Kapoeta are known as artisanal gold mining sites (Figure 3.3).

Most artisanal gold works are located on alluvial deposits derived from iron-rich rocks, suggesting intense surface oxidation that appears widespread on the operational land imager ratio of B4/B2, the result of the presence of ferric oxides (ilmenites/hematite) (Figure 3.6). The mining activities are restricted to areas of mainly weathered or altered metasediments (e.g., marble and tremolite-actinolite schists) (Hunting Geology and Geophysics Ltd., 1980). Other rock units on which mining takes place are graphitic gneiss and chlorite-sericite schist with interfoliated quartz veins (Hunting Geology and Geophysics Ltd., 1980). Similarly, the band ratio B6/B7 refers to clay minerals, of which kaolinites are the most abundant in the area shown in Figure 3.9.

The principal component analysis technique helped identify iron and clay minerals but was not definitive in discriminating the various possible minerals that may constitute the brighter color shown by a particular group of pixels at a specific location on the image. Lithologic discrimination by remote sensing does not delineate sharp

boundaries, but rather gradational ones. That is because mapping in this case depends on color recognition, which could be blurred or obscured by loose floats or soil stains washed from one rock unit to another (Vincent, 1997; Hubbard and Crowley, 2005).

The validity of the applied remote sensing techniques was tested on published and unpublished geologic maps, as well as on known sites for artisanal mining conducted by the natives of the Didinga Hills (Figure 3.3).

Because the geology of South Sudan has been under surveyed, the results of this study have been used to allocate minimal exploration concessions based on the identified hydrothermal alteration zones as shown on Figure 3.12.

Following this research, concessions were granted for the study area to mining companies, some of whom conducted high-resolution geophysical surveys together with limited geologic and geochemical surveys, resulting in identification of important targets (e.g., granite terrains, greenstone belts, anomalous areas at Anak-nak and Kawokono) (Figure 3.11). In addition, some structures (e.g., Chukudum Shear Zone and a variety of faults and folds associated with alluvial and eluvial gold occurrences) have been recommended for further exploration.

## **Conclusions**

The study focused on the spatial distribution of the main types of hydrothermally altered rocks (iron oxide and aluminum hydroxyl) as a means of determining the general extent of potential mineralization in the Didinga Hills. The results obtained have identified hydrothermal alteration zones in the Didinga Hills. The demonstrated approach has the potential to reduce the cost and duration of the preliminary stage of ground reconnaissance that is necessary for decision makers to prioritize their allocation of mineral exploration titles.

Remote-sensing techniques hold the potential to provide information needed for socioeconomic planning; identifying natural hazards (such as earthquake faults, areas of landslides); building the nation's infrastructure of roads and highways, railroads, pipelines, utilities, and dams; and making wiser decisions about land use, specifically in development of the country's mineral resources. In addition, Landsat images are free, so the cost of conducting the needed survey is low; hence, the application of remote sensing

is economically viable in case of the absence or scarcity of geologic survey data, which is the current situation in South Sudan.

Mapping hydrothermal alteration zones in the Didinga Hills by remote-sensing techniques would enable future application of this type of analysis to map the under surveyed regions of South Sudan for further exploration and sustainable development of the country's mineral resources.

**Table 3.1.** List of both Landsat 7 and Landsat 8 bands. NIR=near infrared. SWIR=shortwave infrared. TIR=thermal infrared.

Landsat-7 ETM+ Bands ( $\mu\text{m}$ )			Landsat-8 OLI and TIRS Bands ( $\mu\text{m}$ )		
Band #	Resolution/ Spectral Band	Wavelength	Resolution/Spectral Band	Wavelength	Band #
			30 m coastal/aerosol	0.435–0.451	Band 1
Band 1	30 m blue	0.441–0.514	30 m blue	0.452–0.512	Band 2
Band 2	30 m green	0.519–0.601	30 m green	0.533–0.590	Band 3
Band 3	30 m red	0.631–0.692	30 m red	0.636–0.673	Band 4
Band 4	30 m NIR	0.772–0.898	30 m NIR	0.851–0.879	Band 5
Band 5	30 m SWIR-1	1.547–1.749	30 m SWIR-1	1.566–1.651	Band 6
Band 6	60 m TIR	10.31–12.36	100 m TIR-1	10.60–11.19	Band 10
Band 7	30 m SWIR-2	2.064–2.345	100 m TIR-2	11.50–12.51	Band 11
Band 7	30 m SWIR-2	2.064–2.345	30 m SWIR-2	2.107–2.294	Band 7
Band 8	15 m Pan	0.515–0.896		15 m Pan 0.503–0.676	Band 8
				30 m cirrus 1.363–1.384	Band 9

**Table 3.2.** Feature-oriented principal component selection data (bands 2, 4, 5, and 6) for iron oxide minerals.

Eigenvector	Band 2	Band 4	Band 5	Band 6
PC 1	0.500	0.502	0.497	-0.501
PC2	-0.457	-0.415	0.780	0.098
PC 3	-0.521	0.097	-0.351	0.772
PC 4	-0.518	0.753	0.144	-0.380

**Table 3.3.** Feature-oriented principal component selection data (bands 2, 5, 6, and 7) for clay minerals.

<b>Eigenvector</b>	<b>Band 2</b>	<b>Band 5</b>	<b>Band 6</b>	<b>Band 7</b>
PC 1	0.500	0.500	0.500	0.500
PC2	-0.598	-0.388	0.540	0.447
PC 3	0.626	-0.770	0.124	0.019
PC 4	0.007	-0.083	-0.666	0.742

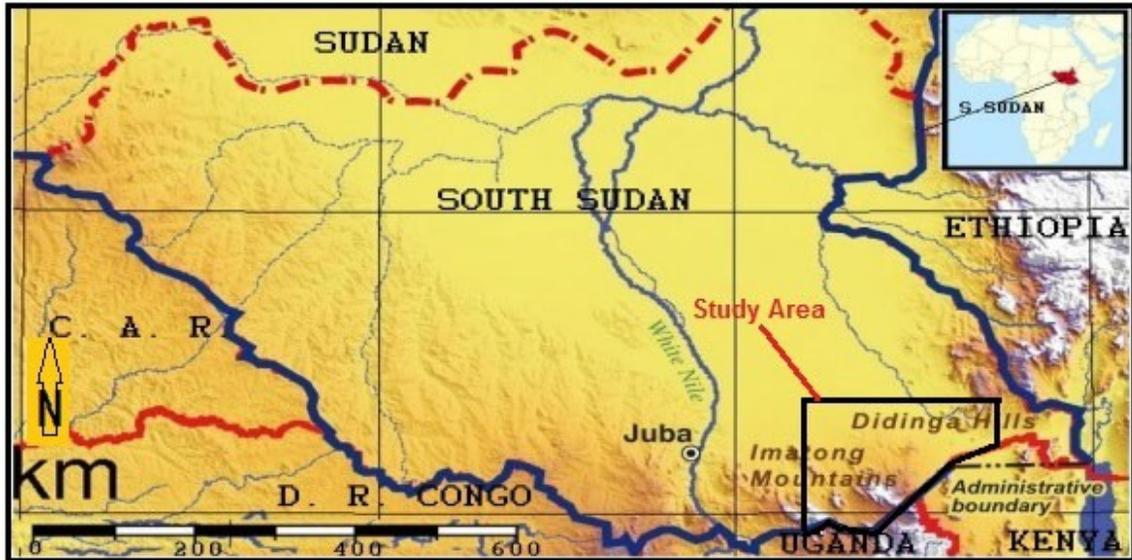


Figure 3.1. Location of the Didinga Hills (after [www.nationsonline.org](http://www.nationsonline.org)).

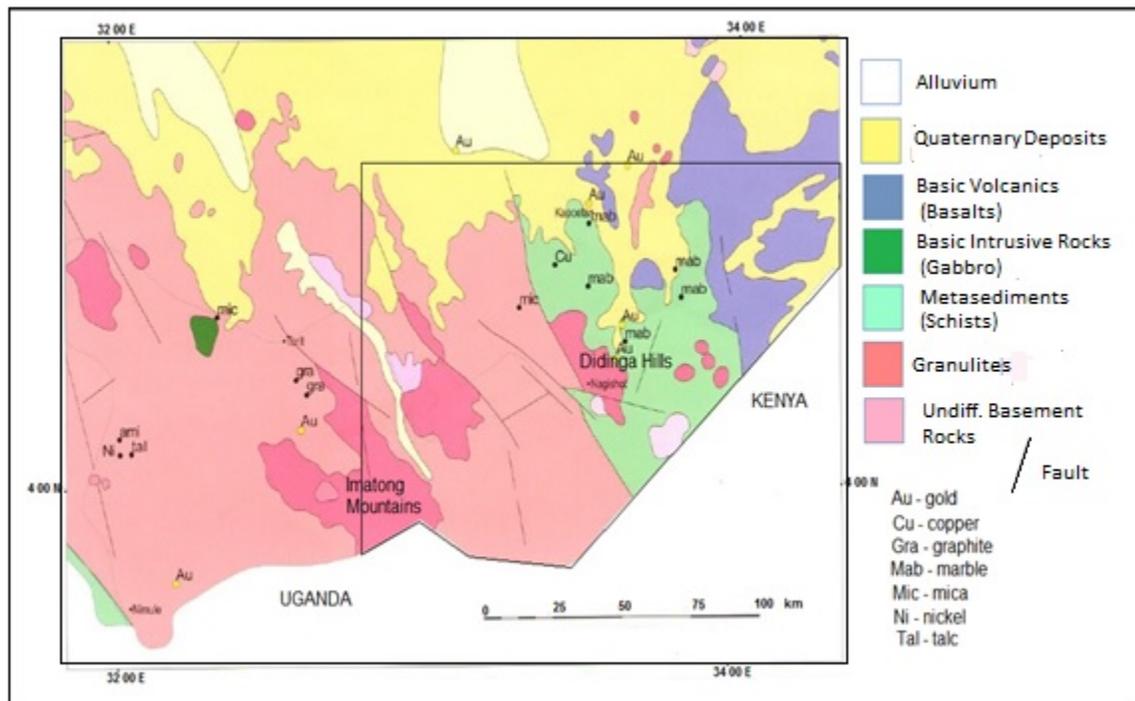


Figure 3.2. Geology of the Kapoeta Mineral District with study area demarcated (after BGS International, UK, 2011).

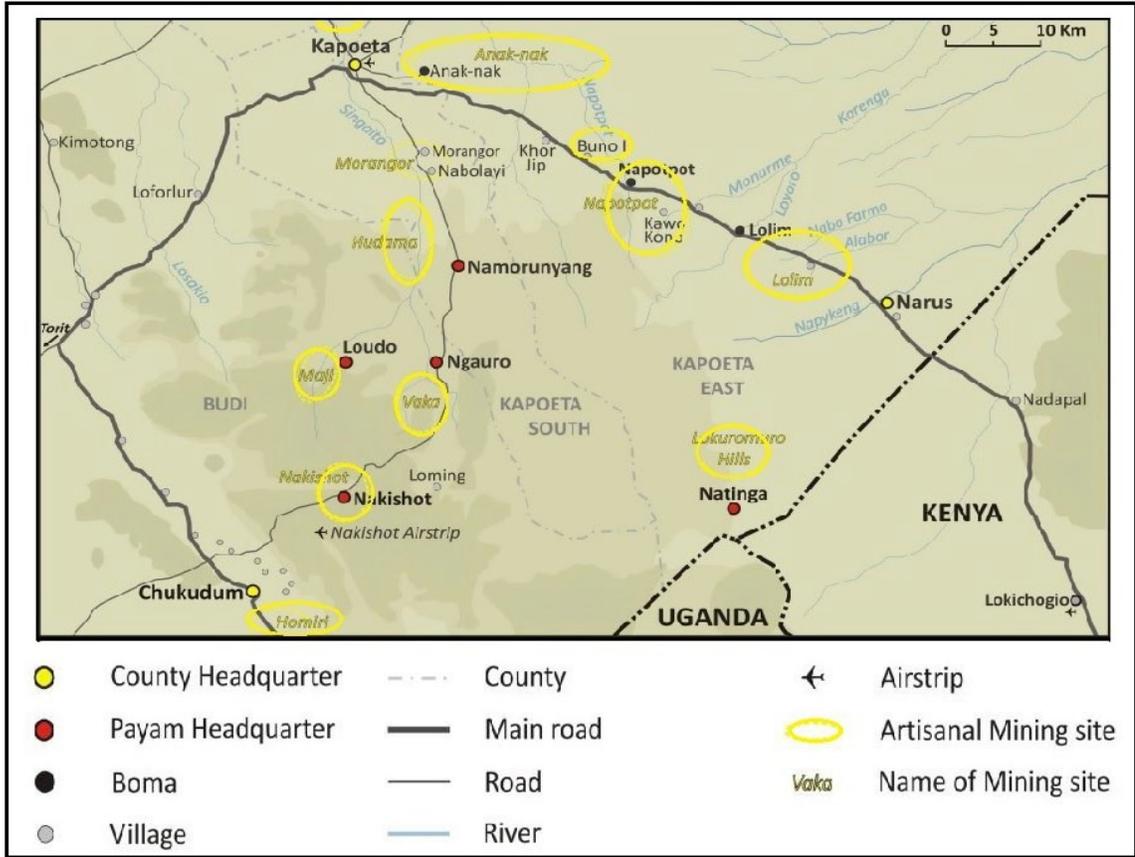


Figure 3.3. Artisanal gold mining sites in the Didinga Hills area (after De Zeeuw, 2016).

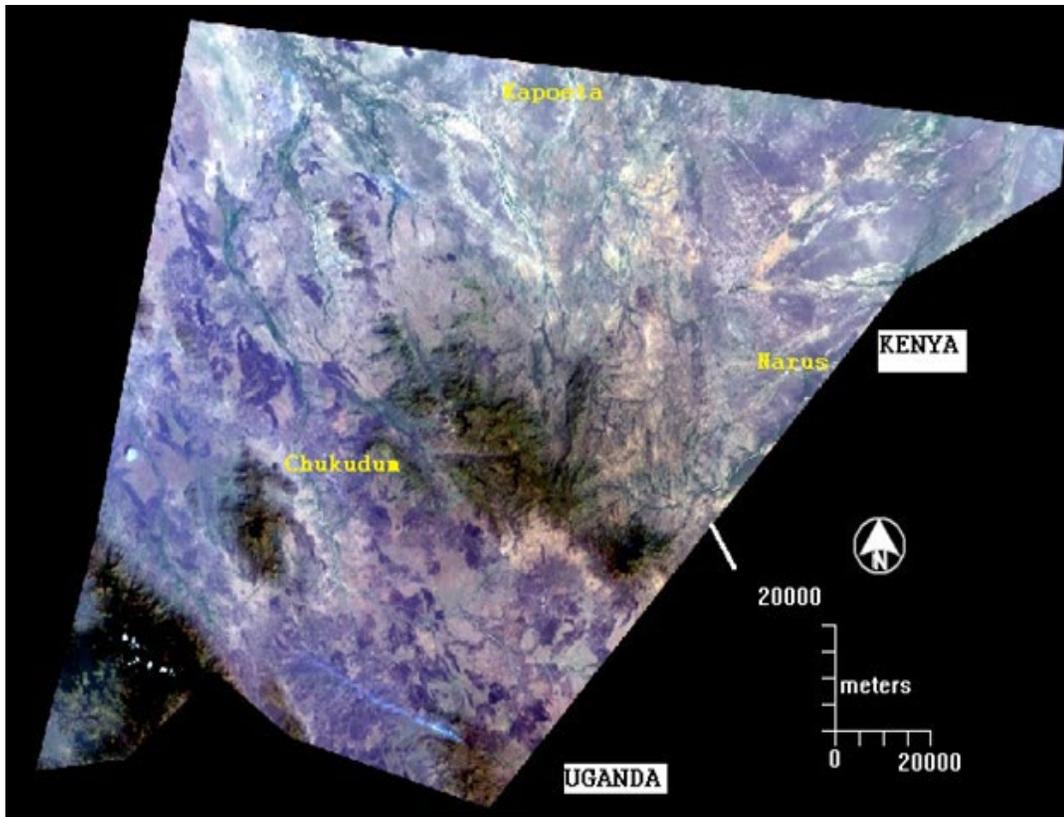


Figure 3.4. Simulated true-color image of the Didinga Hills formed with the combination of bands 4, 3, and 2 assigned to the red, green, and blue colors, respectively.

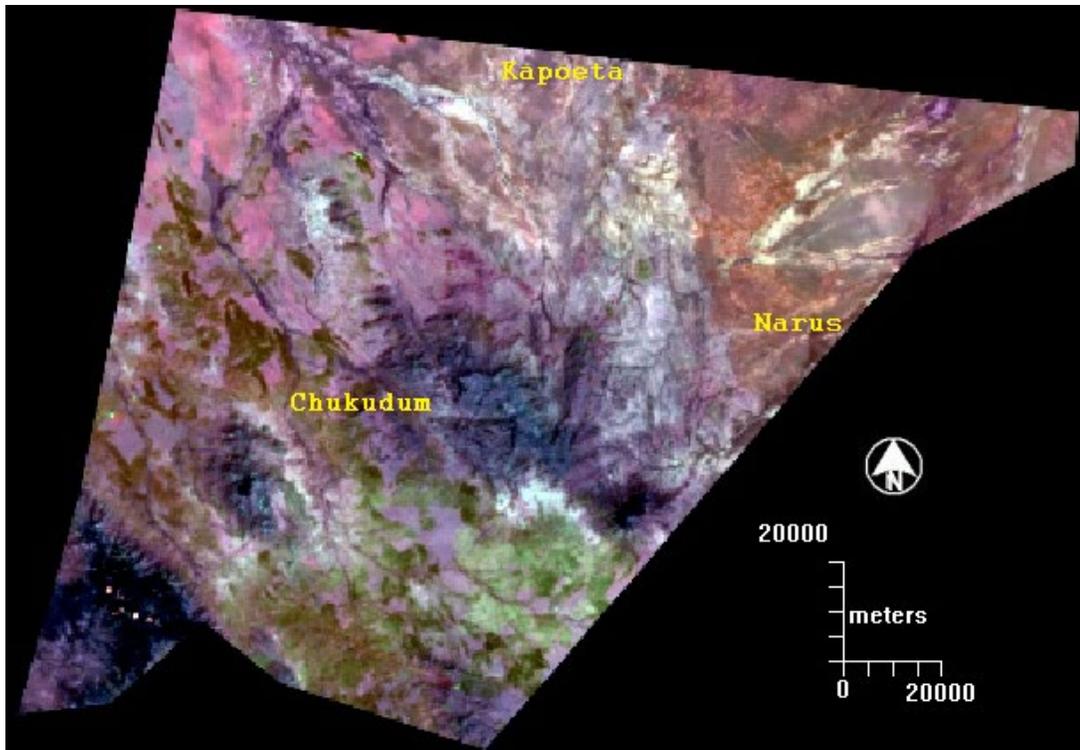


Figure 3.5. FCC image 475 RGB of the Didinga Hills for better lithologic identification.

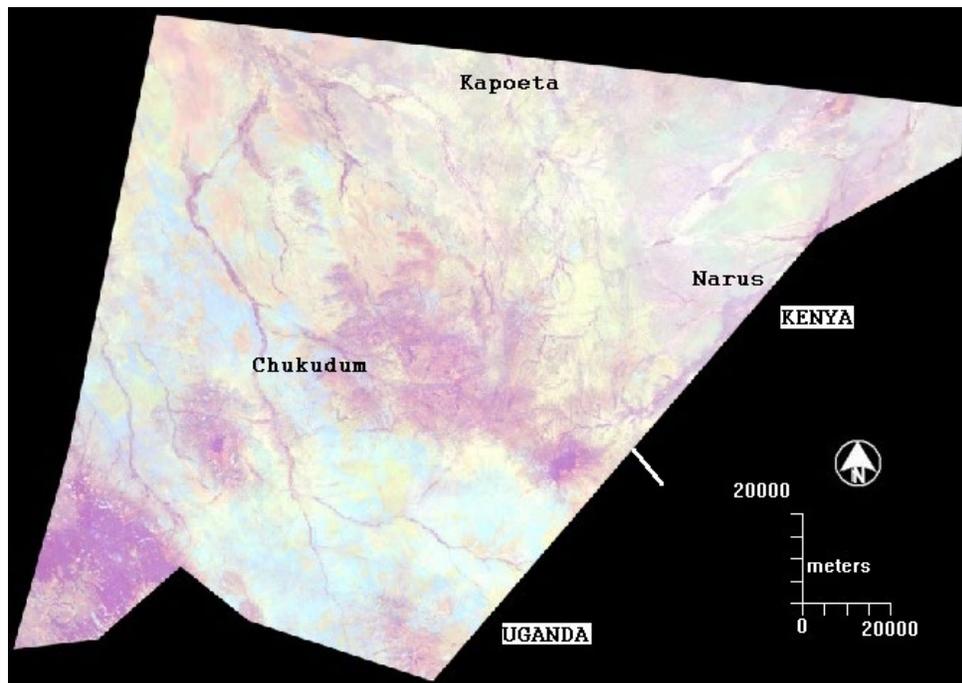


Figure 3.6. Color combination of the band ratio images B4/B2, B6/B5, and B6/B7 assigned to red, green, and blue colors, respectively. Hydrothermal alteration zones appear as bright yellow (almost equal amounts of displayed colors of red and green).

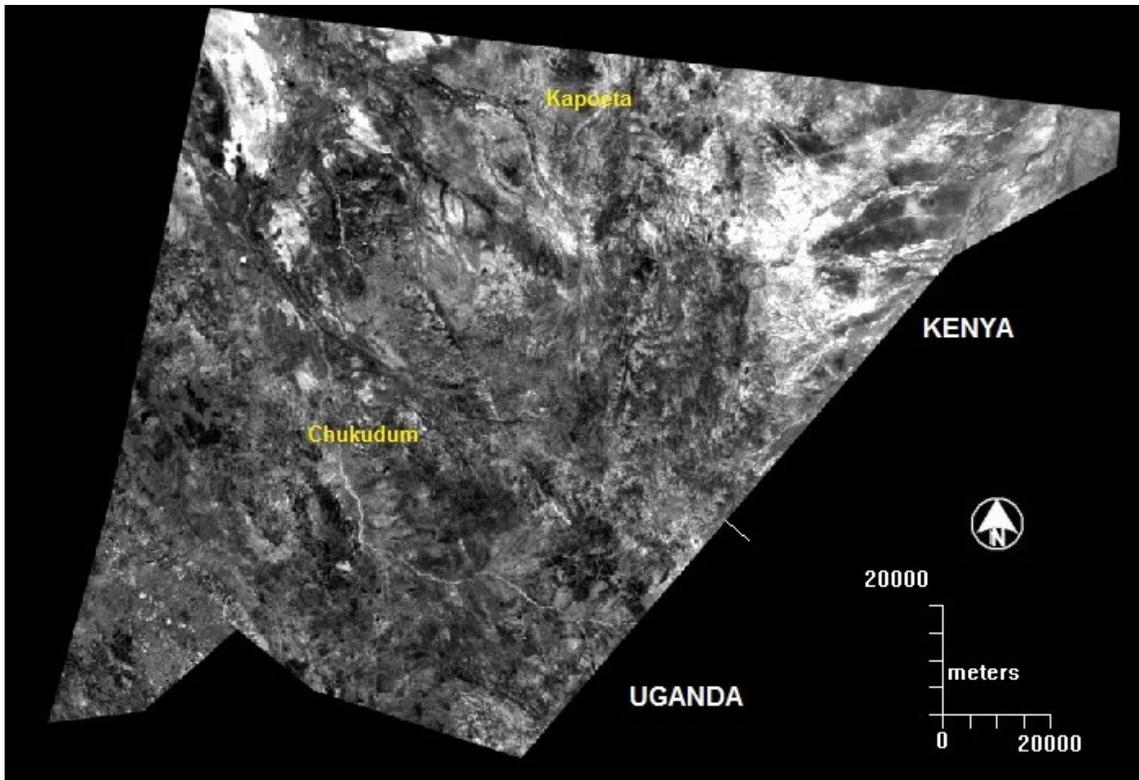


Figure 3.7. PC 4 (bands 2, 4, 5, and 6) showing iron oxide alterations as pixels of bright tones.

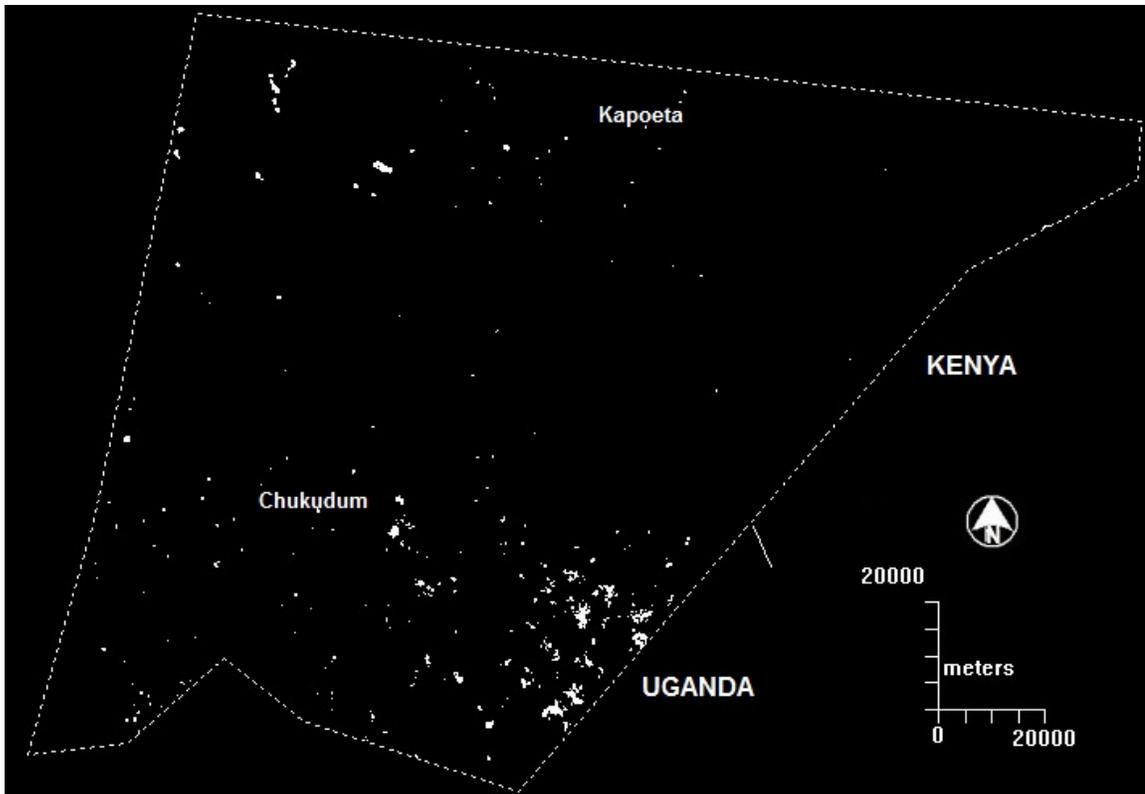


Figure 3.8. PC 4 (bands 2, 5, 6, and 7) showing clay alteration minerals as dark pixels because eigenvector values of the numerator (band 6) are negative. See the principal component analysis methods section. Gradation within the dark pixels is difficult to observe and therefore its coloring pattern is reversed in Figure 3.9.

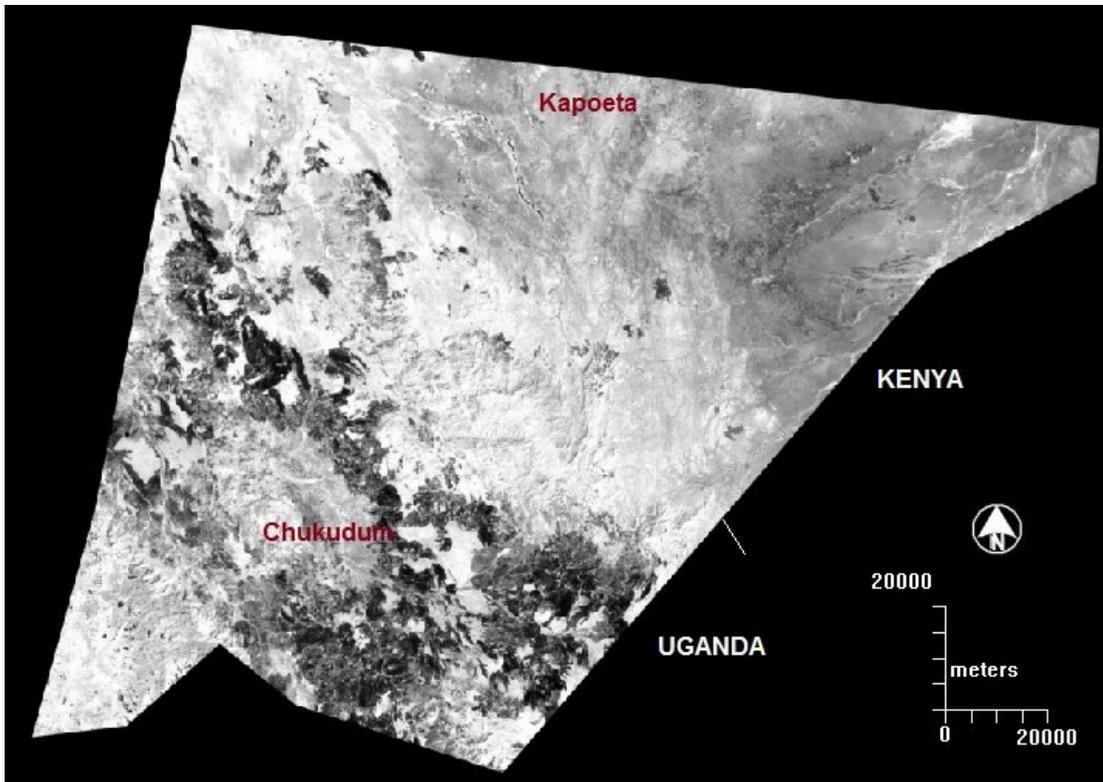


Figure 3.9. Clay minerals alteration in PC 4 appears as bright pixels after the dark pixels in Figure 3.8 have been enhanced.

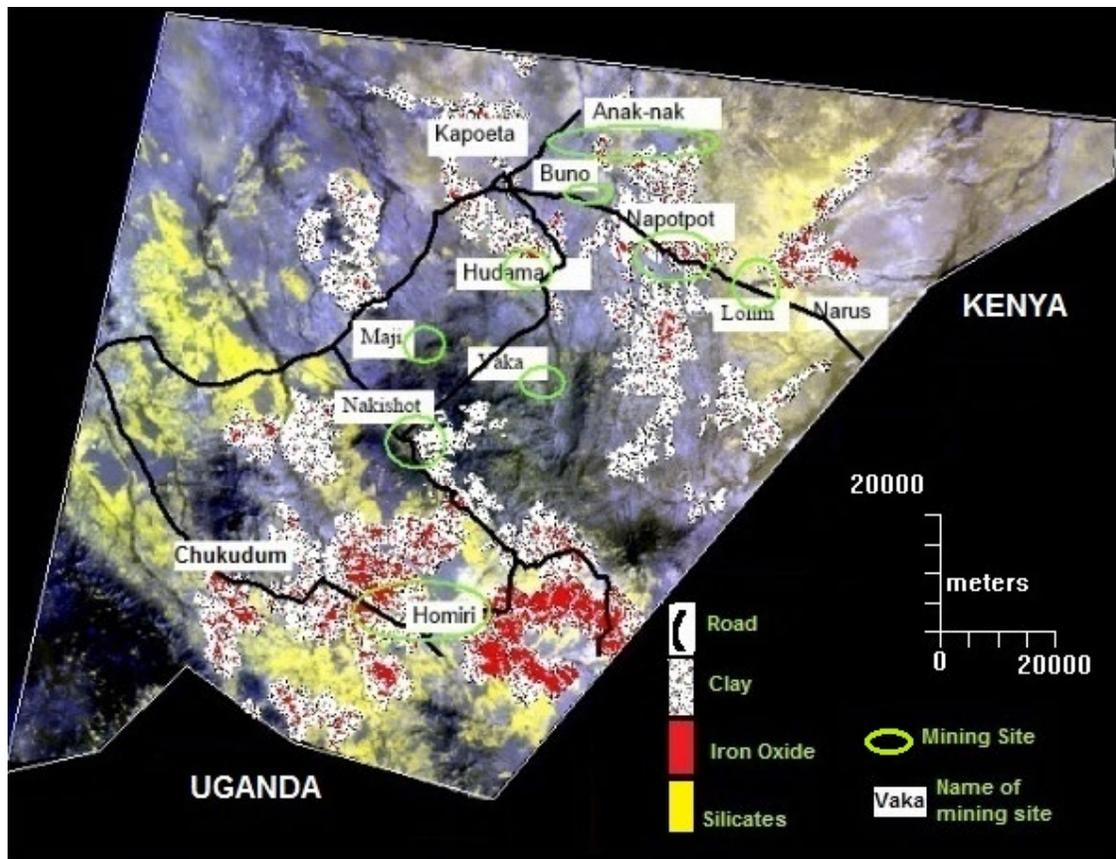


Figure 3.10. Spatial distribution of hydrothermal alteration zones relative to artisanal mining sites in the study area.

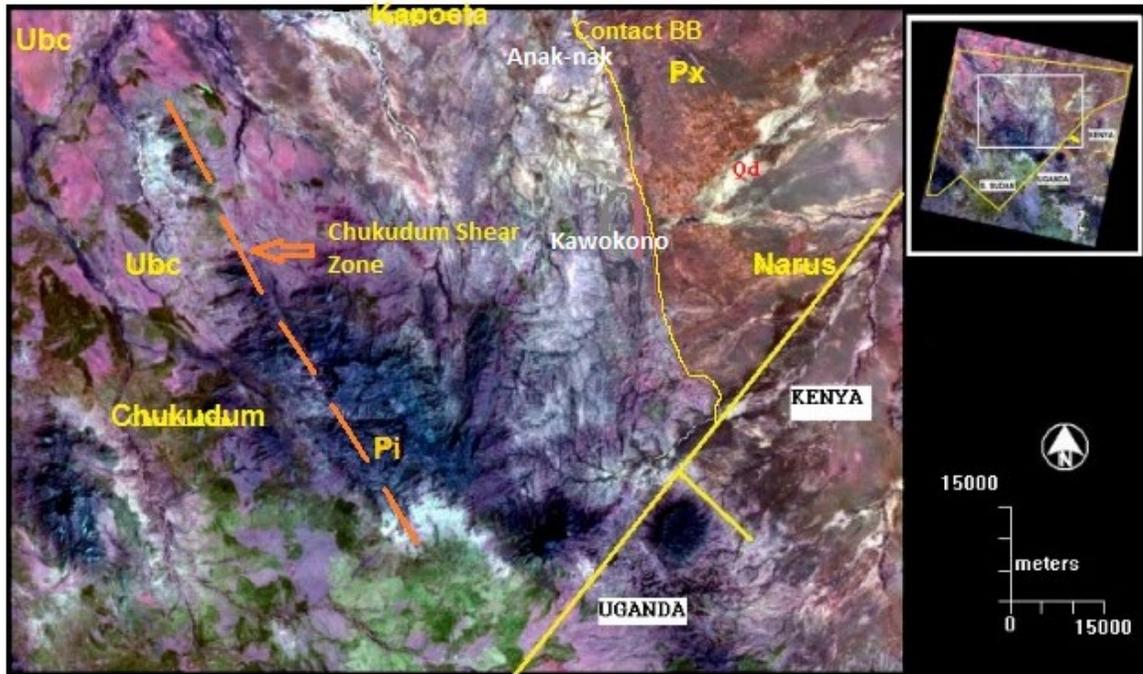


Figure 3.11. FCC image 475 RGB zoomed in to the central part of the Didinga Hills for better lithologic identification. Ubc is undifferentiated basement complex, Pi is Precambrian intrusive rocks, and Px is Precambrian extrusive rocks.

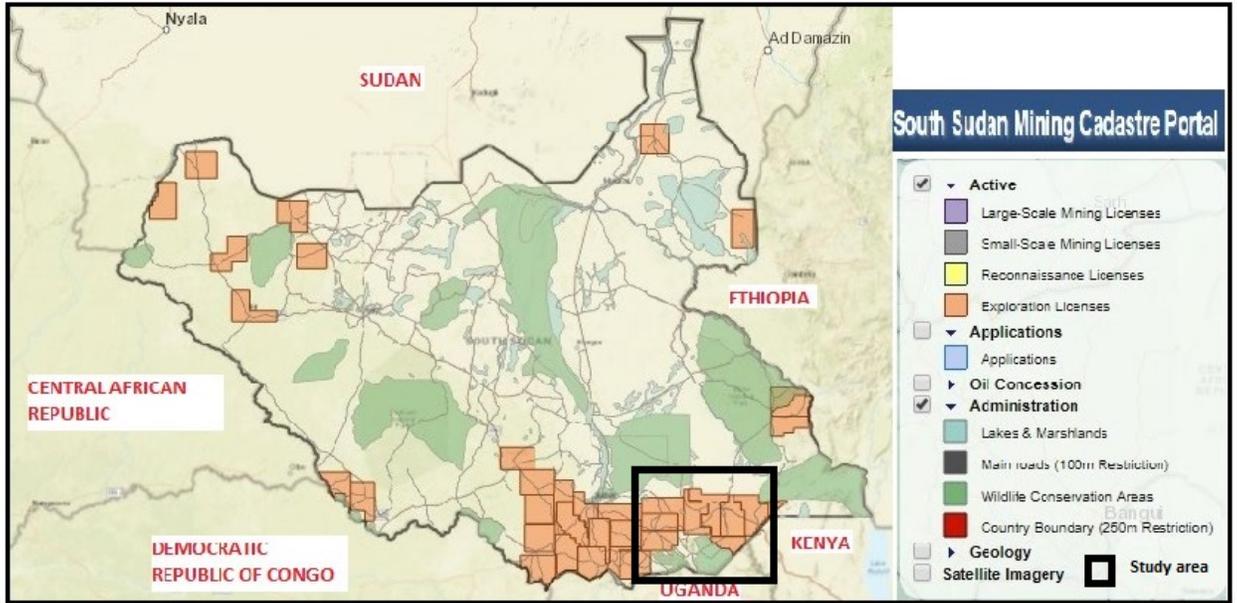


Figure 3.12. South Sudan Mining Cadastre Portal showing mineral title concessions (brown polygons) and the study area marked by a black square.

## **CHAPTER 4: GEOPHYSICAL MAPPING IN SOUTH SUDAN AND ITS ROLE IN EXPLORATION**

### **Introduction**

The aim of geophysical mapping in this study is to expose the basement architecture and relate major structures in South Sudan and those extending into neighboring countries of east and central Africa. Mapping of basement morphology in the study area will aid in assignment of mineral title blocks in the country, especially in regions that are occupied by sedimentary basins in swampy lowlands with no rock exposures.

Potential field data can be utilized in mapping basement architecture because gravity and magnetic responses are caused by contrasting physical properties (density and magnetization) of the bedrock (Fairhead et al., 2007). Generally, because of the large contrast in susceptibility values in comparison to the corresponding contrasts in density, the magnetic patterns in the data are most useful for mapping variations in types of rocks in the Precambrian basement.

The potential field data for South Sudan and the Sudan obtained by the African Gravity/Magnetic Map Project were provided by the Getech Company of Leeds, U.K. Unfortunately, the available Getech gravity and magnetic data (Figure 4.1) cover mostly the oilfield in South Sudan, as the interest was initially for petroleum exploration. Since this study is targeting mapping of basement rocks, there was a need to utilize satellite data because of their vast coverage and cost-effectiveness.

The limitation in using the Getech magnetic data in this study was the location of South Sudan, which straddles the geomagnetic equator, and so there is less of a role being played by the magnetic data in structurally mapping the basins and basement rocks (King et al., 2012). The problems in using wavenumber domain methods at magnetic equators are nearly always related to noise in high frequencies in the denominator of the transformations (Blakely, 1996).

Other available geophysical data include seismic, which in the study area are restricted to the oilfields in the central part of the study area.

### **Processing of Gravity Data**

The processed data in this study are the free-air satellite gravity data derived from the “DNSC08 Global Gravity” of the Danish National Space Center, which has been augmented with EGM08 over land (Andersen et al., 2008).

The main aim of constructing a Bouguer anomaly map from the free-air gravity anomalies is to eliminate the large effect of topography in free-air anomaly data (Blakely, 1996; Fullea et al., 2008), which masks the anomalies caused by subsurface sources. A Bouguer anomaly map derived from the satellite data can also be compared with the Bouguer anomaly map produced using Getech ground gravity data, particularly in areas that are well covered by gravity surveys in South Sudan. In case the Getech Bouguer gravity map shows good correlation, then the extensive coverage of the satellite-derived Bouguer gravity map could be used to delineate geologic structures as well as in mapping basement architecture in other parts of the study area that are lacking ground gravity data.

The Getech data were derived from land gravity stations, with a resolution of 5 minutes (~10 km). Bouguer reduction density of  $2.67 \text{ g/cm}^3$  was applied to the data (D. Ravat, 2011, personal communication).

The correction applied to the free-air anomaly in order to convert it into a complete Bouguer anomaly map consists of the following steps using the Geosoft Oasis Montaj package:

1. Bouguer slab correction (Bullard A), which assumes a slab of finite lateral extent, constant density, and thickness equal to the elevation of the data location with respect to sea level, is applied.
2. The curvature correction (Bullard B), which replaces the Bouguer slab with a spherical cap of the same thickness to a distance of 166.735 km, is applied.

3. The terrain correction (Bullard C), which accounts for the effect of surrounding topography in the Bullard A and B corrections, is applied above and below the point of calculation (Nowell, 1999). Land terrain corrections with a regional DEM GTOPO30 model (gtopo30 is 30 arc-second latitude/longitude or approximately 1 km spacing), are applied.

The Bouguer gravity maps based on satellite data (Figure 4.2) and Getech data (Figure 4.3) and show similar high and low anomalies in the central part of the study area where the oilfields are located. There is no correlation in areas known to lack data, however; these areas have been labeled by question marks in Figure 4.1.

The two datasets were compared in profile form with successive low-pass filters of 20, 50, 100, 150, 200, and 300 km wavelength. The profile in Figure 4.4 demonstrates wavelength content and fidelity of satellite data because it extends across both the Muglad (MG) and Melut (MT) rift basins. The results show that the low-pass filter with a wavelength  $> 20$  km produced the best visual correlation between the two datasets, although a few shorter-wavelength features are displaced and there are very large regional differences (Figure 4.5).

### **Analysis of Gravity Data**

The gravity data were analyzed by applying filters that are available in the Geosoft program. There are many methods to enhance potential field data; some are applied to the profile, whereas others are applied to gridded data. Each method has its advantages and disadvantages (Blakely, 1996). Generally, there is no single method for interpretation of potential field data, but some methods may be better suited to a particular case study than other methods, depending on the purpose and quality of the data.

The methods used in this study are horizontal gradient, tilt angle, and analytical signal. Theoretical and mathematical details of these methods can be found in the literature by authors including Roest and Pilkington (1992), Blakely (1996), Verduzco et al. (2004), and Nabighian et al. (2005). These interpretation methods were selected because of their capability of edge detection and depth determination of sources, such as

delineation of geologic structures, lithologic boundaries, rock intrusions, accretional boundaries, or tectonic lineaments that can be visually identified by edge-detection processing methods.

The horizontal gradient filter was applied to the gravity field data in the northeast-southwest direction with the aim of obtaining the expression of any of the major linear geologic structural patterns of the Precambrian basement and lithologic boundaries in the study area that are mostly trending northwest-southeast. Results using the horizontal gradient filter are shown in Figure 4.6.

The tilt-angle derivative filter displays the inverse tangent of the ratio of the first vertical derivative to the horizontal gradient (Nabighian et al., 2005). Zero contour of the tilt-angle derivative marks the edges of sources (Verduzco et al., 2004). The filter was applied to highlight variations in geology and structure in the study area, as shown in Figure 4.7, which portrays clear northwest trends of blue and red features representing sedimentary basins and basement rocks, respectively. Figure 4.7 also shows a clear correlation between the tilt-angle derivative map and the rift basin index map, which illustrates that both the Muglad and Melut rift basins are composed of other smaller sedimentary sub-basins separated by basement ridges. Likewise, in various gravity maps of the study area there are high-gravity anomalies separating low-gravity anomalies corresponding to those ridges and sub-basins, respectively.

The analytic signal is also a derivative filter, which leads to suppression of low wavenumbers, and thereby delineates areas of basement high and deep basement. The advantage of this method is that its maxima occur directly over faults and contacts, regardless of the structural dip present (Nabighian et al., 2005; Saibi et al., 2006). The application of the method on Bouguer anomaly (Figure 4.8) shows basement architecture with shallow basement (red colors) and deep basement (blue colors). The Muglad and Melut rift basins are shown (Figures 4.4, 4.5, and 4.6) and basin-margin fault structures are delineated as white lines.

Since the aim of this reconnaissance is to identify areas of potential mineralization to be licensed to mining investors, a quantitative interpretation (e.g., depth estimation)

has not been done. Modeling and depth estimates could be done by investors in further detailed exploration stages, however.

### **Interpretation of Gravity Data**

Both gravity maps, Getech and DNSC08, depicted in Figure 4.4 reveal that a series of major northwest-trending linear gravity anomaly patterns dominates a large part of the study area, along with a few orthogonal northeastern trends that are discontinuous. The sedimentary basins (Muglad and Melut) are easily identified on both satellite and Getech maps by their negative gravity anomalies, which are oriented in the dominant trend of northwest-southeast. These basins are mainly separated by high-gravity anomalies of the same trend (Figures 4.2, 4.3, 4.4). The topography of the central part of the study area is almost uniformly low; consequently, alternating negative and positive gravity anomalies in combination with analytic signal variation suggests that the subsurface may have features such as horst and graben blocks, some of which have been detected by seismic surveys (Figure 4.9) and confirmed by drilling in the oilfields (Schull, 1988; Genik, 1993).

The basement complex units in South Sudan are shared with neighboring countries and contain a continental-size shear zone (Aswa), many sutures, accretionary structures, and reworked Proterozoic crust (Figure 4.10), all of which have potential for harboring minerals (Kröner and Stern, 2004). All of these different rock units are revealed on gravity maps as variations in density, depending on their respective contrasts with the surrounding rocks.

### **Discussion and Recommendations**

Processing and interpretation of the satellite-derived gravity data for the purpose of mapping basement morphology can augment exploration, hence reducing risks by avoiding excessively deep ore zones and focusing on anomalous areas of intrusive rocks, contact metamorphism, and linear geologic structures.

Chapter 3 describes using multispectral remote sensing to map mineralization in the arid to semi-arid region of the Didinga Hills; however, the method becomes less effective in vegetative areas such as the vast basement complex of southwestern South

Sudan, which is expected to have potential for mineralization based on mining activities on similar rock units in neighboring countries.

DNSC08 gravity data augmented with EGM2008 free-air gravity anomalies over land were processed, and the resulting Bouguer anomaly map compares well with the Bouguer anomaly map from Getech data for the Sudan and South Sudan and thus can be used for interpretation of features with wavelengths  $> 20$  km. The maps show major northwest-trending anomalies corresponding to the Muglad and Melut rift basins, which are separated by high-gravity anomalies of the same trend believed to represent shallow basement rocks in the form of horsts and grabens (King et al., 2012; Fairhead et al., 2007; Mohamed et al., 2002).

Analysis techniques including analytic signal, tilt angle, and horizontal gradients were applied to the data, and resulting maps revealed major rift basins with boundary structures, including faults (Figures 4.6–4.8). Other studies conducted in South Sudan (King et al., 2012) similarly identified the rift basins and the basement architecture using satellite gravity observations (Figure 4.11).

Observations from the Gravity Field and Steady-State Ocean Circulation Explorer satellite observations have been utilized to map geologic units around the Congo Craton that was the nucleus of Gondwana; the craton has a thick lithosphere against which crustal deformation occurred (Begg et al., 2009).

The different geologic units in this region have been studied by Kadima et al. (2011) and results generally show that younger sedimentary units exhibit lower density and have an average density of  $2.35 \text{ g/cm}^3$  due to compaction. In comparison, metamorphic units and magmatic units (e.g., basalts) have higher density in comparison to granites and have an average density of  $2.65 \text{ g/cm}^3$ .

Figure 4.12 shows selected geologic units that are expected to generate variations in the bulk density in the region (Braitenberg, 2012). The most important geologic units that are shared by Congo, Uganda, and South Sudan have been numbered as unit 3 on Figure 4.12 and comprise sediments of east African rifts (e.g., the Muglad and Malut

Basins in South Sudan). Another unit, designated 11 in Figure 4.12, is the Kibalian basement, comprising a greenstone belt with syn-tectonic granites, and some amphibolite outcrops (upper Precambrian), corresponding to the Precambrian basement trending northwest-southeast in the Republic of South Sudan.

The lateral extent and considerable thickness of these basement rock units are related to major geologic and tectonic events during the evolution and accretion of the Congo Craton (Toteu et al., 2004); hence, such events contribute to the diversity in rock densities that are of prime importance in a gravity survey. The Bouguer field reduced by isostatic Moho shown in Figure 4.12 shows correlation of various gravity anomalies corresponding to different rock densities representing denser basement rocks—e.g., the Kabalian (high anomaly) and lighter basin sediments that occur in the Muglad and Melut Basins in South Sudan (low anomaly) (Braitenberg, 2012). “Isostasy” is the term used to describe a state of equilibrium between the Earth’s crust and the underlying mantle (Watts, 2001). The isostatic correction of gravity anomaly removes the mass compensation of the topographic effects from Bouguer anomaly, assuming Airy isostasy, and allows the focus to be on intracrustal density variations. The remaining isostatic anomalies in the map after reduction of the Bouguer field by isostatic Moho suggest the presence of geologic features of anomalously high or low density relative to the surrounding crust and sediments, which in turn can be further interpreted by modelling (Close, 2010; Watts and Fairhead, 1997).

Similarly, the Republic of South Sudan can benefit from airborne surveys by embarking upon a program of geologic, geophysical, and geochemical mapping, which is critical for providing geologic information to be used in solving problems related to its natural resources and environmental and socioeconomic development issues.

The government has mandated that the Directorate of Geological Survey in the Ministry of Mining carry out such mapping programs. Academia, companies, and local and national governments should cooperate, however, in setting out short- and long-term programs, including setting priorities for geologic mapping at both local/state and national levels.

The Directorate of Geological Survey should collect all data, maps, and reports of South Sudan that are being kept in databases of the Republic of South Sudan, since it is now a sovereign state. The available information will constitute the basic data for future use in planning and exploitation of natural resources. In addition, the data could be used to assess and mitigate hazards, risks, and natural disasters.

Important questions concerning mapping are: What kind of mapping is a priority? Why? Where? When? and How? Currently, much of the land has not been surveyed or mapped at all. So airborne surveys are cost- and time-effective and will provide the basic data needed for promotion of exploration activities in the republic. Priority areas should be where there are already clues of mineral potential, and most important, in areas where the security is stable. This will make fast-tracking of sustainable mineral development possible, in order to contribute to the nation's economic development. Such mapping programs can be successful through cooperation of specialized regional and international firms and institutions willing to undertake such projects by contracts or other mutually acceptable agreements. Execution of airborne geophysical surveys depends on regional infrastructure and overcoming limitations, including political instability and hazards.

Assuming security is stable, priority should first be given to areas of effective artisanal gold mining in Eastern Equatoria (Area 1 in Figure 4.13), where the Precambrian geology is characterized by metamorphic rocks and syn- to post-tectonic igneous intrusions. Volcanic activities also occurred in the area during the East African Orogeny. Part of this region has already been investigated through remote-sensing techniques (described in Chapter 3) and found suitable for exploration of gold deposits. The second area to be surveyed is the former Central Equatoria region, where the continental-scale Aswa Shear Zone occupies most of its southern and western parts. The presence of granite, syenites, and quartzites constitutes a favorable geologic environment for mineralization. The third area is the Western Equatoria and Western Bahr El Gazal regions, where lateritic diamond mining is taking place across the border in the Democratic Republic of the Congo and the Central African Republic. The presence of greenstone belts and igneous batholiths also makes this area suitable for mineral exploration. Other smaller areas (e.g., Jebel Buma and Awil) could be surveyed as part of a survey of the Eastern Equatoria and Western Bahr El Gazal regions, respectively. The

Maban district could be the fourth region to be surveyed, although not much artisanal mining is taking place in the region at present.

Figure 4.13 shows the areas recommended for airborne surveying based on the above logic.

Qualitative interpretation of satellite-derived Bouguer gravity data has aided mapping of the basement geology of South Sudan, and the results are consistent with the known oilfields and areas of Precambrian basement complexes. Consequently, the information would aid in identifying additional mineral prospective areas, where more detailed gravity, magnetic, electromagnetic, and seismic surveys can be carried out; the combination of these data will assist decision makers in matters related to land use, mineral titles, and exploration of natural resources.

This study has shown that regional geophysical mapping using satellite-derived gravity data is feasible for South Sudan, because data are available for free and processing and interpretation software is available. Information about regional gravity anomalies has been confirmed by the study, and geologic understanding of the region has improved; it has also helped demarcate priority areas for further detailed airborne geophysical mapping to help mineral exploration in the country.

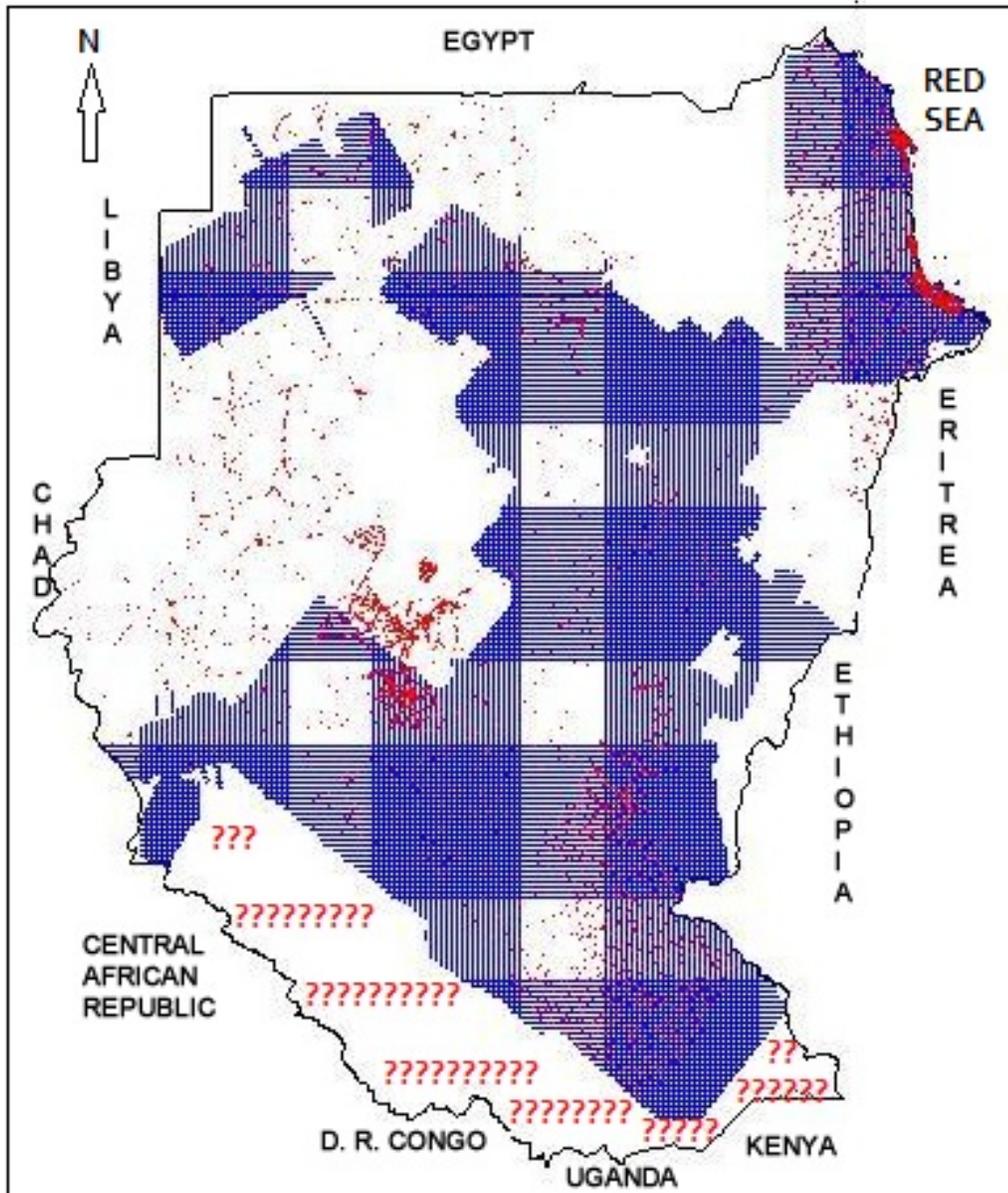


Figure 4.1. Potential field data coverage of South Sudan and Sudan showing magnetic data grids (blue lines) and gravity data stations (red points). The question marks represent zones with no data coverage.

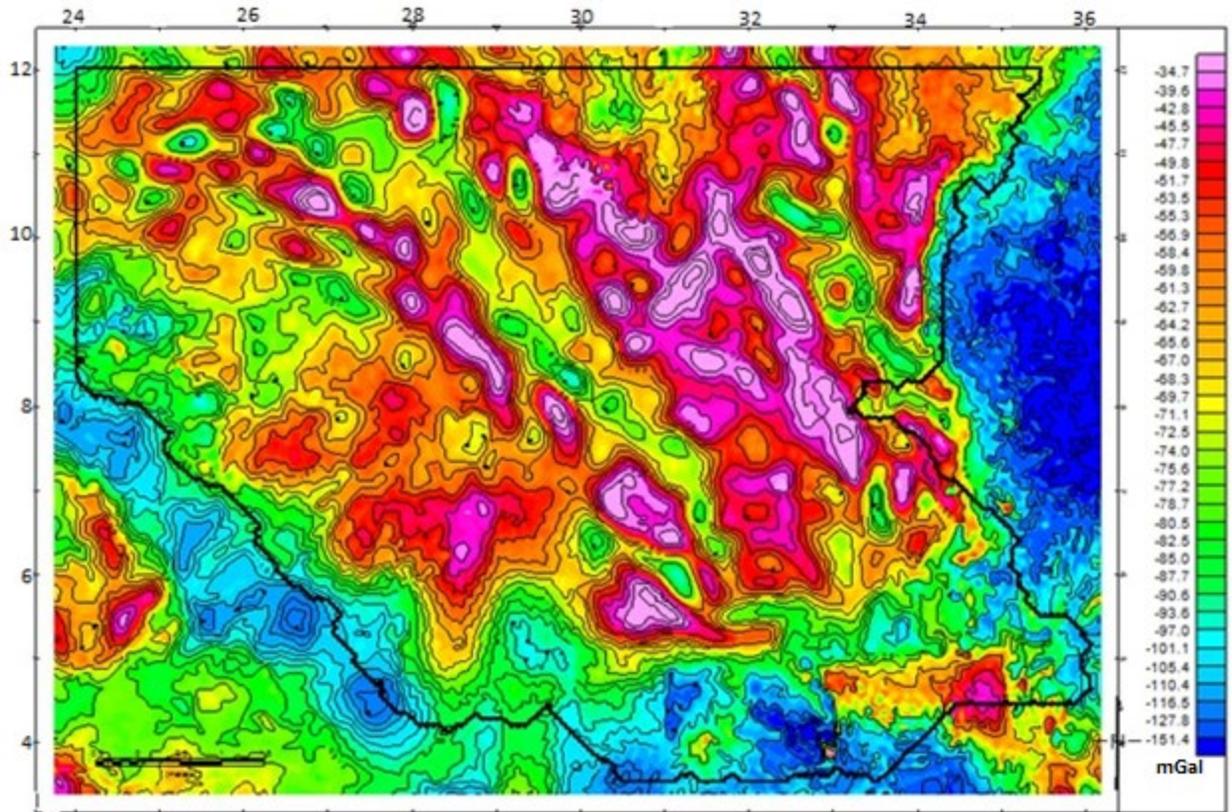


Figure 4.2. Complete Bouguer gravity map of the study area and vicinity produced from DNSC08 global gravity data.

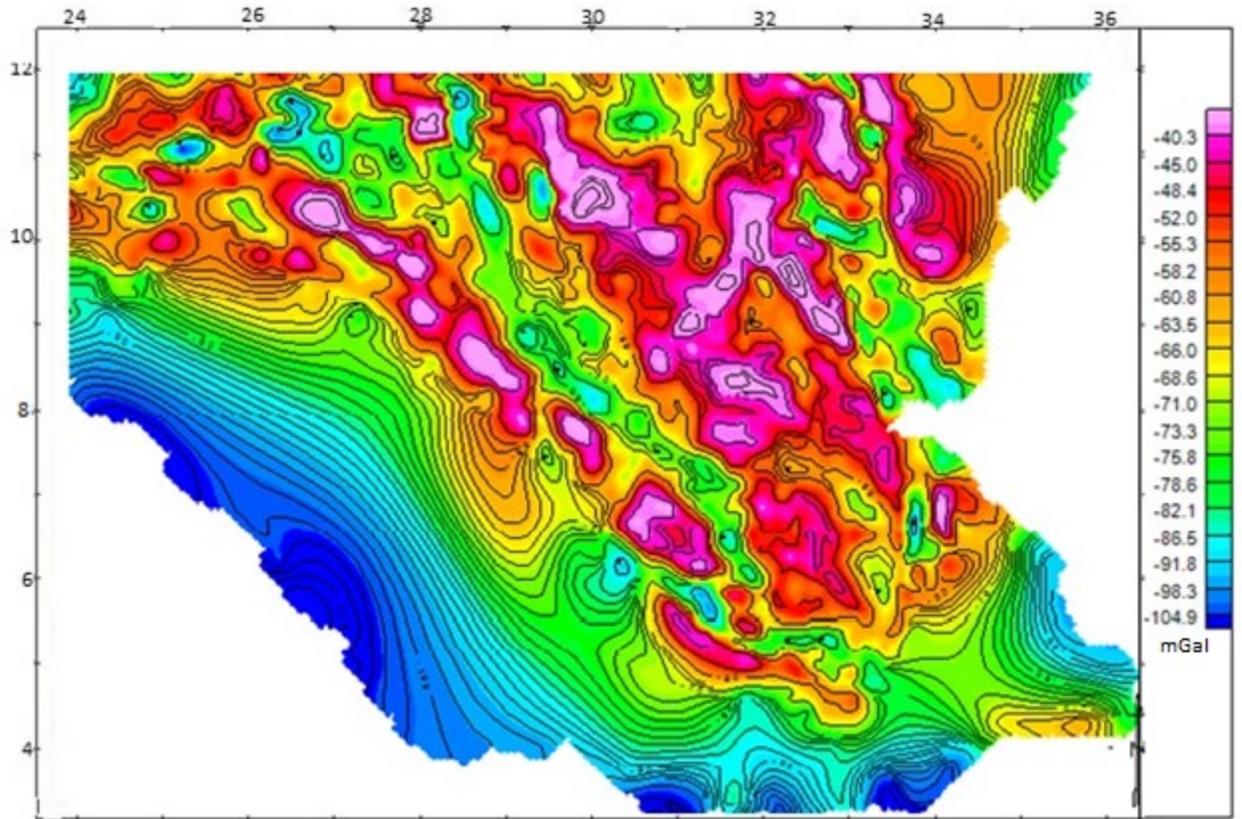


Figure 4.3. Bouguer anomaly map from data provided by Getech.

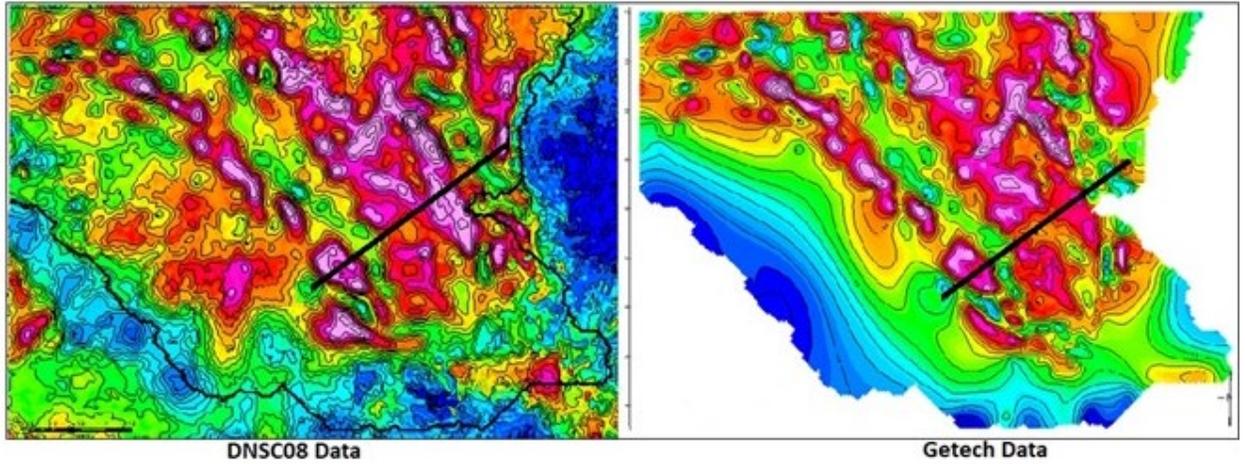


Figure 4.4. Location of profiles used for comparison of DNSC08 and Getech Bouguer anomaly gravity maps.

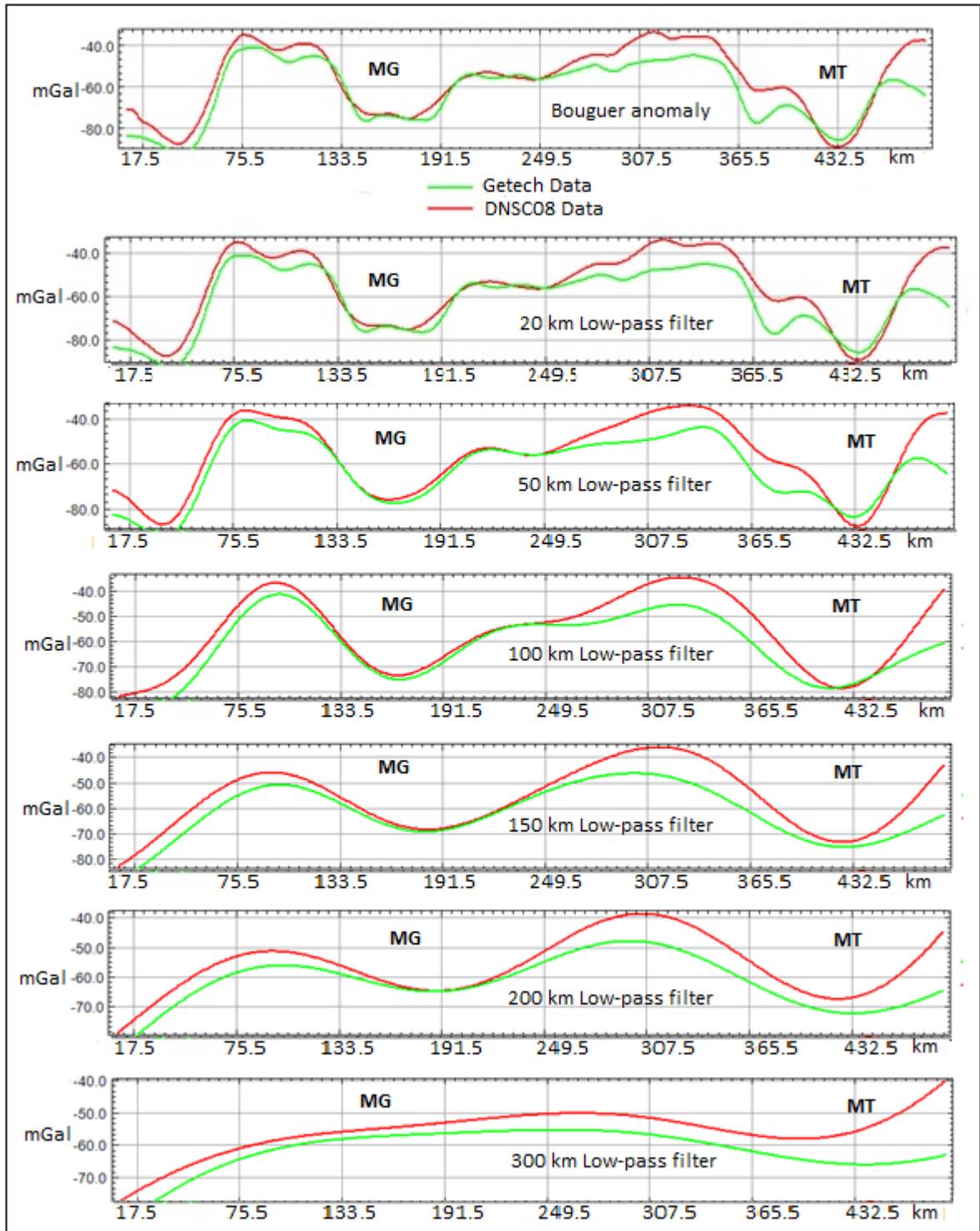


Figure 4.5. The profile in Figure 4.4 before and after application of successive low-pass filters.

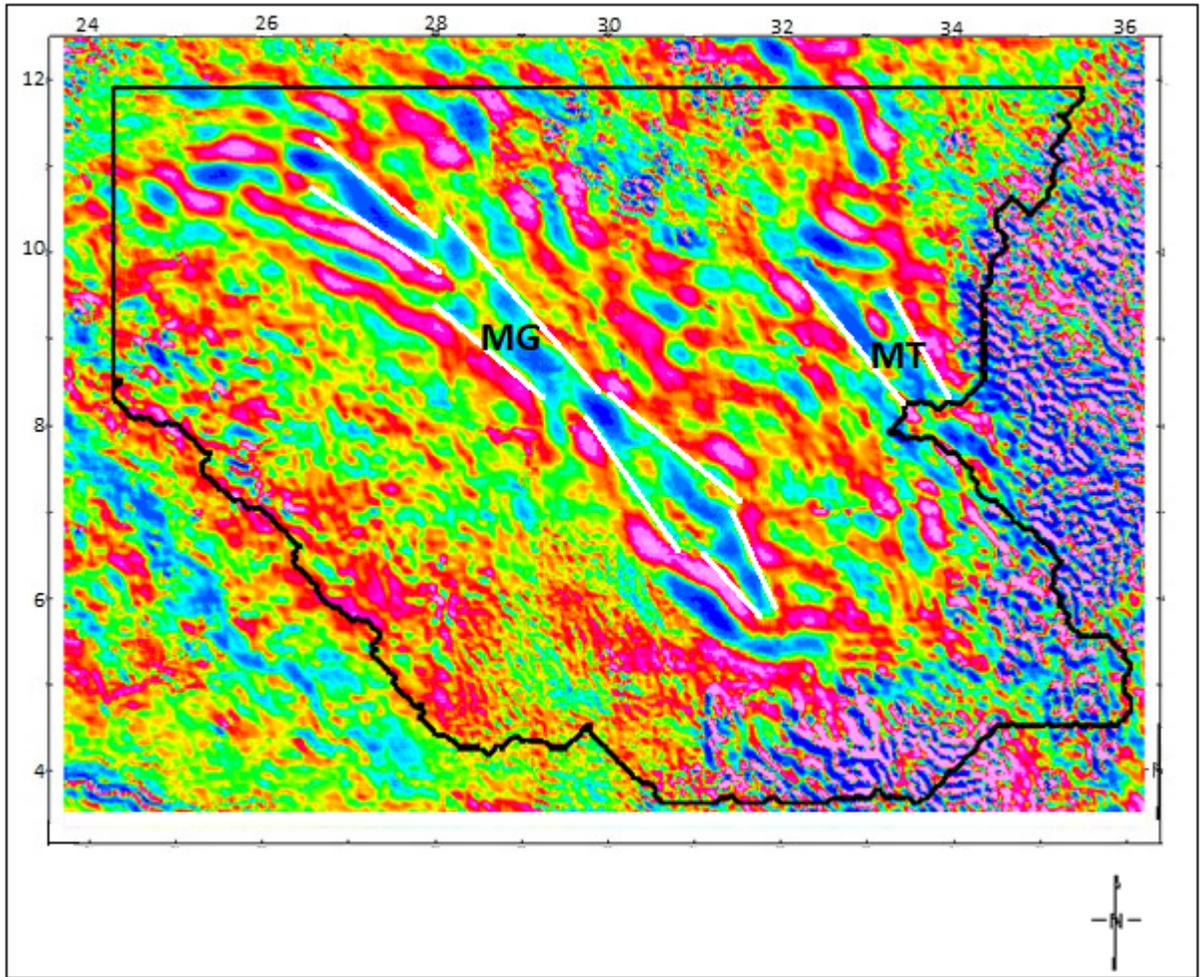


Figure 4.6. Horizontal gradient of Bouguer anomaly taken in the northeast-southwest direction showing northwest-trending geologic features (e.g., the Muglad and Melut rift basins).

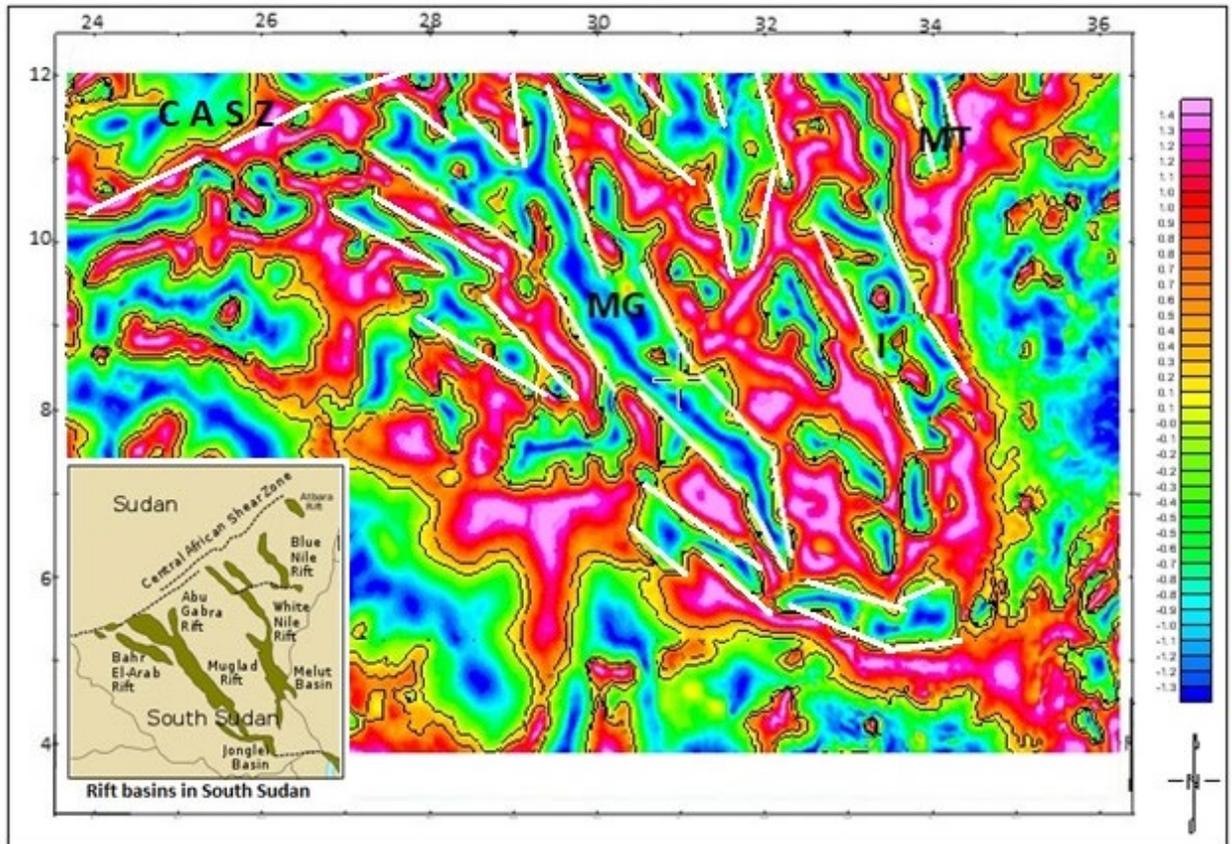


Figure 4.7. Tilt-angle derivative of the Bouguer anomaly map of the study area correlated with locations of rift basins in South Sudan and Sudan shown in the index map.

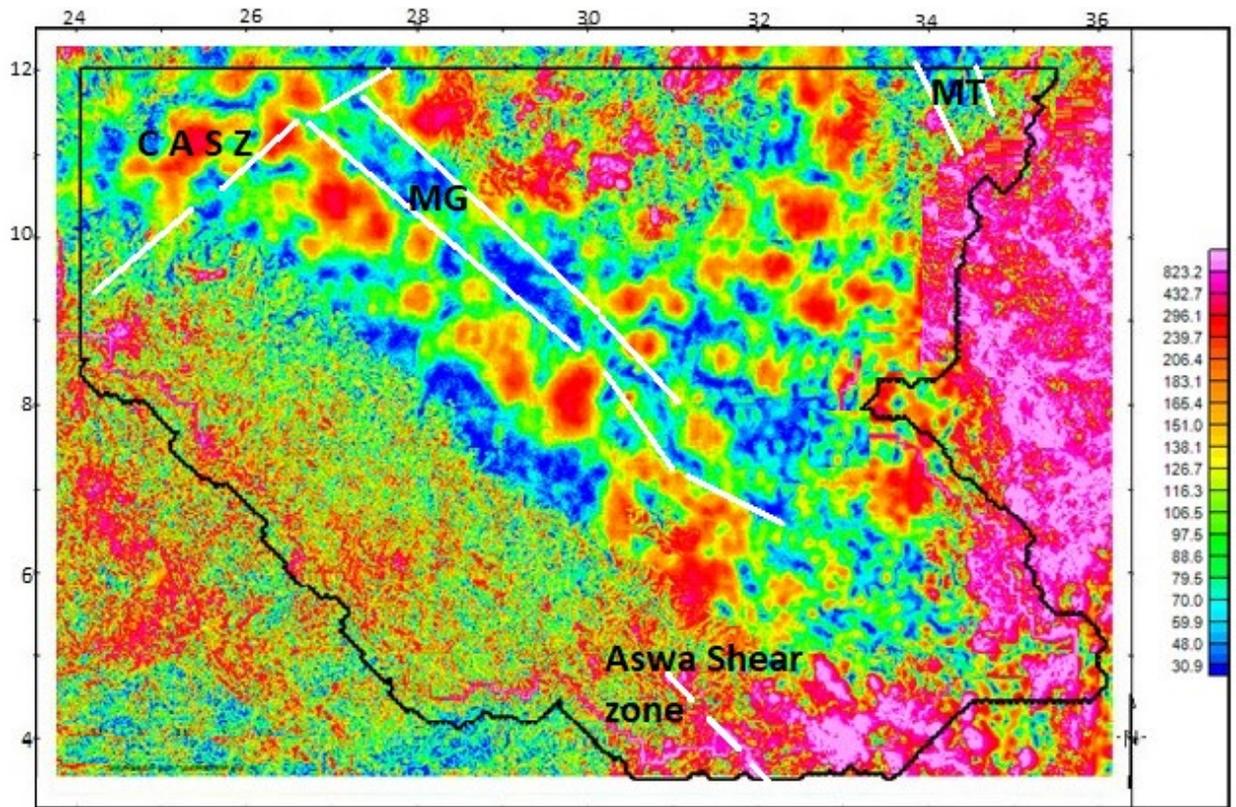


Figure 4.8. Basement topography determined from applying analytic signal to gravity data. Shallow basement areas are in shades of red and deeper parts are in shades of blue. Locations of the Central African Shear Zone (CASZ) and the Aswa Shear Zone are shown.

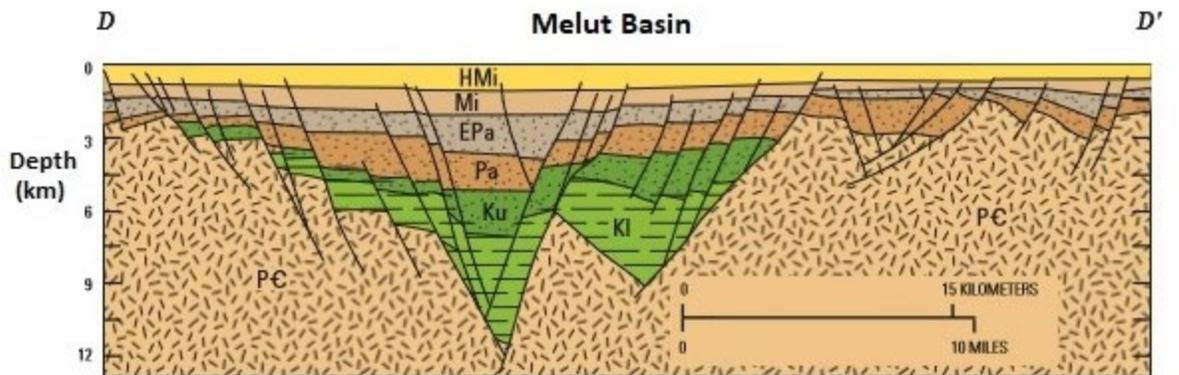
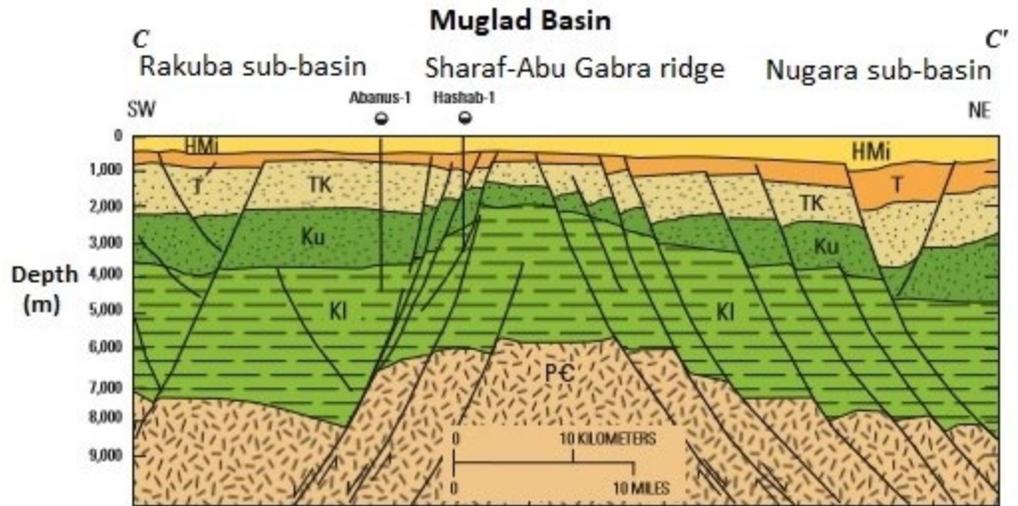


Figure 4.9. Schematic cross section showing depth to basement in both the Melut and Muglad Basins (after Genik, 1993; U.S. Geological Survey, 2011).

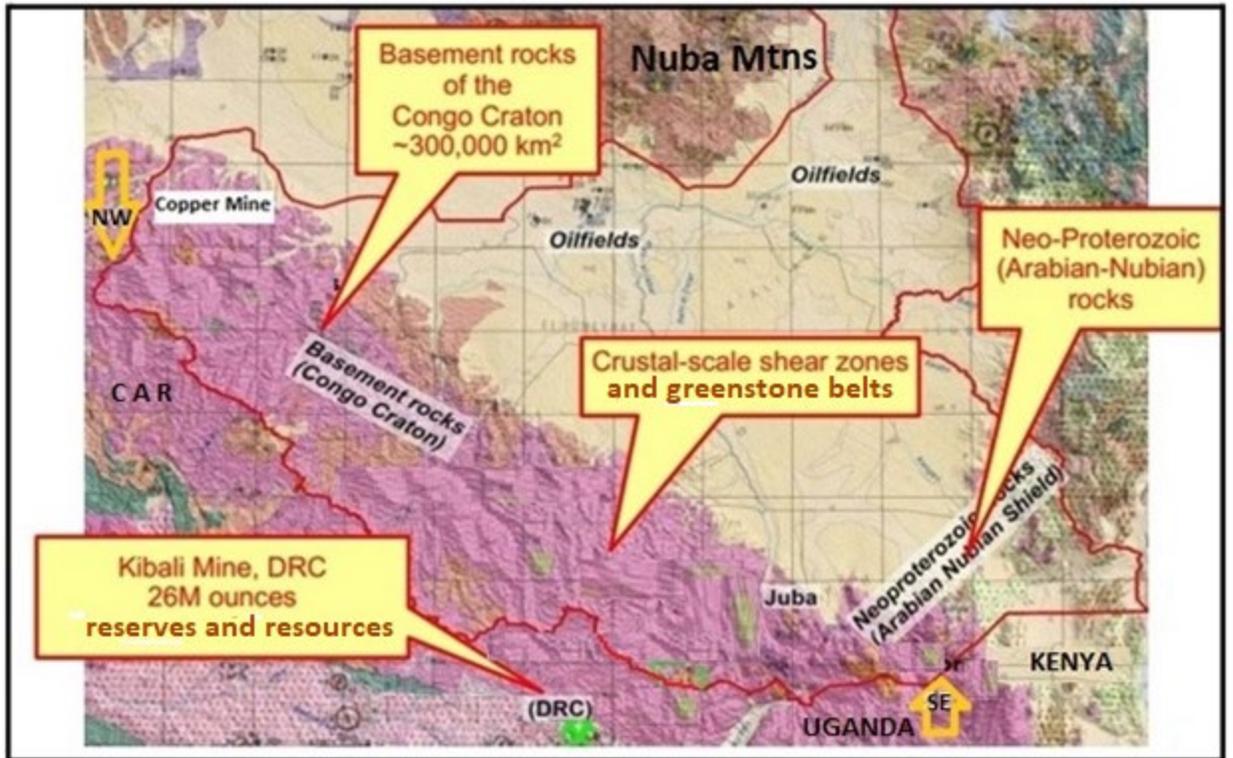


Figure 4.10. Precambrian basement geology and structural elements in South Sudan (after Equator Gold, 2015).

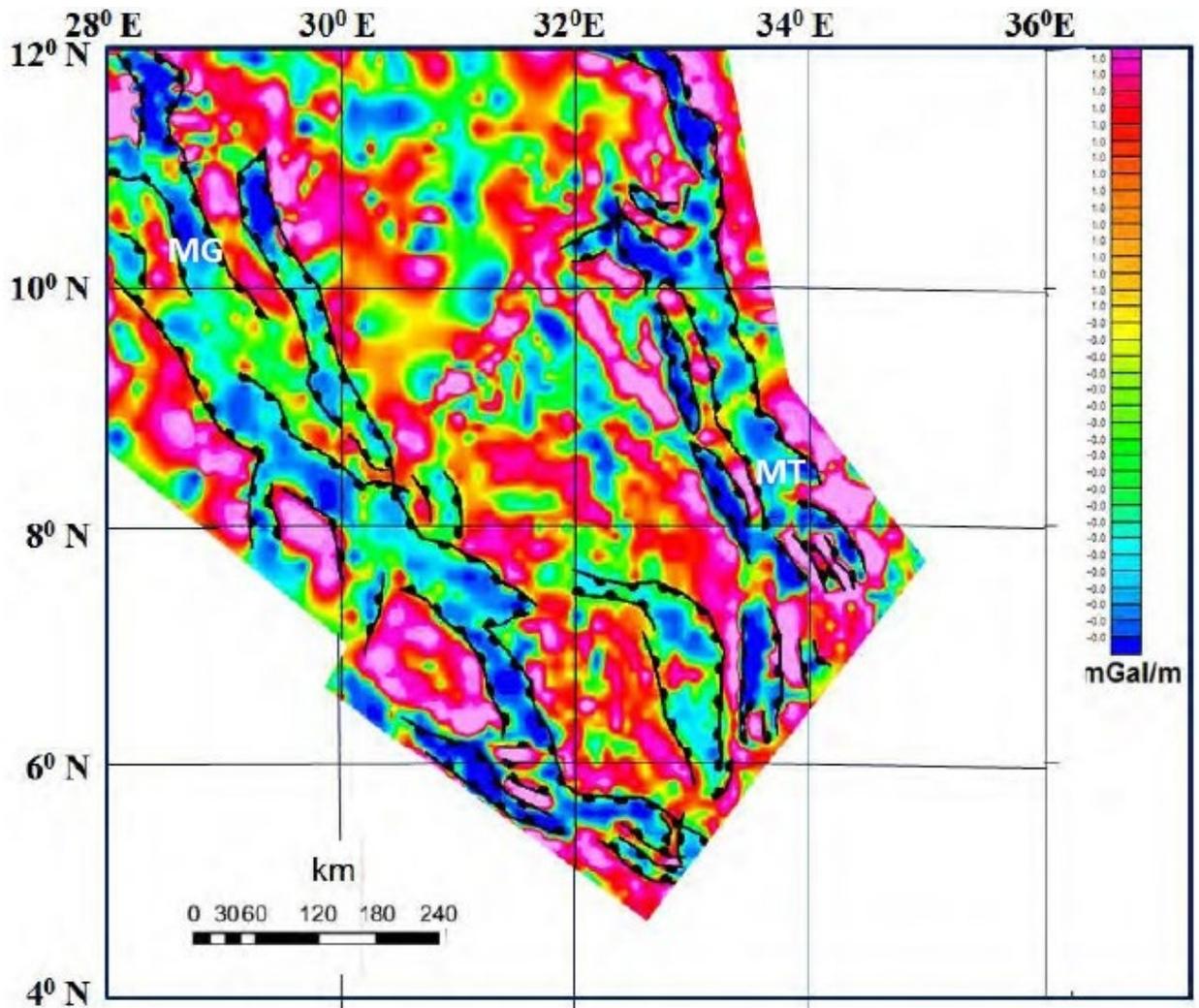


Figure 4.11. Vertical derivative of Bouguer anomaly showing basement architecture as deep (blue) and shallow (red) with superimposed basin margin faults. Compare gravity anomalies in the Muglad and Melut rift basins on this and derivative maps (Figures 4.6–4.8) of the study area. After King et al. (2012).

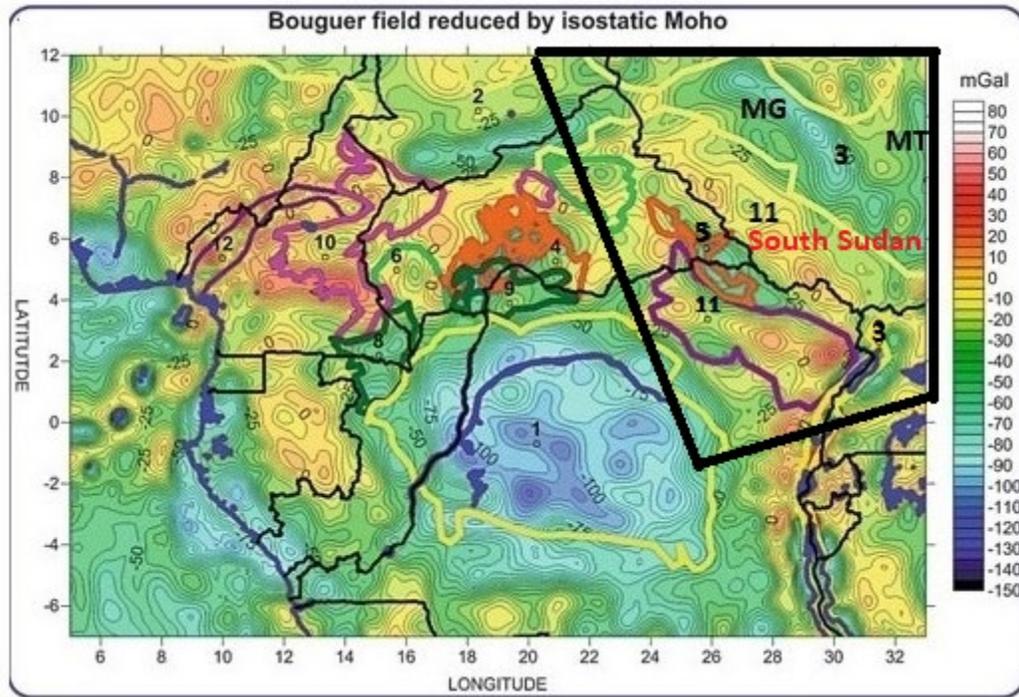


Figure 4.12. Comparison of the Bouguer field indicated by the Gravity Field and Steady-State Ocean Circulation Explorer satellite, reduced by isostatic Moho, to several of the geologic units from the UNESCO geologic map (Commission for the Geological Map of the World, 1990). The Muglad (MG) and Melut (MT) rift basins of South Sudan and the Kabilian basement unit (11), together with unit 3 representing East African Rift sediments, are identified. The shared area of rock units is marked by a black square. Other geologic units identified by numbers on the map are outside the region of interest. After Braitenberg (2012).

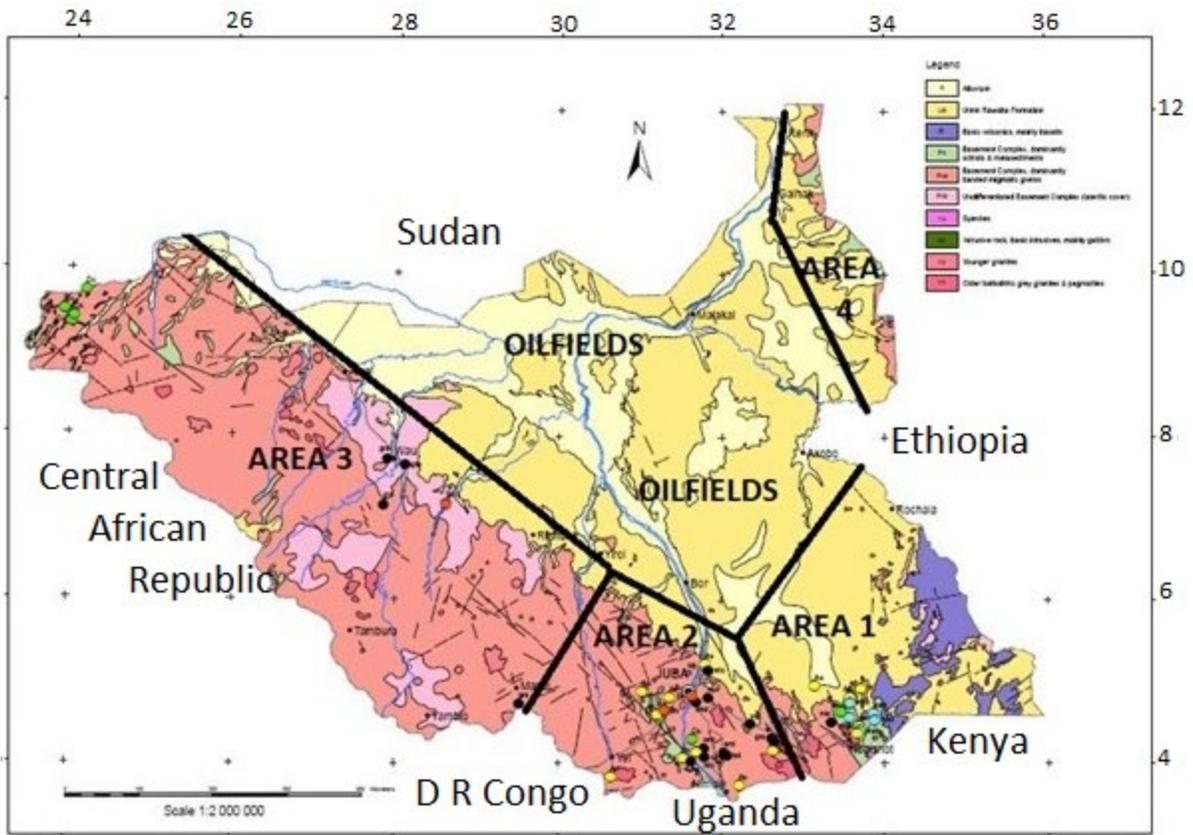


Figure 4.13. Areas recommended for airborne geophysical survey (see discussion in text).

## **CHAPTER 5: MANAGEMENT AND SUSTAINABLE DEVELOPMENT OF MINERAL RESOURCES IN SOUTH SUDAN**

### **Introduction**

“Sustainable” is a word heard almost daily, and although its definition varies from one field to another, according to Brundtland reports it commonly means “meeting the needs of today without compromising the ability of future generations to meet their needs” (Dixon and Fallon, 1989).

Minerals are nonrenewable and therefore are inherently unsustainable. Thus, continued mining will eventually exhaust the available mineral resources, which in the case of South Sudan have not been explored or exploited in a real sense yet. Consequently, proper decisions should be made for the appropriate exploitation of mineral resources for the sustainable development of the nation.

As a geoscientist, I needed training on governance and sustainable development. I attended training courses, workshops, seminars, and conferences to meet this goal. These events were organized by credible mining institutions in Canada, South Africa, Australia, the U.K., and Switzerland.

I participated in reviewing a draft of the “Mineral Title Regulations at the Ministry of Justice and Constitutional Affairs” in the Republic of South Sudan. I also attended a training course in Vancouver, Canada, in 2015 organized by the Canadian International Resource Development Institute; the course was for government delegates from countries around the world. This three-week course improved my understanding of mining legislation, licenses and permits, transparency and accountability, socioeconomic development, mitigation of environmental impacts, and social corporate responsibility.

As a delegate, I also participated in the 5th Conference of the International Forum for Sustainable Development Indicators in the Mineral Industry. The forum organizes a series of conferences that help enable transition of traditional mineral industries to more conservation-minded industries that have as goals sustainable development and conducting business in a way in which environmental conservation is essential.

The Mining Cadastre of South Sudan was sponsored by the Australian government and has been administered by a South African company that, before the

system was installed, organized training sessions for executives and staff of the Ministry of Mining in both Cape Town and Juba, respectively.

The Republic of South Sudan is a member of the Intergovernmental Forum on Mining, Minerals, Metals, and Sustainable Development, which supports member governments in resource governance and decision making. Other technical assistance includes capacity building, and I attended a recent event on this topic organized by the forum in Geneva, Switzerland.

In cooperation with the above-mentioned institutions, I have been implementing the acquired knowledge and expertise in managing the mining sector of the Republic of South Sudan. The republic was declared open for mining business in 2015, after the Mineral Title Regulations were reviewed and enacted. More than 50 exploration licenses have been granted to companies since then.

Since 2015, the mining sector has been operating independently under a separate Ministry of Mining, which has a mandate to promote exploration, production, and sustainable development of the mineral resources of South Sudan.

### **Management of Mineral Resources**

Management means optimizing the use of human and material resources, together with financial and other contributions, in effecting policy goals. Sustainable mineral-resource management is thus a process for implementing the sustainability principles expressed in a sustainable minerals policy.

Management of mineral resources is not only vital to economic growth of a country but is also important for the country's social and environmental sustainability. The role of mineral resources has been important in global politics because global powers are influenced by the ownership of such resources. Consequently, management of mineral resources has become an important responsibility of governments.

Management of the mineral resources of South Sudan as a sovereign country has been mandated by the government to the Ministry of Petroleum and Mining, whose vision is to create a country in which mining plays a significant role in the economy, employment, and social fabric of the country, and to help diversify revenues away from oil (South Sudan mining policy; Republic of South Sudan, Ministry of Mining, 2013).

In building its capacity of “good governance,” the Republic of South Sudan has joined several international institutions that are offering professional consultation and training for decision makers in the field of natural resources. The ideas and principles acquired from these institutions have been useful in guiding the government in developing its mineral strategic plan.

### *Mineral Resources Governance*

Management of mineral resources involves strengthening of legal and regulatory frameworks as a first step, followed by transparency and accountability in implementing the various stages of the mine life cycle. Below are examples of “best practices in governance of mineral resources,” which could be used as guidance in this respect.

The first example of such guidance is extracted from the “Natural Resources Charter,” a product of the Natural Resources Governance Institute (2014). The general overview of the charter is displayed in Figure 5.1.

To help governments make decisions, the charter contains 12 precepts. The first 10 precepts provide guidance on how a country and its government might manage natural resources. The last two precepts speak to international actors—extractive companies and those responsible for international governance.

Other sources of guidance include the International Institute for Sustainable Development in Canada and the Canadian International Resource Development Institute in Vancouver ([www.cirdi.ca](http://www.cirdi.ca)), which provided the framework shown in Figure 5.2.

The Republic of South Sudan has recently joined the Intergovernmental Forum on Mining, Minerals, Metals, and Sustainable Development, which is a voluntary initiative supporting more than 60 nations committed to leveraging mining for sustainable development to ensure that negative impacts are limited, and financial benefits are shared. Members have access to several resources, including the forum’s “Guidance for Governments, Mining Policy Framework” and capacity-building and training opportunities ([www.igfmining.org/guidance-for-governments](http://www.igfmining.org/guidance-for-governments)).

After digesting the various scenarios of integrated resource management and sustainable development, we can conclude that starting with exploration and discovery, then extraction, followed by management of revenues, and ending with sustainable

investment of revenue for the prosperity of the nation constitute the most important pillars of sustainable development.

Mineral supply chain or the life of a mine is a sequence of four major stages (Figure 5.3), which includes exploration and mapping of resources (discussed in the previous chapters), followed by development, production, and reclamation of the area.

These activities require proper management and compliance with best standards and practices, which are governed by policies and regulations set forth by the authorities in charge of minerals and mining in a country in its role of responsibility or management.

### *Regulatory Framework*

The business of mineral exploration, development, and production is risky and consumes both money and time before any revenue is generated. For investment, it involves stakeholders, and so setting a regulatory framework is a necessity to guarantee the rights of all stakeholders (International Institute for Environment and Development, 2002).

Considering these factors, the authorities in the Republic of South Sudan have introduced laws and regulations that streamline the process and at the same time reduce/remove the risk and other impediments that confront investors, including reducing bottlenecks to exploration and changing mineral fiscal regimes, as well as providing investment incentive packages that include tax and custom exemptions.

The government started its mission of fostering a climate that supports and encourages internal and external investment in the minerals and mining sector by drafting mining laws and regulations in collaboration with Adam Smith International, U.K. The regulatory process led to drafting of the “Mining Policy for South Sudan” (Republic of South Sudan, Ministry of Mining, 2013), which contains the following provisions:

1. “This policy applies to all mineral-related activities undertaken by the Government and private sector, including geological data gathering, mineral exploration, mining, beneficiation, smelting, environmental impacts, mine closure, social impacts, and community development.
2. “It includes all mineral resources except that artisanal mining for State Natural Resources shall be regulated by the States.

3. “Mining legislation shall pay due regard to Constitutional requirements and to other enacted laws of South Sudan.”

The “Mining Policy” paved the way for the Mining Act of 2012 (Republic of South Sudan, Ministry of Mining, 2012), which was followed by the Mining (Mineral Title) Regulations of 2015, which provided detailed and comprehensive regulations including official forms, general regulations, regulations to ensure that communities benefit, health and safety regulations, and a model exploration and mining agreement. The Mining (Mineral Title) Regulations of 2015 became the main regulatory tool for the management of national mineral resources through a licensing system whereby qualified companies are awarded mineral titles to search for minerals and undertake mining in return for explicit and enforceable obligations.

Apart from the mining laws and regulations, there are the fiscal regime and the investment incentive package, including tax and custom exemptions, which are being offered to the mining companies. There is also a guide prepared to encourage and facilitate investment opportunities for international firms who are interested in the mining business.

Learning from the bad experiences of some African countries in randomly granting licenses and permits, the Republic of South Sudan cancelled all previously granted mineral titles/licenses and instead declared new concessions for mineral exploration, thus avoiding conflicts between the government and companies holding past licenses or contracts. Previously in the Democratic Republic of the Congo and Liberia, the government was confronted with issues of renewal of past contracts that were granted by various agencies (Bekoe and Parajon, 2007).

#### *Transparency and Accountability*

An essential component of accountability is transparency, and so the government should disclose information about the whole chain of decisions made in compliance with what has been referred to in the “Natural Resource Charter” (Natural Resource Governance Institute, 2014). In applying principles of transparency and accountability to the mining sector, the Republic of South Sudan has implemented the Extractive Industries Transparency Initiative, by granting Mining (Mineral Title) Licenses using the online “Flexicadastre” system produced by Spatial Dimension Inc. of South Africa. The

system facilitates transparency and assists in decision making involving other stakeholders, such as local communities and civil societies, hence curbing the expected social and environmental impacts of mining.

The Flexicadastre system is a solution used to implement Mining Cadastre Systems to facilitate all aspects of the application, evaluation, granting, and compliance monitoring of mineral rights and related permits, as well as using the system to facilitate application and concession management ([www.spatialdimension.com](http://www.spatialdimension.com)).

Utilizing the Flexicadastre system, the Republic of South Sudan has been granting licenses to transnational and international companies since March 2015, and the projected number could rise dramatically in a short period given the boom in mineral exploitation in the region. The online portal of the South Sudan Mining Cadastre ([portals.flexicadastre.com/southsudan](http://portals.flexicadastre.com/southsudan)) allows the public to follow the progress in the various stages of granting licenses to investors in the mining sector. The Republic of South Sudan is one of only 15 countries in Africa that are currently using the Extractive Industries Transparency Initiative cadastre system.

South Sudan has joined the East African Community and therefore adopted the legal framework and constitution of the community (e.g., the Mining Bill). It is also a member of the International Conference on the Great Lakes Region, which has a protocol against illegal exploitation of natural resources implemented by the Regional Initiative Against the Illegal Exploitation of Natural Resources.

Tools for implementing the initiative include:

- “The establishment of a regional mineral tracing and certification scheme
- “The domestication of the Protocol and the harmonization of mining legislation
- “The creation of a regional database to track the production of and trade in minerals
- “The formalization of ASM [artisanal and small-scale mining]
- “The promotion of EITI [the Extractive Industries Transparency Initiative] within the region
- “The establishment of a mechanism to facilitate and protect whistleblowing.”

The Ministry of Mining publishes annual reports of the country's mining and quarries activities and production by compiling reports it receives from the licensed companies investing in the mining sector, in addition to reports produced by its Mining Inspectorate.

### **Sustainable Development of Mineral Resources**

Mining, minerals, and metals are important to the economic and social development of many countries. The sustainable development of them requires actions at all levels.

Mining has an important role to play in achieving the United Nations' "Sustainable Development Goals" (United Nations Development Programme, 2019):

"Goal 1. End poverty in all its forms everywhere.

"Goal 2. End hunger achieve food security and improved nutrition and promote sustainable agriculture.

"Goal 3. Ensure healthy lives and promote well-being for all at all ages.

"Goal 4. Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all.

"Goal 5. Achieve gender equality and empower all women and girls.

"Goal 6. Ensure availability and sustainable management of water and sanitation for all.

"Goal 7. Ensure access to affordable, reliable, sustainable and modern energy for all.

"Goal 8. Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all.

"Goal 9. Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation.

"Goal 10. Reduce inequality within and among countries.

"Goal 11. Make cities and human settlements inclusive, safe, resilient and sustainable.

"Goal 12. Ensure sustainable consumption and production patterns.

"Goal 13. Take urgent action to combat climate change and its impacts.

“Goal 14. Conserve and sustainably use the oceans, seas, and marine resources for sustainable development.

“Goal 15. Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss.

“Goal 16. Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels.

“Goal 17. Strengthen the means of implementation and revitalize the global partnership for sustainable development.”

### *Socioeconomic Development*

Community definition of sustainability is developing the capacity (human, economic, and social capital) to achieve the quality of life that we desire. This involves investing in people, their education, organizational and administrative skills, business development, and, most important, social and cultural activities identified by the community (Sustainable Development in the Minerals Industry, 2015).

Private investment is the driver for economic growth, but to be socially responsible investment should abide with best practices, which include respecting and obeying the law, making ethical business decisions, respecting and protecting the environment, respecting and protecting the rights of people, assisting local populations to improve their lives, allowing the involvement of local stakeholders, and contributing to sustainable development (Sustainable Development in the Minerals Industry, 2015).

Mining projects are sources of livelihood and well-being for millions of people (Jennings, 2003). For emerging nations such as the Republic of South Sudan, these projects attract foreign direct investment, domestic investment, foreign earnings, and government revenues. At the local level they provide an opportunity for employment, support for entrepreneurs to provide goods and services needed by mining activities, and contribute to infrastructure and services in the local community (International Council on Mining and Metals, 2019).

Mining as a source of profit to indigenous people of South Sudan has been known since pre-colonial times, especially in the area of Kapoeta, which borders Ethiopia,

Kenya, and Uganda; gold has been traded across the border for exchange for the local inhabitants' needs. As a source of income and wealth for families, the mining activities have been accompanied by many challenges related to land ownership, community rights, government interference, and mining companies' liabilities (Bebbington and Bury, 2009). Currently, artisanal mining activities have widely spread to almost all the mountainous areas in the country following the 1980s gold rush in the neighboring countries of Democratic Republic of the Congo, Uganda, Kenya, and Central African Republic. Unfortunately, mining was utilized as a source of fueling armed conflicts in this region that is famous for rebels opposing incumbent rulers (Carpenter, 2009).

Following the secession from the Sudan, the Republic of South Sudan started paying much attention to the petroleum sector since its gross domestic product depends mainly on oil (98 percent). Given that oil prices fluctuate in international markets, the republic planned to utilize the country's mineral resources for diversifying the economy. To be on the right track, the Ministry of Petroleum and Mining assigned the mining sector the authority to implement the country's strategic mineral plan.

The government, in collaboration with some nongovernmental organizations, began enlightenment of the concerned communities on the regulatory framework, the importance of dissemination of information, as well as community engagement in policy and decision making. This vitally important activity started before the declaration of mining concessions for business or before granting of mineral titles to companies following the signing of the Mining Regulation in March 2015.

Apart from the regulatory framework, the communities were informed of the impacts of mining operations, including a variety of social risks such as resettlement and in-migration, loss of traditional livelihood, poor governance in relation to deterioration of basic services (education, health, transportation, etc.), human rights and gender-related issues, in addition to conflicts arising from employment opportunities and distribution of wealth from mining.

This enlightenment process was aimed at avoiding conflicts that might arise from the risks mentioned above, as well as to bridge the expected gap between the companies and communities concerned. The government has adapted the "Good Practice Guide," which was published in March 2011 by the International Council on Mining and Metals,

and highlights good practice principles. The guide discusses the challenges in applying these principles at the operational level and provides real-world examples of how mining projects have addressed these challenges. The “Good Practice Guide” is not intended as a one-size-fits-all, but is designed to provide useful information and direction for both companies and indigenous communities when considering issues around engagement and participation, agreements, impact management, benefits sharing, and dealing with grievances (International Council on Mining and Metals, 2011).

The Republic of South Sudan, in compliance with the social development guidance adapted from a variety of international institutions, has mandated the Corporate Social Responsibility program as a prerequisite for obtaining title licenses. A company must submit to the cadastre officer a Corporate Social Responsibility program, which it must promote as part of its decision-making in support of South Sudan citizens, especially women and youth, the environment, and fiscal operations. This is done prior to signing a Community Development Agreement, which is usually reached after a series of meetings with the host communities (Figure 5.4). The agreement would be made accessible to the public during working hours at the cadastre office or online through the South Sudan Mining Portal ([portals.flexicadastre.com/southsudan](http://portals.flexicadastre.com/southsudan)).

In implementing the legal framework, the government conducted a series of workshops, seminars, and meetings at various levels, including national and state governments, local communities, and nongovernmental organizations. This was considered a first step in preparedness for conflict resolution. Some of the enlightenment activities have been depicted in Figure 5.5.

A question always arises about who is responsible for sustainable development in the mineral prospect areas. Mining companies have often been at the frontline as far as sustainable development is concerned, rather than the government (Contreras, 2004). In the case of the mining industry, governments have the responsibility of regulating development in order to protect the environment and save resources for future generations (Kabir, 2005).

Among the main challenges in the development of a mining community is the formalization of artisanal and small-scale mining, a task undertaken by the Republic of South Sudan to avoid future consequences of artisanal and small-scale mining taking

place in the neighboring countries of Sudan, Democratic Republic of the Congo, Uganda, and Central African Republic.

Artisanal and small-scale mining consists of those activities that exploit mineral deposits that allow for simplified forms of exploration, extraction, processing, and transportation (Hilson, 2002). It is a form of mining in which the exploration and exploitation phases can occur simultaneously and in which all phases of the mining cycle can involve low capital-intensive and high labor-intensive technology (Hentschel et al., 2003; International Institute for Environment and Development, 2002). This type of mining can include men and women working on an individual basis, as well as those working in family groups (Figure 5.6), in partnership, or as members of cooperatives or other types of legal associations and enterprises (Barreto, 2011).

Formalization is an essential prerequisite for facilitating support of any kind for artisanal and small-scale mining (Lowe, 2006). In line with that, the Republic of South Sudan has taken the important step of regulating artisanal and small-scale mining by issuing a regulatory framework (Republic of South Sudan, Ministry of Mining, 2015) for that kind of mining activity. The main challenge is differentiating between artisanal and small-scale mining and large-scale mining. Consequently, some proposed regulatory frameworks follow the same requirements as those for large-scale mining, leading to complications in implementation. For instance, until the 1990s, only a few countries had regulated their artisanal and small-scale mining—e.g., Brazil (1968), Papua New Guinea (1975), and Ecuador (1975). The delay in formalization has been attributed to lack of state regulations (Hilson, 2001; Barreto, 2011).

In South Sudan, the regulatory framework gives exclusive title ownership of artisanal and small-scale mining to nationals, with some exceptions for locally incorporated or registered corporations (with a specific percentage of shares by nationals). It also gives consideration to the location and area of operation, its size, license duration, and renewal.

Formalization of artisanal and small-scale mining is a process, not a one-off action or law, as some international experts have insisted (Barreto, 2011), and it may deliver positive outcomes only if effective coordination between institutions is guaranteed. Consequently, participation of local authorities and communities in any

decision-making processes is important, to ensure inclusion of their specific matters of concern. Examples include community demands for services of health, education, and water.

Such ambitious legislation needs effective monitoring; otherwise, lack of political will, insufficient financial and human resources, corruption, and conflicts of interest of stakeholders may make these regulations ineffective, if enacted at all (Hentschel et al., 2003).

Formation of cooperative societies and associations for women is an effective means of organizing the local communities to facilitate formalization of artisanal and small-scale mining (e.g., in Bolivia and Brazil). Participation of women in artisanal and small-scale mining is generally high—75 percent in Guinea; 50 percent in Madagascar, Mali, and Zimbabwe; and 40 percent in Bolivia (Hilson, 2001; Hentschel et al., 2003). Empowering women in these communities could lead to substantial alleviation of poverty, because women tend to spend wisely on family more often than men. Precautions should be taken in operations that involve hazardous materials that could affect unborn or breastfed babies, however.

Cooperative societies are voluntary associations owned and managed by and for the benefit of individuals who are not employees, whereas in the case of mining companies the workers are “employees,” not owners or partners, and do not have rights in decision making (Barreto, 2011). Given that most of the economic relationship between the mines is more typical of a formal company, there is a necessity for the miners to engage in different types of legal entities (e.g., family business, solo company, consortium, joint venture, etc.). Unfortunately, the idea of cooperative societies has some contradiction with tribal and cultural beliefs about people having good or bad luck. Presumably, these two categories of people cannot have or share common interest. Assuming that bad luck will ultimately prevail, there will be no profit.

It is important for the government to be able to hold these legal entities responsible to the head or chairperson of the respective community regarding issues of health, safety, and the environment, as well as child labor. Government coordination and cooperation with the legal miners is also easier. Considering incentives to cooperatives, enterprises, and associations in the form of financial services (e.g., loans, capacity

building or training, and technology transfer) will encourage formalization of artisanal and small-scale mining (Hentschel et al., 2003). Other incentives to remove obstacles in the formalization of artisanal and small-scale mining are discussed in Table 5.1.

### *Environmental Impacts in the Mining Sector*

Mining inevitably disturbs the environment at various stages of the mine life; i.e., exploration, development, production, and closure (Clark, 1995). The land, water, air, and host community are impacted as well.

The government has taken the responsibility of enforcing regulations on companies to use cutting-edge technology in order to reduce the damage to the environment caused by mining-related sources. In addition, the government requires companies to submit an environmental impact assessment prior to obtaining licenses.

In an attempt to reduce environmental impacts caused by mining, various stakeholders (governments, companies, universities, civil societies, and communities) need to do many things, including:

- Employ exploration methods characteristically of low impact to the environment, such as airborne and ground geophysics, satellite imagery, and remote-sensing techniques for geologic mapping.
- Use environmentally friendly drilling equipment during feasibility studies.
- Employ standard mining techniques as much as appropriate to the type of ore deposit (e.g., open-pit, underground, *in situ* leach, heap leaching, and brine mining).

Mineral extraction is commonly associated with a variety of environmental problems (Clark, 1995), including water pollution, radioactive tailings, erosion, sinkholes, biodiversity loss, and soil contamination, all of which require strong involvement of governments through implementation of stricter regulations or best practice standards set out by the International Council on Mining and Metals and the Extractive Industries Transparency Initiative.

Currently, no mines have been developed yet in South Sudan, which makes it easier for the authorities to assure compliance with environmental regulations before the start of any major mine development. In preparation for tackling environmental impacts, I

attended training at the Canadian International Resource Development Institute ([www.cirdi.ca](http://www.cirdi.ca)) in Vancouver, Canada, during which we visited a copper mine; this visit was effective in helping me understand how to tackle environmental impacts, as shown in Figure 4.7.

Artisanal gold mining is widely practiced in the Republic of South Sudan without use of any chemicals, as has been reported by the Mining Inspectorate in the Ministry of Mining. This could be attributed to the strict regulations and enlightenment of the tribal chiefs, community elders, and local government administrators. There have been frequent attempts by immigrant workers from the Darfur region of Sudan to use mercury in extracting gold, but in most cases, they have been prevented by the local authorities and the community to the extent of ordering violators to leave the area immediately. Other illegal mining activities have been practiced by Europeans, Americans, and Asians who tried to legitimize their work by signing local agreements with community chiefs. Such actions have been halted during the community sensitization campaign that followed enactment of mining laws and regulations in 2015.

Small-scale gold mining companies have been granted licenses to operate using centrifugal concentrator machines as a start to mining activities. These companies must operate in compliance with all relevant government laws and regulations for the protection of the environment. Where such laws and regulations do not adequately protect the environment, best contemporary practice in environmental management standards shall be maintained in conjunction with effective exploration, regardless of the location of operations.

The Ministry of Environment in the Republic of South Sudan, in cooperation with the United Nations Environmental Programme, has prepared guidelines for environmental protection in South Sudan.

## **Conclusion**

Sustainable development as a result of mineral exploitation requires responsible management of the resource by all stakeholders: government, companies, civil societies, and community. This is demonstrated by the global call for high standards of performance regarding mineral exploitation, environmental and community issues, transparency, as well as participation of all stakeholders in decision making.

South Sudan has adapted several regional and international legal frameworks to sustainably develop its mineral resources in order to contribute effectively to the national economy and help diversify the country's dependence on oil revenues, which amounts to about 98 percent of the country's gross domestic product.

Focusing on identification and mitigation of the negative impacts on society and environment that have been the dominant practices of mining companies in past decades or centuries in neighboring countries, the Republic of South Sudan is requesting that mining companies submit an environmental impact assessment and an agreement with the host communities before the Cadastre Office in the Ministry of Mining grants a license. South Sudan is planning to apply an agreement with host communities similar to a practice called "social license to mine" that is being applied in Canada and other developed countries.

Most communities inhabiting the basement complex along the border with Kenya, Uganda, Democratic Republic of the Congo, and Central African Republic practice artisanal mining as a source of livelihood and economic empowerment, even though there are no proper laws regulating their activities. The disadvantages of artisanal mining include harsh working conditions, environmental degradation, gender-based violence, and child labor, in addition to other crime and health issues.

Mining activities in South Sudan, as in other African countries, involves the government providing protection to company personnel and properties. The deployment of security and sometimes military personnel causes concern for civil organizations, however, because the hosting communities often complain of restricted access to roads, forest, and water sources. Intimidation and threats of mass resettlement are other issues that the government should seriously take into consideration.

Combining adequate management, good governance, best practices in environmental protection, and community development by all stakeholders, including government, companies, and civil societies, will ultimately lead not just to sustainable mining but to the effective contribution of mining to sustainable development and prosperity of the nation of South Sudan.

**Table 5.1.** Impediments and incentives to promote formalization of artisanal and small-scale mining.

Impediment	Incentive
<ul style="list-style-type: none"> <li>◆ Complex bureaucratic procedures.</li> <li>◆ Lack of knowledge and proper regulatory and fiscal regimes.</li> <li>◆ Traditional and cultural practices—e.g., operating individually and illegally without seeking permits; chieftaincy systems.</li> <li>◆ Miners have to travel to large centers to apply for license or renewals.</li> <li>◆ Free access to most convenient buying agents (including non-licensed) as informal enterprises.</li> <li>◆ Rare visits and inspections of artisanal and small-scale mines by the authorities.</li> <li>◆ Corruption and lack of transparency and accountability.</li> </ul>	<ul style="list-style-type: none"> <li>◆ Simplified licensing processes.</li> <li>◆ Provision of knowledge transfer, capacity building, and financial credits.</li> <li>◆ Enlightenment of communities to increase local participation, including traditional and local authorities, in initiatives linked to formalization.</li> <li>◆ Providing decentralized support to miners in the formalization process, including ease of renewals of licenses for long periods.</li> <li>◆ Government agent (e.g. Bank of South Sudan) purchasing commodities at a higher price than informal markets.</li> <li>◆ Decentralization of offices to mining areas, for closer inspection and monitoring. Also, upgrading miners' skills to monitor health, safety, and environmental practices, as well as gender and child labor violations.</li> <li>◆ Exercise Extractive Industries Transparency Initiative in licensing and management of the sector.</li> </ul>

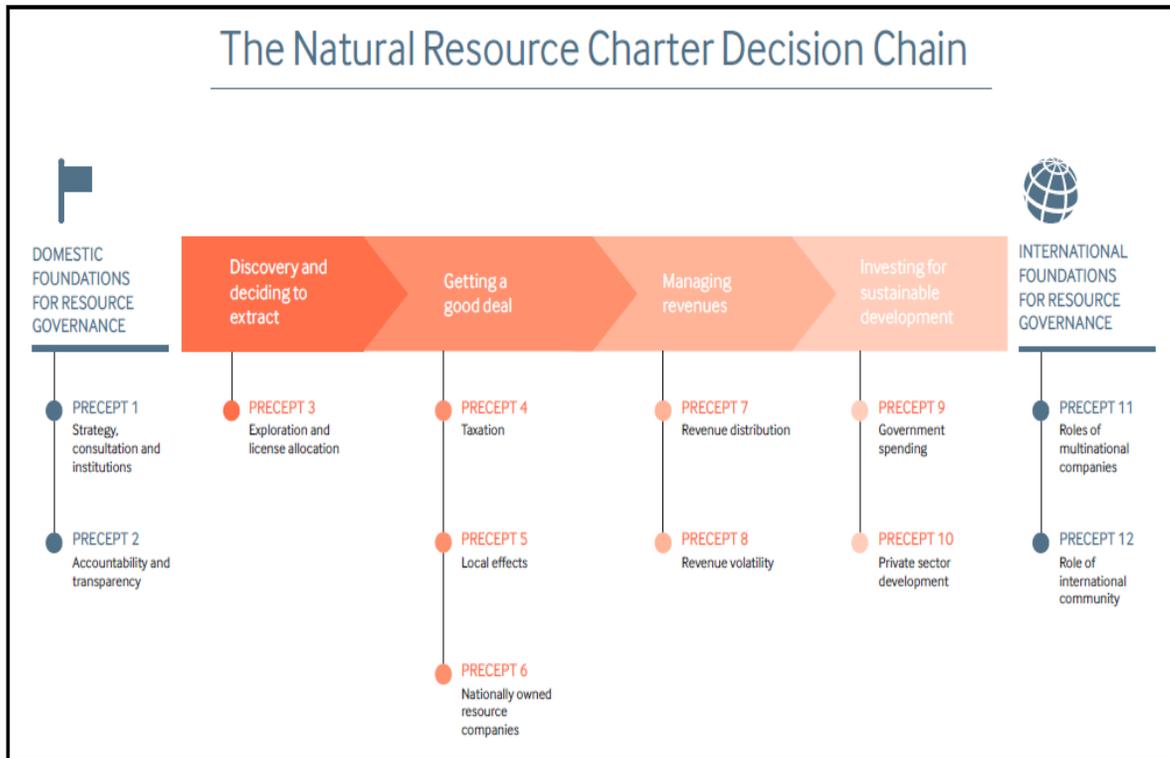


Figure 5.1. Illustration of the Natural Resource Charter (from Natural Resource Governance Institute, 2014).

# Resources and Development Governance Framework

Supporting Sustainable Livelihoods and Cultural Diversity				
Integrated Resource Management				
Natural Capital	Human & Intellectual Capital	Social Capital	Financial Capital	Manufactured Capital
Resource Endowment Delineation & Assessment	Health & Safety	Human Rights & Gender	Resource Rent & Taxation Regimes	Infrastructure Development
• Biodiversity	Community Health	Culture, Traditional Knowledge & Spirituality	Revenue Distribution Management	• Food Security
• Water	Skills Development & Livelihood Training	Community Engagement & Participatory Development	Financial System Policy and Management	• Water
• Energy	Leadership & Mgmt. Development	Governance Systems, Policies and Regulation	Sovereign Wealth Management	• Energy and Electrification
• Minerals		Sustainability Strategies	Transparency	• Tele-communications
• Air and Climate Change		Contract Negotiations	Anti-corruption	• Information Systems
Resource Planning		Conflict Management	Transfer Pricing	• Transportation
Environmental and Resource Stewardship		Organizational Structures	(Integrated) Reporting	• Minerals Stewardship
• Project Waste Management & Reclamation		Livelihoods & Employment		• Goods and Equipment
		Supply Chains & Procurement		Product Beneficiation
		Performance Management & Reporting		Cross-Sector Linkages

Governance Processes and Capacity Building

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Figure 5.2. Governance framework for resource development (Parker, 2015).

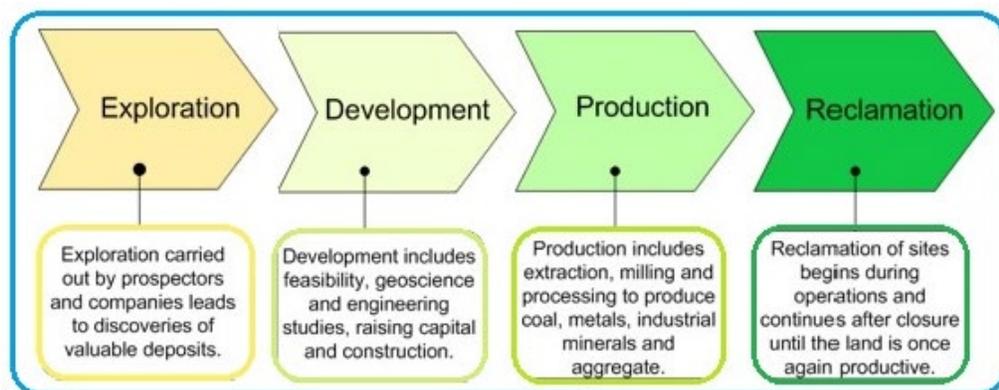


Figure 5.3. Mine life cycle (modified from Barreto, 2011).



Figure 5.4. Village community engagement meeting ([www.cordaid.org](http://www.cordaid.org)).



Figure 5.5. Enlightenment of Community Leaders workshop, Juba ([www.cordaid.org](http://www.cordaid.org)).



Figure 5.6. Artisanal gold mining in the Kapoeta area, showing women and children participating.



Figure 5.7. Produced water from a copper mine in Canada is treated and used for irrigation or as fish ponds.

## **CHAPTER 6: CONCLUSION AND RECOMMENDATIONS**

### **Conclusion**

In this study, freely available data such as satellite gravity and remote-sensing images have been utilized in preparing geoscientific maps that could be useful in mineral or petroleum exploration. These maps correlate well with available maps showing areas of artisanal mining, especially in the Eastern Equatoria region. Likewise, the sedimentary basins in the central part of the country are well depicted in the interpreted gravity anomaly map produced from the satellite gravity data. Satellite remote-sensing imagery of the southeastern part of the country has been processed, analyzed, and interpreted. The obtained results conform with the available maps of artisanal and small-scale gold mines of the region. The study proves the usefulness of applying satellite gravity and remote-sensing data to aid in mapping of mineral resources in the Republic of South Sudan, which is an important step for exploration and sustainable development of the mineral and mining sector.

The mining sector in countries throughout the world can contribute to global economic growth, as exemplified by its positive impacts on the lives of the communities, in which mineral extraction is considered to be the backbone of their economy. Poor management and development of potential mineral prospects is causing conflicts among governments, companies, and societies in most countries endowed with such natural resources, however.

Learning from the experience of resource-related conflicts in the region (e.g., in the Democratic Republic of the Congo and South Africa) and beyond (e.g., in Chile and Mongolia), the present study considers solutions that will suit the sustainable development of the mining sector in the Republic of South Sudan through good governance, transparency, compliance, involvement of all stakeholders in decision making, and equal and just sharing of information and profit.

The Republic of South Sudan, in compliance with the Extractive Industry Transparency Initiative, has introduced a cadastre system to grant licenses to companies interested in investing in the country's mineral resources. The system allows transparency and accountability and therefore combats corruption. In addition, in practicing good

governance, authorities have introduced a framework of laws and regulations to manage the development of mineral resources in the country, as well as provide fiscal incentives to investors in the form of tax and customs exemptions, among other benefits.

The mineral resources in South Sudan have not been mapped in detail, and the little information available to investors is historic geodata obtained by the colonial regimes (Britain, France, etc.) in the past. In an attempt to overcome that deficit in geodata, the Geological Survey in the Ministry of Petroleum and Mining has produced a national mineral resources prospectivity map by digitizing historic geodata, which were then combined with newly acquired geologic, geochemical, geophysical, remote-sensing, and artisanal and small-scale mining data. Although the World Bank has indicated that that initiative was encouraging to investors (EI SourceBook, 2012), proper airborne mapping of the shared basement rocks of the Congo Craton, extending from the Central African Republic to Uganda, in addition to the Arabian-Nubian Shield Neoproterozoic rocks along the border with Uganda, Kenya, and Ethiopia, is essential for better exploitation of the mineral resources in these rocks.

## **Recommendations**

Mineral development in the Republic of South Sudan started with the preparation of its legal framework (Mining Act of 2012 and Mining Regulations of 2015), whose main purpose was to promote the exploration, development, production, and utilization of the country's mineral wealth in order to effectively contribute to sustainable socioeconomic development of the country.

The main components for such development are the following recommendations:

1. Establish an authority (ministry) solely in charge of the mining sector, which would be structured to strengthen transparency and accountability or effective management of the sector and subsidiaries (e.g., state-owned enterprises). Being part of the Ministry of Petroleum means this authority has less attention and priority and is of secondary importance.
2. Upgrade the legal and regulatory framework for mining to best standards to encourage investors of serious intent, with best technical and financial capabilities, to profitably exploit the mineral resources of South Sudan while satisfying the expectations of the nation for prosperity. The simplest way to

achieve this is to harmonize the country's regulatory framework with the East African Community countries.

3. Develop a comprehensive plan for airborne and ground mapping of the basement rocks to produce detailed maps of base and strategic minerals, as well as rare earth elements. These maps could be offered to the private sector or as a joint venture with international organizations such as the World Bank, the U.S. Geological Survey, British Geological Survey, French Geological Survey, etc.
4. Coordinate or develop partnerships with specialized educational and research institutions in order to give easy access to information and geoscientific data that are stored in the Mining Cadastre and the Geological Survey of South Sudan database, so it can be used to improve the mining sector and prepare skilled and qualified employees for the mining industry.
5. Formalize artisanal and small-scale mining as a source of livelihood and economic empowerment for the local community. Community leaders would be assigned the responsibility of organizing their respective communities to operate artisanal and small-scale mining not as individuals, but as a group of people, much as associations or cooperative societies operate.
6. Protect the environment through a well-established inspection and monitoring system that enforces laws and regulations pertaining to health, safety, and the environment. Similar monitoring and enforcement of exploitive labor practices against women and children is essential throughout the exploration and mining process.
7. Provide free access to buying centers, and the government can assume a role in setting attractive prices for precious minerals as an incentive to discourage smuggling of precious minerals across borders. Such responsibility could be assigned to the country's financial institutions (e.g., the Central Bank) to be kept as reserve gold and so could strengthen the country's currency.
8. Add value to mining products (e.g., a refinery) to contribute effectively to the socioeconomic development of the nation.

This comprehensive study of sustainable development of mining and mineral resources in South Sudan starts with the essentials of exploration (geomapping), the regulatory framework, transparency in licensing, and accountability (governance) to the government-community-company relationship (sustainable development) and ends with environmental issues. Further research in relation to mineral resources in this underexplored part of the world will contribute effectively to eradication of poverty and conflicts (provision of peace), thus leading to the sustainable development and prosperity of these war-torn communities in the new country of South Sudan.

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  - Mineral Exploration Using Magnetic and VLF, in Darfur State, 1998
  - Geophysical Surveys in the Nubian Desert Gold Project Using Magnetic & Radiometry, 1998
  - Site Investigation of the Khartoum Oil Refinery Using Refraction Seismic, 1997
  - Merowe Dam Site Investigation on the River Nile, in Cooperation with Hydro-project Company (Russian), Using Seismic, Electric and Magnetic, 1995
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