3D geophysical modelling used for structural interpretation in the southern Mali and northeast of Guinea, West Africa

Mamadou YOSSI

Person Number: 565434

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DECLARATION

I declare that this dissertation is my own work. It is being submitted for the Master of Science Degree in Science in the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination in any other University.

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Mamadou YOSSI

______________Day of______________________2014.

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ABSTRACT

1.0. INTRODUCTION

1.1. Preamble

The exploration of first-order scale crustal structures is the main role of geophysical modelling for structures that have the potential to host gold mineralisation. This is now possible because of the evolution of airborne geophysics, which was developed in the 1980s to assist regional geological mapping (Jessell, 2001).

Geophysical data surveys are interpreted in two ways:

1. Qualitative interpretations to improve the data quality by reducing the non-geological noise that affects data from which anomalies may be defined (magnitude, direction, form). It is a mathematical manipulation of geophysical data (Mickus, 2008).
2. Quantitative interpretation facilitates quantification, i.e., it determines and estimates geological features, their depth, geometry, and block displacements. Quantitative interpretation facilitates the construction of a geological model that can better explain the geological phenomena of the sub-surface using existing geological information (if available). Forward modelling and inverse modelling are used to solve geophysical interpretations analytically or numerically.

Geophysical modelling provides a conceptual description of the sub-surface; it begins with simple models that may liberate analytical or numerical representations. The results of simple models can be used to select the type of geophysical method for future data collection. This stage is direct or forward modelling (analytical modelling), and the construction of a model from the data surveyed is inverse modelling (numerical modelling).

According to Wijns (2004), numerical modelling is affected by two factors including:

1. The *distance*, corresponding to the error between the initial and final model. This error is considered to be an accumulation of errors from the initial model to the final model, and is equal to the sum of errors from the beginning of the collection of data to the production of the model.
2. The *input parameters* that determine the final model. These parameters take into account the geometry, the physical properties, the rheological description, the approximate depth, and the thickness of the weathering profile. These factors increase the ability to interpret the final model that can explain the geological phenomena at depth.

To be realistic and consist in geophysical modelling for geological exploration, it is necessary to combine and integrate information from both geological and geophysical surveys (Lelievre, 2009).

The objective of geophysical modelling is to respond to the uncertainty and a non-uniqueness of solutions resulting from inverse modelling, and to constrain them. The main problem of inversion is the fact that several geological models can fit the same geophysical data, thus creating ambiguity when choosing a reliable model that matches and responds well to the real distribution of subsurface properties among a multitude of other solutions.

Also most geological structures are not detectable by only one geophysical method, which therefore requires a combination of several geophysical methods to constrain structures and geological domains. The combination of geophysical methods is an optimization that supports the geophysical interpretation and contributes in determining the geological elements that are important in developing an understanding of the subsurface geology. The limitation in optimisation is the cost of applying multiple geophysical techniques and methods.

With this in mind, this project aims to use a combination of geophysical methods for modelling by integrating the available geological data to build a 3D geophysical model of the study area, and to interpret geological structures and geological domains. Specifically, the aims are to (1) establish tectonic domains in the south of Mali and northeast of Guinea; (2) to determine if structures (shears, faults, etc.) beneath the thin sedimentary cover (up to 100m) potential to host structurally-hosted gold mineralization for known gold deposit; and (3) constrain a strato-tectonic history for the region of study from extracted geophysical attributes. Furthermore, this study will make comparison between gold-bearing structures that crop out at surface (e.g., at Syama Mine, Komana prospect, Morila mine and Kalana mine), with those under cover to search for potential gold exploration targets at depth.

1.2. Location and Physiography

The study area covers the south of Mali and the northeast of Guinea in West Africa (Figure 1.1). Geologically the study area is hosted in the Palaeoproterozoic Baoulé-Mossi domain of the West African craton (Figure 1.2).

The study area is bounded by 10° 13'N to 12° 47'N latitude, and 9° 60'W to 5° 55'W longitude. It covers an area of 114,750 km^2 mostly across the province of Sikasso in Mali and Sirgui in Guinea. It includes the 1:200,000 map sheets of Yanfolila, Tienko, Bougouni, Bamako east, Bamako west, Tingrela, Massigui and Nielle in Mali, and 1:200,000 map sheets of Siguiri, Sirakoro, Faraba, Kankan and Falama in Guinea (Figure 1.3) (IGN, 1993).

The topography in the east of the study area is dominated by a set of slightly inclined plateaus with low mountains and extensive plains. In the west of the study area, the topography is dominated by tabular massifs and cliffs that attain 900m elevation. Undulating plains occur between the massifs at 400 to 450m elevation above sea level. The cliffs of the Kenedougou massif rise to 800m.

Hydrographically, the Guinean portion of the study area hosts a number of rivers that have their source in the elevated plateaus of Guinea. These rivers include the Bafing River, Niger River (at Kouroussa, Siguiri) and its tributaries Sankarani, Fié, Tinkisso (at Faranah), Mafou, Dion and Niandan (in Kissidougou) and Milo (in Kankan). In Mali, the study area is traversed by the tributaries of the Niger River including the Sankarani in the north that debouches into the Niger River upstream of the city of Bamako, and the Bani which joins the Niger at Mopti after collecting waters from the Baoulé, Bagoé and Banifing rivers.

1.3. Objective

Most of the geological studies completed at the scale of the study area have typically been based on the interpretation of magnetic and radiometric data, or satellite images such as Landsat and Aster (Lohondère et al., 1999; Egal et al., 2002; Feybesse et al., 2006a). There are in fact, very few geological studies that combine geophysical methods apart from those at the regional scale designed for mineral exploration targeting and research. These include studies by Hasting (1982), Ritz (1986), Bonvalot et al. (1991), Toft et al. (1992), Tidjani et al. (1993), Mickus (2008), Hein (2010), Baratoux et al. (2011), Metelka et al. (2011), Miller (2012), Perrouty et al. (2012), and Tshibubudze (2014), and there is often limited integration of geological data into the geophysical interpretations; rather the geophysics constrain the regional geological interpretations. The majority of these studies needed to collect large primary geological datasets to be significant, but large primary datasets do not exist across all the Palaeoproterozoic of the West Africa craton, and certainly not in the study area. Regardless, studies which may have relevance to the field area include Baratoux et al. (2011) and Metelka et al. (2011), who interpreted the geology of the southwest Burkina Faso on the eastern margin of the study area map, and a compilation by Miller (2012) that forms the basis for geological constraints in the south of Mali and into the NE of Guinea.

The main aim of this project is to define and interpret the volcano-sedimentary belts of the study area, batholiths, and regional structures that correspond to known zones of gold mineralisation. Using geophysical 3D modelling the project will:

1. Undertake an advanced processing of combined geophysical and radiometric data, satellite images and topographic data to develop an interpretative geological map that can be compared with published geological maps to measure similarities and differences.
2. Identify structures, geological domains and the architectures of basins, and the basement in key belts.
3. Integrate geological data into the processed geophysical database to define the parameters for inversion modelling.
4. Process a 3D inversion of geophysical data constrained by the available geological information.
5. Test optimum inversion data parameters.
6. Produce a 3D model of the study area (or key localities) that could help to interpret deep regional geological structures and domains and perhaps suitable exploration targets.

1.4. Hypothesis

Geophysical modelling is never able to determine the exact geology in a complex zone, particularly if there is no geological information known for the area of study (Mickus, 2008; Lelievre, 2009). A geophysical model can only be used to characterise the subsurface geology, and to expand and verify the geological information already available, which can be confirmed with drilling of boreholes.

Geological information is qualitative and/or quantitative. It includes drill hole, lithological, geochemical, structural, and relative and absolute geochronology data. This information is collected from studies that precede modelling. Importantly geophysical models must be validated against the geological models to measure the usefulness of geophysical modelling for targeting in regions of geological difficulty, or under sedimentary cover. Geological data is certainly needed to constrain models which are derived from inverse modelling.

The available geological fact data for the study area has been extracted from maps and plans presented by Girard et al. (1998), Egal et al. (1999), Bentley et al. (2000), Standing (2006), Feybesse et al. (2006a) and Miller (2012) without extracting the accompanying interpreted data. Together with rock property data, the extracted fact data has been used to constrain the geophysical inversion model to:

1. Identify structures under sedimentary cover.
2. To evaluate which geological rock property data has more influence on the geophysical data inversion in the study area.
3. Established tectonic domains.
4. Establish a tectonic history based on relative chronology of geophysical events.
5. Characterise those structures under sedimentary cover that could control gold mineralization in the volcano-sedimentary belts and local batholiths and plutons.

1.5. Thesis structure

This thesis is divided in eight chapters including the Introduction.

Chapter 2 presents the regional geology of the study area.

Chapter 3 presents a review of geophysical methods used and modelling processes, and the methodology procedures. Also describes the image processing adopted in this study.

Chapter 4 is for data extraction from geophysical maps and geological fact data.

Chapter 5 is based on presentation of the geophysical modelling results in 2D and 3D.

Chapter 6 present the key zone interpretation.

Chapter 7 concerns the discussion of the study result.

The Conclusions are summarised in Chapter 8.

1.6. List of abbreviations

BRGM:	Bureau de Recherche Géologique et Minière.
DMA:	Defence Mapping Agency (USA)
DNRGH:	Direction National de la Recherche Géologique et des Hydrocarbures
DNGM :	Direction Nationale de la Géologie et des Mine.
GRAV:	Gravity or Gravimetric
GPS:	Global Positioning System
IGN:	Institut Géographique National (France)
MAG:	Magnetic
ORSTOM:	Office de la Recherche Scientifique et Technique Outre-Mer
TMI:	Total Magnetic Intensity
TTG:	Tonalite Trondjemite Granodiorite
WAC:	West Africa Craton

2.0. REGIONAL SETTING

2.1. West African Craton

The West African Craton includes the Reguibat Shield in the north of the craton and the Leo Man Shield in the south (Figure 1.1). These shields represent two nuclei which formed in two stages of crustal evolution in West Africa (Naba, 2007). The shields are overlain by three main sedimentary basins; the Tindouf basin in the north, the Taoudeni basin in the centre, and the Volta basin in the southeast of the craton.

The West African craton is considered as stable since the end of the Palaeoproterozoic at approximately 1.8 Ga (Kusnir et al., 1999). The Leo-Man Shield includes the Archaean Kenema-Man domain in the west and the Palaeoproterozoic Baoulé-Mossi domain in the east. The Palaeoproterozoic Kayes and Kedougou-Kenieba inliers are situated in the west of the craton between the Reguibat and Leo-Man shields. The Leo-Man Shield is divided into the Archaean Kenema-Man domain and Palaeoproterozoic Baoulé-Mossi domain. The Baoulé-Mossi domain is made up of linear greenstone belts composed of metamorphosed plutono-volcanic, volcaniclastic and sedimentary rocks, and TTG suite granitoids (Lompo, 2010).

2.2. Regional geology setting

2.2.1. The Archaean Kenema-Man domain

The Kenema-Man domain is marked by pre-Leonean granitic-gniessic basement, Leonean and the Liberian domain. The degree of regional metamorphism observed in the Kenema-Man domain attains amphibolite to granulite facies (Béssoles, 1977). The Leonean is composed of tonalite and granodiorite equivalent to TTG suite granitoids (Egal et al., 1999a, b). In contrast, the Liberian is characterized by granite, monzogranite, tonalite or granodiorite (Lahendere et al., 1999a, b).

2.2.2. Palaeoproterozoic Baoulé-Mossi domain

The study area is composed of metamorphosed clastic, volcanic and volcaniclastic sequences assigned to the Birimian Supergroup (Davis et al., 1994). The Tarkwa Group 2133 ± 4 Ma Pigois et al. (2003) and Perrouty et al. (2012) unconformably overlies the Birimian Supergroup (Tunks et al., 2004).

Two models have been proposed for the tectonic evolution of the granite-greenstone belts in the Baoulé-Mossi domain. Baratoux et al. (2011) assigned the major crustal thickening phase to nappe-stacking along orogeny-parallel thrust faults, while Lompo (2010) and Vidal (2010) interpreted a dome and basin geometry for the Baoulé-Mossi domain. The domain and basin geometry is interpreted to be the result of vertical magmato-tectonics.

The lithological composition and structural architecture of the Baoulé-Mossi domain has been discussed and described by Milési et al. (1991), Feybesse and Milési (1994), Hirdes et al. (1996), Egal et al. (2002), Lohondère et al. (2002), Hein et al. (2004), Naba et al. (2004), Feybesse et al. (2006b), Roddaz et al. (2007), Lompo (2009, 2010), Hein (2010) and Baratoux et al. (2011). The greenstone belts are composed of metamorphosed volcano-plutonic rocks of the calc-alkaline series (TTG suite), ultramafic-basalt-andesite units, and sedimentary and volcano-sedimentary rocks. TTG suite batholiths and granitoids are generally composed of tonalite, granodiorite, trondjemite and monzogranite.

The stratigraphy of the Palaeoproterozoic of Baoulé-Mossi domain was discussed by many authors (Hein, 2004 and 2010; Baratoux et al., 2011; Perrouty et al., 2012 and Waxi, 2013). According to these authors, the Palaeoproterozoic of Baoulé-Mossi domain stratigraphy can be established. The stratigraphy of the southern part of WAC includes: the pre-Birimian gneiss in the Oudalan Goroul Belt at about 2253±15Ma (Hein, 2013). The pre-Birimian is overlay in unconformity to the Neo-Archaean.The pre-Birimian is overlay by basalt in this area. The simplify model of the Baoule-Mossi domain was established by Baratoux et al. (2011) in the southwest of Burkina Faso. This model was characterised by basalt (tholeiitic and calco alkaline), gabbro, ultramafic lens, megacrystic basalt, andesite, pyroclastic flow, pyroclastic and volcaniclastics, dacyte and rhyoloyte, Birimian sediments and volcano-sediments; and finial the Tarkwaian composed of conglomerate, sandstone and arkose (Figure 2.1).

The metamorphism of the Palaeoproterozoic in the Baoulé-Mossi domain was discussed by many authors. They all indicated the presence of greenschist facies and amphiboloite facies. In Burkina, Debat et al., 2003 indicated three phase of evolution. These phases included greenschist facies metamorphism, following by granitoid emplacement causing the medium pressure of metamorphism. The last step was thrusting. As for Baratoux et al., 2014, the Southwest of Burkina is characterised by two phases. These phases include a regional greenschist to lower amphibolite facies metamorphism and intense folding in the early-Eburnean deformation. In Ghana, quartzite, pelite, quartzofeldspathic and granitic gneisses up to 2150Ma (de Kock et al., 2012) were found under static crustal condition. Several deformation episodes were also found.

According to the metamorphic data collected in Burkina Faso, SW Ghana and eastern Senegal by Ganne et al., 2014 the metamorphism of Baoulé-Mossi Palaeoproterozoic domain were established. The metamorphism of the Baoulé-Mossi domain is characterized by greenschist to amphibolite facies assemblage caused by moderate geothermal gradient of 20 to 30 degree Celsius by kilometre.

The structural style of the Baoulé-Mossi domain has been described by Davis et al. (1994), Hirdes et al. (1996) and Hirdes and Davis (2002). The domain is interpreted as having formed as (1) an accretion orogeny resulting from a collision of island arcs and oceanic plateaus with an Archaean craton, and (2) a phase of transcurrent tectonics characterized by regional scale faults (Lompo, 2010) and also a tectonic evolution of oceanic crust and continental crust with Archaean basement (Hirdes and Davis, 2002).

Tectonic events recognized in the Baoulé-Mossi domain include:

1. Deformation, during the Tangaean, Eburnean I and Eoeburnean at approximately 2190-2140 Ma as recognised in the northeast of Burkina Faso by Tshibubudze et al. (2009), Hein (2010) and Tshibubudze and Hein (2013), and in Ghana by Allibone et al., 2002; de Kock et al. (2011, 2012). This event corresponds to accretion tectonics and was accompanied by the emplacement of syn-tectonic TTG suite granitoids (Tshibubudze and Hein, 2013) from a subduction slab, or the mafic lower crust (Baratoux et al., 2011);
2. Deformation which corresponds to the Eburnean Orogeny at approximately 2130-1980 Ma (Feybesse et al., 2006b; Hein, 2010; Baratoux et al., 2011); and
3. Deformation which occurred during the Wabo-Tampelse Event (Hein, 2010) either in the late-Eburnean or the Pan African Orogeny at 1.1 Ga (Baratoux et al., 2011).

The structures produced from these tectonic events are characterized by the development of:

1. NW to NNW-trending fold-thrust belts, and NW-trending mylonite zones, shear zones and F1 folds (Hein, 2010; Perrouty et al., 2012; Tshibubudze and Hein, 2013);
2. Regional folds that trend NNE, sinistral-reverse shear zones, a penetrative schistosity, and dextral strike-slip faults (Feybesse et al., 2006b; Hein, 2010); N to NE-trending transcurrent faults that affect all lithologies and localized at the contact zones between the granites and greenstones (Baratoux et al., 2011);
3. Formation of WNW-trending dextral-reverse thrusts, E-W trending folds (Hein, 2010) and shallow N or S dipping thrust faults (Baratoux et al., 2011) during the Wabo-Tampelse Event.

2.2.3. Cover sequences

The Palaeoproterozoic of the Baoulé-Mossi is cover by Quaternary formation particularly the lateritic which occupied the third of the continent (Brown et al., 1994). The study area is covered by late formations including the Neoproterozoic, Mesozoic and quaternary formation (Kusnir et al., 1986, Egal et al., 1999; Feybesse et al., 2006).

The late formations of the study area are overlain the Tarkwaian group (2100Ma to 2070Ma) (Feybesse et al., 2006, Waxi, 2013) which is composed by conglomerate, sandstone and arkoses. The late formations of the study area according to (Feybesse et al., 2006) it included: (1) The Neoproterozoic which is characterised by unclassified formation overlay in unconformity to the Palaeoproterozoic. (2) Mesozoic composed of massif and dyke dolerite at about 200Ma (Lahondère et al., 1999a). They are also the Kimberlite at about 175Ma (Feybesse et al., 2006). (3) The recent formation characterised by quaternary formation include the ferricrete layer and alluvium which is composed generally by Silt and clay (Égal et al., 1999).

2.3. Architecture and geological setting of southern Mali and northeast Guinea

The study area in southern Mali and northeast Guinea is composed of metamorphosed sedimentary units including greywacke, siltstone and conglomerate that are intercalated with volcanic rocks (Liégeois et al., 1991).

The rocks of the study area are grouped from west to east into the Siguiri, Bougouni, and Bagoé basins, which are divided by greenstone belts including the Yanfolila, Massigui and Syama belts (Figure 2.2). They are unconformably overlain by the Neoproterozoic sediments of the Taoudeni basin.

The Siguiri basin is dominated by the Siguiri-Kankan Formation in Guinea, and is composed of siltstone, mudstone and subordinate arkoses, with pelitic schist (Egal et al., 1999; Lahondère et al., 1999). These sediments are intercalated with pyroclastites or tuffs that are composed of rhyolite and quartz lithic fragments (Lahondère et al., 2002). The basin is bordered by the Yanfolila granites in Mali (Figure 2.3).

The Yanfolila belt is the northwest-trending extension in Mali of the Ziemougoula volcano-sedimentary belt in Guinea and the Ivory Coast (Figure 2.2). The Yanfolila belt and several outliers are composed of massive mafic volcanic rock (Girard et al., 1998; Parker and Wilkinson, 2011). The Yanfolila belt is crosscut by the northerly trending Yanfolila shear zone in Figure 2.2 (Randgold, 2008) which separates the Siguiri basin from the Bougouni Basin.

The Bougouni basin (locally called the Bougouni-Kerekoro basin) is situated between the Yanfolila and Banifing shear zones (Figure 2.2 and 2.3). The basin is intruded by a TTG suite batholith located in the centre and north and granite plutons (Girard et al., 1998, Miller, 2013). The basin is composed of shale, sandstone, greywacke, and intercalated volcano-sedimentary rocks (Feybesse et al., 2006a; Parker and Wilkinson, 2011). The NW-trending Bougouni belt (Figure 2.2) of Girard et al. (1998) and Randgold (2008) is situated in the southeast of the Bougouni basin. The NE-trending Massigui belt of Girard et al. (1998) is situated in the NE of the basin and is composed of porphyry rhyodacites with basalt, breccia and conglomerate units (Kušnir, 1989; Girard et al., 1998).

The Banifing shear zone separates the Bougouni basin to the west from the Bagoé basin to the east (Figure 2.4). The northwest trending Bagoe volcano-sedimentary belt is the western extension of the Bondiali-Bagoé-Diaoula belt in Ivory Coast which splits to form the Bagoé volcano-sedimentary belt and the Banfora belt (Bessoles, 1977). The Bagoé belt has been subdivided into Syama belt at Syama (Girard et al., 1998), and the Kadiana-Madinani domain to the west of the Syama Shear Zone and the Kadiolo domain to the east of the Syama Shear (Standing, 2000).

The Kadiana-Madinani domain is interpreted by Bentley et al. (2000) as a back-arc basin that was accreted onto the Kadiolo terrane during the peak of the Eburnean orogeny (ca. 2.2-2.0 Ga). The

Syama belt at Syama can be divided into sedimentary sequences of the Tarkwa Group in the east, and volcano-sedimentary rocks of the Birimian Supergroup to the west (Girard et al., 1998). The NNE trending Syama Shear Zone crosscuts the Syama belt (Standing, 2006).

The structures that predominate in the study area include first-order scale crustal shear zones, and second-order shears, faults and folds. The Siguiri basin is dominated by north to NNE trending dextral strike-slip shear zones (Steyn, 2012), and a second order scale WNW trending faults. The Yanfolila belt is dominated by the northerly trending Yanfolila Shear Zone (Feybesse et al., 2006a; Randgold, 2008; Miller et al., 2013). The eastern margin of the Bougouni basin is bounded by the Banifing Shear Zone. The Kadiana-Manankoro greenstone belt is the eastern boundary of the Bagoé basin. It is represented by a contact that is faulted with gneissic rocks (Girard et al., 1998).

Metamorphism in the study zone is characterised by regional and contact metamorphic mineral assemblages. Regional metamorphism is characterised by mineral assemblages to middle to upper greenschist mineral assemblage (Tunks et al., 2004). Contact metamorphism is characterised by the amphibolite facies observed in the contact aureole of granitoids.

2.6. Geophysical interpretations in the regional scale

Regional scale geophysical studies have been conducted in Burkina Faso by Mickus (2008) and Metelka et al. (2010) and in the Gawler craton in Australia by Stewart and Betts (2010). A large scale study was the gravimetric analysis conducted in Burkina Faso by Mickus (2008). The goal was to control the relation between the gravimetric anomalies and metal deposits throughout Burkina Faso. This study highlighted the use of the geophysical datasets on a large scale and the use of geological data in direct modelling even in the absence of geological data.

The studies of Metelka et al. (2010) from the west of Burkina Faso demonstrated the importance of airborne data interpretation in reconstruction of the geology of southwest Burkina Faso where for the most part, there is little outcrop. It was possible to resolve lithology and structures.

The study in the Gawler craton in Australia by Stewart and Betts (2010) was based on the analysis of shear zones with interpretation of the geophysical data by direct modelling. Geological data was used as a constraint in building the forward model. The results of this study demonstrated that interpretations by forward modelling, across large regions with little or absent outcrop, can be extremely useful when building tectonic models.

In a similar way, this study will use large-scale geophysical airborne data for interpretation by modelling of southern Mali into northeast Guinea, as a case study region, where there is currently limited geological data.

3.0. METHODOLOGIES IN GEOPHYSICAL INVERSION MODELLING AND IMAGE PROCESSING TECHNIQUES

3.1. Introduction

Geophysical modelling has historically been the method by which applied geophysicists interpret geophysical data. Modelling is performed as forward and inversion modelling. Inversion modelling allows construction of a model using data collected during fieldwork.

Inversion modelling addresses the non-uniqueness problem (Tikhonov and Arsenin, 1977). The non-uniqueness problem was studied by Tarantola and Valette (1982), Li and Oldenburg (1996; 1998; 2000), Lelièvre et al. (2008; 2009) and Williams et al. (2009). They concluded that constraints in modelling were necessary as the only solution to non-uniqueness.

In this project, advanced processing of combined geophysical datasets was undertaken to create a 3D geophysical model. A work flow diagram is presented in Figure 3.1 and outlines the fundamental steps taken in the development of the 3D geophysical model in this study.

The geophysical data available for the study area includes gravity, magnetic, radiometric and limited electromagnetic data. The gravity and magnetic data were accessed as raw line data corrected from non-geological effects. Images were created using the GEOSOFT 6.4® gridding algorithm. Specific datasets included:

1. Public domain gravity data provided by M. Jessell of the University of Western Australia. The data were surveyed by ORSTOM (Office de la Recherché Scientifique et Technique Outre-Mer) in collaboration with DMA (Defence Mapping Agency) and IGN (Institut Géographique National). The gravity data is divided into two surveys (Albouy et al., 1989) with 4 km spacing between station points in Guinea, and 3 km spacing between station points in Mali. The Bouguer anomaly was calculated with the POTSDAM 1930 system for 2.67 densities. An example of the gravity data sheets is presented in Appendix A.
2. Magnetic, radiometric and topography data were acquired by SAGAX Afrique specifically for use in this project. In Guinea, the data were collected by High-Sense Geophysics Ltd for the Ministère des Mines Géologie et de l'Environnement de Guinée between 1997 and 1998. In Mali, the data was collected by Kevron Pty Ltd for the Ministère de Mines de l'Energie et de l'Eau between 2000 and 2001. The line spacing for both surveys were 400 m. The survey lines were orientated 135 degree north and 315 degree north, and 80 m for the average flight altitude. Base lines were 3000 m. Radiometrics were also collected at the same time with the magnetic data. Magnetic and radiometric data corrections were completed by FUGRO Airborne Survey Pty Ltd. An example of the data sheet is presented in Appendix B.

4. Electromagnetic data were acquired by SAGAX Afrique specifically for use in the project. The data was collected as part of the SYSMIN project, with surveys conducted in 2002 by the FUGRO Airborne Survey Pty Ltd. The electromagnetic (EM) data available covers only two portions of the study area: the Yanfolila volcano-sedimentary belt and the Syama belt (Figure 2.1).

5. Geological data was taken from public domain company technical reports, research work, and the SYSMIN project. In Guinea it included geological maps of the Sirakoro (Egal et al., 1999a; Costea et al., 1999), Siguiri (Egal et al., 1999b), Kankan (Feybesse et al., 1999), Falama (Lahondère et al., 1999a; Iliescu et al., 1999) and Faraba sheets (Lahondère et al., 1999b) (Figure 1.3). There are no geology technical reports available at the regional scale for Guinea. In Mali, maps include the Kadiolo or Niellé (Kusnir et al., 1986) Massigui (Claessens et al., 1988) and Kadiana or Tingrela sheets (Kusnir et al., 1989), and additionally the Yanfolila, Tienko, Bougouni, Massigui, Tingréla, Nielle, Bamako East and Bamako West sheets of Feybesse et al. (2006) (Figure 1.3) The reports include the geological map of Mali by Girard et al. (1998), the geophysical data interpretation of southern Mali by Randgold (2007, 2008), a technical report by Parker and Wilkinson (2011) and finally, a geological map produced by Miller et al. (2013) covering the entire study area (southern Mali and northeast of Guinea).

3.2. Data Constraints

The geological data available for the study area includes fact map data such as strike and dip of bedding and cleavage, lineation, absolute geochronological age data, and petrophysical properties. Interpreted data included polygon line data, the trend of structures and bedding, and interpretations of homogeneity within polygons. Interpreted data attributes for many published geological maps and reports have been extracted from magnetic and radiometric data; it is thus difficult to use these data attributes to constrain the inversion modelling. However, fact data were extracted to fact attribute files when fact data was recorded on maps, or raw fact map files were obtained. The geological data available can thereby be classified into three groups:

1. Qualitative data maps constructed from interpretation of magnetic and radiometric data (with limited fieldwork data to constrain the interpretation) included the SIGAFRIC map, Miller et al. (2013), and the magnetic data interpretations completed by Randgold (2007, 2008). The geological maps by Girard et al. (1998), and Parker and Wilkinson (2011) do not report raw fact data points and are classified as qualitative because they are effectively interpreted geological maps.
2. Qualitative data based on quantitative field data including maps by Kusnir et al. (1986; 1989) and Claessens et al. (1988), which were based on GPS georeferenced field data sampling point (Figure 3.2). For example, the SYSMIN project created numerous maps of West Africa but was based on extensive field data collection and validation. This fact data was extracted to

fact attribute files for input into the inversion modelling. These maps include those by Feybesse et al. (2006).

3. Quantitative data including petrophysical data (magnetic susceptibility and density) and lithological and structural datasets measured on the rocks at GPS georeferenced field data sampling point (Figure 3.3.).

3.3. Geophysical data processing and attribute extraction

In this study, images created from reprocessed magnetic and gravity raw line data were combined with radiometric grid data from SYSMIN. The gravity data were stitched to form one database and resampled. The gravity data included gravity values, Bouguer anomaly values and free air anomaly values. They were gridded using 1000m grid cells and 4000m for blanking distance to fill the dummy spaces. From this, gridding filters were used on the new resampled gravity grid to highlight geophysical attributes as discussed in this chapter. The minimum curvature algorithm in GEOSOFT 6.4® was used to grid the gravity data.

Magnetic data for Mali and Guinea were merged into a single magnetic database covering the entire study area. The geographical coordinates were calculated using GEOSOFT 6.4®, which helped to determine the inclination and declination of each point in the database. The magnetic image was created using minimum curvature algorithm in GEOSOFT 6.4® with 200 cell size. This grid was used for image processing.

Radiometric data for Mali and Guinea were merged into one grid. The potassium, thorium and uranium grids were created by FUGRO Airborne Survey Pty Ltd. They were compared with gravity and magnetic data to confirm attribute similarities.

The combined dataset were processed using edge detection filters with WinDisp® version 5.06 and GEOSOFT® version 6.4. Geophysical attributes were extracted after processing to create an attribute map (Figure 4.13). Attributes were ranked as very high, high, medium or low confidence (Table 3.1). A high level of confidence was awarded to attributes that occurred on all geophysical datasets while a low level of confidence was awarded to attributes that only occurred on one dataset. The highest confidence level map is shown in Figure 4.17. Key areas for inversion modelling were selected from this high confidence level map and included the **********.

3.4. Fact geology attributes extraction

Fact geology attributes (quantitative data) were extracted from georeferenced geological (raster) maps. Geological maps were compiled in MapInfo® version 11.0 or ArcGIS® version 10.03. Images from reports were imported into GEOSOFT® v 6.4 and georeferenced. All maps and images were georeferenced using WGS84 projection UTM Zone 29N. Arc-GIS® V10.3 was used to extract fact geological attributes in a number of attribute files. Extracted fact geological data was imported into GEOSOFT® v 6.4 and is presented in Figure 4.17. The extraction and integration are considered GIS work and is presented in Chapter 5. However, the key areas defined from geophysical attributes extraction constrained the fact geology used in inversion modelling. Thus, high confidence level geophysical attributes were combined with fact geology (and petrophysical data) for key areas as an input into the inversion modelling.

3.5. Geophysical Modelling

Modelling is defined in the broad sense as the model design. It corresponds with the spatial distribution of physical properties such as density, magnetic susceptibility, conductivity and other physical properties. The type of modelling is defined by the *objective* and the method used. Modelling can be mathematical, geometrical, mechanical and kinematic. It proceeds generally by using the available field parameters (fact geology and petrophysical data) as the constraint.

The modelling is characterized by:

1. D*irect modelling (forward modelling)* in geophysics involves finding the solution model by fitting iteratively the computed field to the field parameters until a good correspondence is found. These iterations correspond with trials where errors may be introduced. To reduce these errors a beginning model must be fixed according to the available field parameters. Forward modelling is controlled by the interpreter and supported by geological information that reduces the errors considerably. In this study, the magnetic field in nT (nano Tesla) was computed using the magnetic susceptibility and the gravity response in milligal was computed from the density values. WinDisp® simultaneous computes gravity and magnetic fields from the drawn polygon. All distances were reported in meters, density in g/cm^3 and magnetic susceptibility in SI.10^6.

2. I*nverse modelling* creates an algorithm based on the response of a particular geometry and calculates automatically the result. The algorithm permits the introduction of the field parameters (fact geology and petrophysical data) which controls the accuracy of the result. The main problem with this type of modelling is the fact that it depends on the input, i.e., qualitative data, qualitative data based on quantitative field data, or quantitative data. In this study quantitative field parameters were used as the only input. The schematic in Figure 3.4 outlines the framework of interaction between forward and inverse modelling.

In this research forward modelling was performed in key areas ******. *** was used to construct the forward modelling in 2D. Physical properties used are from the handbook by Telford et al. (1990) taking into account the petrophysical properties of the study area. The general formula of forward modelling is expressing by Equation 1, Appendix 3.4 after Lelièvre (2003).

However, the geophysical modelling is limited by factors such as the accuracy of data, the integration of parameters into the modelling, the use of simple geometries for modelling, the fact that the inversion……… and finally, the quality control of the modelling result is not possible without geological modelling.

3.6. Geophysical inversion

Geophysical inversion is an iterative mathematical procedure that can take several forms. The inversion is carried out using field parameters (fact geology and petrophysical data), and inversion algorithms that represent the basic tools for inversion (Telford et al., 1990). The outcome is the model. However, the model is limited by the inherent problem of non uniqueness of solution. According to the Gauss's law for gravity, two factors can explain the non-uniqueness of a model: -

1. A surface for which the potential field values are known (in this case gravity and magnetic) are not unique because there will be other bodies inside of this surface that will have the same values of potential field corresponding to those of the surface as a whole, e.g., two rock types which give the same potential field values.
2. Potentials field data are finite values that are not unique to a rock types or sub unit.

To resolve the non-uniqueness (in part), inversion algorithms must use the input field parameters to reduce the error between the measured field parameters and the calculated parameters.

Primary knowledge of the body should be used to constrain the solution space to the parameters used. The area of inversion can be divided into a number of cells of defined size and physical property. However inversion algorithms must always address three fundamental questions (Scales et al., 2001):

1. The degree of accuracy of the input data?
2. How accurately can we model the response of the system?
3. What are the known parameters on the system independent of measured input data?

In this project the inversion algorithm used is the code developed by UBC-GIF incorporated into WinDisp® software (Appendix 3.3).

The steps which have been completed for inversion in this study area include:

1. Determination of the inversion area for each geophysical attribute, in particular key zones where constraints are applied because more details on geophysical attributes should be completed to explain the architecture of the study area.
2. Smoothing of gravity and magnetic data using the mean filter of GEOSOFT® with five points in the window for magnetic data, and two points in the window for gravity data to reduce the noise on data.
3. Preparation of the input file for the inversion using Windisp® with X=150 m, Y=200 m and Z = 50 m on 5 km down for maximum depth. These dimensions were selected for inversion cell size

definition according to the survey point spacing. It allows a good resolution in 3 dimensions (X, Y and Z).

4. Execution of an inversion process using default parameters with 3DMag/Grav (3 dimension magnetic/gravity) interface of WinDisp®.

5. The solution space was constrained using the field parameters (fact geology and petrophysical data).

6. Presentation of the results of the inversion model and commentary about the accuracy within the solution space.

3.7. Image processing techniques

Image processing techniques are used worldwide in potential field studies to enhance detection of subtle features that cannot be identified on the conventional gravity and magnetic anomaly maps. They allow the extraction of the maximum information from geophysical data by transforming values into profiles, contours and grids (Milligan and Gunn, 1997). Image processing techniques are derived from mathematical principles from the geophysical data and are used to remove the unwanted information (noise) in the data to improve the signal-to-noise ratio (SNR). Prior to the application of the image processing techniques, the geophysical data are conditioned or smoothed through gridding and the SNR is consequently increased by applying different filtering methods (Milligan and Gunn, 1997). A gridding method is itself a smoothing filter; it uses different mathematical algorithms (e.g., curvature, inverse distance, add more) to transform the data into seamless and continuous images. Image processing techniques are applied in order to produce more explicit information from gridded potential field anomaly maps (Mickus, 2008).

Image processing filters commonly used in potential field data can be categorized into two groups of smoothing operators according to Milligan and Gunn (1997), namely:

1. *Linear filters*, which are defined as the weighted average calculation of the neighbouring data points. These filters obey the principle of superposition and homogenization. The filters general apply to grid processing. So it depends on the separated dimension and the link between the closing data points.
2. *Non-linear filters*; these are moving average filters and have been applied in both one and two dimensional studies. They compute the average of the amplitudes of the potential field at the sample positions within a specific window and remove high frequency background noise. In contrast to linear filters, they do not meet the principles of superposition and homogeneity.

The objective of using image processing filters in this study was to suppress any fluctuation, coherent or incoherent noise that is present in conventional maps such as total magnetic field and gravimetric data, or to remove noise introduced during field acquisition and initial processing workflow. These were computed to enhance detection of signals that correspond to specific gravity and magnetic anomalies. The data processing filters implemented in this study were the upward continuation, vertical derivative (vertical gradient), analytical signal, reduction to the poles, tilt angle, sun-shading, filters, hanning filter, mean filter and Automatic Gain Control (AGC). Colour shading was used to display certain grids in order to strongly highlight features on these images. The shaded colour has the same effect as sun-shading.

It is evident that using the filters on the whole image is not sometimes desirable. So to be consistence, it is better to apply filters to a small zone before applying on the whole image. Consequently fives (5) zones were selected across the study area to apply filters before using on the whole study area grid.

3.7.1. Vertical continuation

The vertical continuation is used to calculate the potential field at some altitude or depth from the plane on which the gravity or magnetic anomaly is measured. It allows the elimination of a range of wavelengths. The vertical continuation depends to the range of wavelength to be removed. Vertical continuation includes:

1. The upward-continuation defined by Gilbert and Galdeano (1985) as a low pass filter and it thus enhances low frequency components of the data at the expense of high frequency attenuation. Mathematically, the filter can be described as follows by Gilbert and Galdeano (1985) in equation 3.1

$$A_z(u,v) = A_0(u,v)e^{-kz} \qquad (Equation\ 3.1)$$

   Where k is the wavenumber and equal to 2μρ, z is the continuation height. The upward-continuation filter smooths the potential field data by highlighting the long wavelength through the elimination of short wavelengths. The short wavelengths could correspond to shallow sources while long wavelengths could result from deep buried sources. The upward-continuation filter was therefore used to remove shallow or near surface effects such as ferricrete, and enhance the regional deep features.

The upward continuation method seems to work quite well with the magnetic grid when compared with the gridded data from the same area.

2. Downward continuation filter increases the spatial resolution of the potential field data through the computation of the magnetic and gravitational fields with the measurements taken closer to the anomalous source. It enhances detection of shallow structures. This filter should be applied with caution, because it is not only the anomalies that are enhanced but the high frequency noise as well, and it is highly depended on the data quality and sampling spacing (Milligan and Gunn, 1997). The mathematical formula for downward continuation was established by Gilbert and Galdeano (1985) as.

$$A_z(u,v) = A_0(u,v)e^{kz} \qquad (Equation\ 3.2)$$

Where k is the wavenumber and equal to 2μρ, z is the continuation height, u and v are the anomalies parameters.

3.7.2. Vertical derivative

Vertical derivative filters are defined as the vertical rate of change in the potential field data. The vertical derivative formula is expressed in the time domain using gravity data by Equation 3.3 (Telford et al. 1993).

$$\frac{\partial g_z}{\partial z} = -\gamma\rho \iiint_{zyx} \left(\frac{1}{r^3} - 3\frac{z^2}{r^5}\right) dxdydz \qquad (Equation\ 3.3)$$

Where γ is the universal gravitational constant; ρ is the density, r is the distance, z is the value of the vertical axis.

These derivatives are often used in the potential field studies to enhance shallow geological features and sharpen edges. This filter is good at delineating linear and elongated features. The vertical derivative maps, shown in Figure 3.3, clearly show smaller and sharper anomalies than that shown in the total field intensity maps. This is owing to its responsiveness to local influences compared to regional effects. The inverse of the vertical derivative is simply the vertical integration of the field. However, the derivative filter is limited by the use of the derivative higher orders; in that case it becomes very sensitive to noise. In simply terms, the higher the derivative order, the more details are enhanced. However they are sensitive to noise, especially the line-levelling errors (Figure 3.4). Therefore, care must be taken when these filters are computed.

3.7.3. Analytic Signal Amplitude

The amplitude of the analytic signal is defined as the total gradient that is independent of the direction of magnetization, which is the representative of the envelope of both the vertical and horizontal derivatives. In fact, this implies that the amplitude of the analytical signal computed for the total magnetic field provides maxima over magnetic contacts regardless of the magnetisation direction. When computed for the vertical integral of magnetic field, it becomes similar to the strength of the magnetization. In the case of three dimensions, the amplitude of the analytical signal can be defined by Macleod et al. (1993) in Equation 3.4

$$|A(x,y)| = \sqrt{\left(\frac{DM}{dx}\right)^2 + \left(\frac{DM}{dy}\right)^2 + \left(\frac{DM}{dx}\right)^2} \qquad (Equation\ 3.4)$$

A is the analytical signal amplitude, M the magnetic intensity.

The equation 3.4 explains the absolute positiveness of its value, implying that it is not affected by the direction of the magnetic field inclination and declination. This filter allows the delineation of circular features such as intrusion and volcano sedimentary belts (Figure 3.5). Its effectiveness involves the location of all bodies of the same geometry in the same analytical signal (Milligan and Gunn, 1997).

3.7.4. The vertical integral applied on the analytical signal map

The vertical integration can be applied to the analytic signal to generate a transformed grid with the same units as the total magnetic field, but the effects of induced and remnant magnetization are almost the same vertical direction (Windisp, 2012). The equation of the vertical integral is presented in Equation 3.5 (Windisp, 2012).

$$f(r,s) = \frac{1}{2\pi\sqrt{r^2+s^2}} \qquad (Equation\ 3.5)$$

With r, s the parameters of the input function.

The application of the vertical integral on the analytical signal shows the limit of circular features. This smoothing operator also optimizes delineation of lithological contours, and it also defines volcanic belts, shear zone and faults (Figure 3.7). The results show less noise compared to the amplitude of the analytical signal (Figure 3.8). It is, however, important to always use the filters in combination to achieve better result.

This filter was applied only on the magnetic grid to enhance the main features and the relationship between the main features. The map also shows dyke intersections and other geological features such as shear zones and faults, which thus helps to understand and unravel the structural tectonic history of the area.

3.7.5. Tilt angle Filter

Tilt angle is a phase based filter that measures the local phase of the potential field data over images. It is mathematically defined as a ratio of the vertical derivative to absolute amplitude of the total horizontal derivative. This filter produces positive phase values when computed over the causative body, zero near body edges and negative outside the body. This filter is amplitude-independent and dimensionless, and has advantages over vertical derivative (Figure 3.9) because of its simple interpretative properties. It harmonises the potential field and show the positive potential field upon the anomaly source and negative potential filed elsewhere (Cooper, 2007). It is expressed by Equation 3.6 (Miller and Singh, 2005) quoting (Cooper, 2007):

$$T = \tan^{-1}\left(\frac{\frac{\partial f}{\partial z}}{\sqrt{\left(\frac{\partial f}{\partial x}\right)^2 + \left(\frac{\partial f}{\partial y}\right)^2}}\right) \qquad (Equation\ 3.6)$$

Where f is the potential field concerned

In this study, tilt angle was used for magnetic and gravity data to highlight linear structures. When comparing this filter to first derivative, it is much superior because it produces more detailed information for both deep and shallow structures. It appears sharper for gravity data than magnetic data due to the level of noise in the magnetic data. The tilt angle map for the gravity data highlights linear features that are not well enhanced by first derivative filters computed for the same data (Figure 3.10).

3.7.6. Automatic gain control

The automatic gain control filter is used to enhance the amplitude of short-wavelength anomalies without diminishing the long-wavelength anomalies (Rajagopalan and Milligan, 1995). The automatic gain control enables transformation of the input waveform (multiple amplitudes) into constant (semi constant) amplitudes. It balances the grid amplitudes. The choice of the window size plays a role in the quality of the final images (Cooper, 2007).

This filter was used on the gravity and magnetic data to highlight particular linear and circular features (Figure 3.11) and confirm continuity. Directional continuity of certain features were not clear using the automatic gain control. The mathematical approach of the automatic gain control is presented in Equation 3.7 (Rajagopalan and Milligan, 1995).

$$A_{xy} = (Gain_{xy})(f_{xy}) \qquad (Equation\ 3.7)$$

$$Gain_{xy} = \frac{1}{(2v+1)(2w+1)}\left[\sum_{i=x-v}^{i=y+v}\ \sum_{i=x-w}^{i=x+w} F_{ij}^{P}\right]^{r}$$

Where A_{xy} is the data after automatic gain control operation; F_{xy} correspond to the data to be analysed by automatic gain control. P is the power and r is the root

The term $\frac{1}{(2v+1)(2w+1)}$=to the window size.

4.0. GEOPHYSICAL ATTRIBUTES AND GEOLOGICAL FACT DATA EXTRACTION

Attributes were extracted from each geophysical image presented in Chapter 4 including upward continuation, first vertical derivative, analytical signal, vertical integral applied on analytical signal, tilt angle and automatic gain control applied on the TMI (Figure 4.1) and Bouguer anomaly (Figure 4.2). The attributes identified in these images were combined to establish a confidence level table (Table 3.1). Fact information was also extracted from geological interpretation and fact maps of Egal et al. (1999) and Feybesse et al. (2006). Key areas were selected using the confidence level, fact data of petrophysics data, as discussed in Chapter 3.

4.1. Attribute extraction from geophysical maps

Using the qualitative interpretation principle of Parasnis (1997), and also the pre-existing maps of the study area, attributes can be extracted from geophysical data and is equivalent to the qualitative interpretation of geophysical data. Thus, the principle of qualitative interpretation can be applied to attribute extraction methodologies.

In accordance with the Parasnis (1997) the first attributes that can be readily extracted from geophysical maps using the shape of anomalies include:

- Circular attributes or attributes of roughly the same extend in all direction. This type of attribute can be generally interpreted as granitic or basic intrusion.
- Long narrow attributes or lineaments are largely dykes, shear zone, and/or folds.
- Offset of attributes, where a displacement can be observed along the trend of the geophysical anomaly. This type of attribute can be interpreted as faults.
- Extensive anomalies with no regular pattern, but where the attributes can be delimited. This attribute can be interpreted as basaltic flows, large gabbro intrusive bodies and/or volcanic or volcano-sedimentary belts.
- Geophysically ‘quiet area’ with little relief in the field values without any distinct shape in the map. This type of region can be interpreted as quartzitic rocks formation, monzonite and/or limestone.

In addition, previous geological interpretations based on field data can be used to classify and named the geophysical attributes as an entity.

4.1.1. Upward continuation

The upward continuation of total magnetic intensity (TMI) map permitted the effective removal of the ferricrete layer (which unconformably overlies the WAC) because the ferricrete has a moderate to high magnetic response. The effectiveness of the upward continuation filter (Section 3.7.1) was tested on the potential field data to improve the resolution, particularly since the study area is covered by a thick ferricrete layer. The results were compared with the original gridded data for both magnetic at 500 m (Figure 3.1) and gravity anomaly and multitude level (500, 1000 and 3000) maps (Figure 3.2). Generally, in all zones, the results show that that the upward continuation algorithm tends to suppress subtle features at the expense of longer wavelength anomalies. Furthermore, the result illustrates that upward continuation up to 500 m is more superior to conventional gridding methods in terms of highlighting the deep magnetic and gravity anomalies.

The effective removal of the ferricrete allowed identification of NE-NNE trending approximately 155 km long and EW trending first-order scale lineaments approximately 270 km long (Figure 4.3). NNE-NE trending lineaments in the west and east of the study area were interpreted as the Yanfolila-Kalana Shear Zone and Banifing Shear Zone, respectively. EW trending lineaments were interpreted as mafic dykes.

A homogenous zone of low magnetic intensity on the magnetic upward continuation map occurs in the southwest (blue) in Figure 4.3. This area is likely hosted by rocks with magnetic minerals such as magnetite and pyrrhotite. A homogenous zone of moderate magnetic intensity (green) is located to the northeast and east. A heterogeneous zone of high magnetic intensity (red) is located between these zones and indicates a region of low and variable magnetic mineral content. A homogenous zone of high magnetic intensity (low magnetic mineral content) is located to the northwest of the study area (Figure 4.3).

The Bouguer anomaly upward continuation map (Figure 4.4) enabled the identification of two zones of low intensity gravity. They are located in the southwest, and south to southeast of the study area. The low intensity gravity zone located to the southwest of the study area in Figure 4.4 is coincident with low intensity magnetic (or high magnetic mineral content) on TMI map, and was mapped by Feybesse et al. (1999) and Lohondere et al (1999) as rocks of the Archaean Kenema-Man domain, which is dominated by TTG suite granitoids. The low intensity gravity zone in the south to southeast of Figure 4.4 was interpreted by Kušnir (1989) and Girard et al. (1998) as the Bougouni and Bagoe basin, and is dominated by shale, sandstone and greywacke, and intercalated volcano-sedimentary rocks, and/or numerous TTG suite granitoids.

Moderate intensity gravity zones in Figure 4.4 are located (1) in the far-east of the study area and coincide with a moderate intensity magnetic zone, and (2) between the low intensity gravity zones and coincides with low intensity magnetic zones. The later was interpreted by Miller et al. (2013) as a zone of volcano-sedimentary rock with granitoid intrusions.

A high intensity gravity zone Figure 4.4 is located in the northwest of the study area and coincides with a low intensity magnetic zone. Egal et al (1999) interpreted this region as forming the Siguiri Basin which is composed of siltstone, mudstone and subordinate arkoses, with pelitic schist (Egal et al., 1999).

4.1.2. Magnetic First Vertical Derivative

The magnetic first vertical derivative map presented in Figure 4.5 was used to identify lineaments of which there are many, circular to ovoid features, extensive attributes and offsets. Lineaments could be interpreted as dykes that trend dominantly EW, and shear zones that generally trending NW, NE and north. The NW trending lineaments correspond with faults mapped by Egal et al. (1999) and Feybesse et al. (2006). The north and NE trending lineaments correspond with shear zones identified by Kušnir et al. (1989), Girard et al. (1998), Egal et al. (1999) and Lohondere et al (1999), and include (from west to east across the study area):

- The Siguiri Shear Zone, which is approximately 81km long and 5km wide and is north trending. The Siguiri Shear Zone has a western branch that trends NW.
- The Yanfolila-Kalana Shear Zone, which is NNE trending. This shear zone extends for approximately 235 km long and is 17 km wide.
- The Banifing Shear Zone (BSZ), which trends NE and is approximately 168 km long and 11 km wide.
- The Fatou Shear Zone which trends NE, and is approximately 131 km long and 6 km wide.
- The Syama Shear Zone which trend NE. This shear zone is approximately 64 km long and 4 km wide. It has also a western branch that trend northerly.

Circular and ovoid features were also identified, and according to Parasnis (1997), can be interpreted as granitic intrusion for qualitative interpretation. This corresponds well with granitic intrusion mapped by Egal et al. (1999) on their interpretation map of Siguiri basin.

A number of extensive anomalies with no regular pattern could also be identified in Figure 4.5 and are interpreted as volcano-sedimentary belts. These features correspond to the maps produced by Girard et al. (1998) and Randgold (2007). These extensive anomalies trend NNW and NW (Figure 4.5) and correspond with:

- The Yanfolila belt that trends NNW and is located west of Yanfolila-Kalana Shear Zone (Girard et al., 1998).
- The Bougouni belt that trends NW and is located to the southwest of BSZ (Randgold, 2007).
- The Kolondieba belt which is located to the west of the BSZ and north of Bougouni belt, and trends NW. The belt was identified by Randgold (2007) who described its volcano-sedimentary character.

A number of curvilinear attributes in the study area can be interpreted as folds (Figure 4.5), and correspond with folds interpreted by Feybesse et al. (2006). These curvilinear attributes are located;-

- Southeast of Yanfolila belt and correspond to the Kalana-Kodiaran fold.
- Northeast of Yanfolila-Kalana Shear Zone and corresponds with the Ouelessebougou fold.
- Northwest of Fatou Shear Zone that can be named the Farako fold (Figure 4.5).

In summary, according to the magnetic and gravity upward continuation map (Figures 4.3 and 5.4) the study area can be divided in four geophysical domains. They include:

- Domain 1 - A south-western domain that is characterized by low intensity magnetic (high magnetic mineral) and low intensity density signature. EW trending dykes crosscut and dominate the domain. The interpreted high magnetic mineral content of this zone could be the due to the presence of dolerite dykes, and/or migmatite and granitoid of Archaean age which were described by Egal et al. (1999) and Feybesse et al. (1999) in this domain.
- Domain 2 - A northeast to east domain that is characterized by moderate magnetic mineral content and moderate to high density mineral. It possible to identify the NE trending Banifing, Fatou and Syama shear zones, and approximately EW trending dykes (Figure 4.5).
- Domain 3 - A domain located between the southeast domain, and northeast to east domain that is characterized by moderate magnetic mineral content and moderate intensity gravity signature. The first vertical derivative of TMI enabled the identification of Yanfolila-Kalana shear zone; Yanfolila belt and Kalana-Kodiaran fold (Figure 4.5).
- Domain 4 - A northwest domain that is characterized by low magnetic mineral content and high intensity gravity zone. This domain includes the Yanfolila Fault and Siguiri Shear Zone (Figure 4.5).

4.1.3. Bouguer anomaly First Vertical Derivative

The Bouguer anomaly first vertical derivative of the study area (Figure 4.6) resolves number lineaments that coincide with attributes extracted from the Magnetic First Vertical Derivative map (Figure 4.5). These features include: (1) the Yanfolila-Kalana Shear Zone and Kalana-Kondiaran fold in Domain 3; (2) The Banifing and Syama Shear Zone in Domain 2. Additionally, the Bouguer anomaly first vertical derivative map resolves a series of NW trend lineaments that are not evident in the Magnetic First Vertical Derivative map (Figure 4.5). These NW trends are interpreted as fault according to the Parasnis (1997) qualitative interpretation principle. They can be named Menakoro fault and Koumantou-Morila fault (Figure 4.13).

4.2.4. Analytical signal

The analytical signal was applied on magnetic data (Figure 4.7). The amplitude of the analytical signal was calculated for the total magnetic field to enhance the linear, circular and elongated features. For example, shear zones, volcanic belts, lineaments and regional dykes manifest as clear positive magnetic anomalies in the analytical signal map. As one would expect, the analytical signal further showed magnetic highs over folded lineaments (Figure 3.5). This filter is less sensitive to noise when compared to the derivative filters. Summarily, comparison of the amplitude of the analytical signal with the vertical derivative across all the zones of interest showed a marked increase in the numbers of structures delineated (Figure 3.6).

The Figure 4.7 attributes coincide with those extracted from the Magnetic First Vertical Derivative (Figure 4.5) but are enhanced and discrete. The analytical signal applied on magnetic data enabled the identification of lineaments that included the Yanfolila volcano-sedimentary belt, and Yanfolila-Kalana and Banifing Shear Zone. The Kalana-Kodienran fold is defiend as a complex fold with multpile fold axes. A NW trending discontinuity (which may be a fault, thrust or unconformity) separates the Kalana-Kodieran fold and Ouelessebougou fold.

In term of magnetic and gravity domains, Domain 1 can be divided into three subdomains (SD) including from north to south;

- (SD1) characterized by moderate to high magnetic mineral content. This high magnetic mineral content can be explained by the presence of dolerite dykes in this part.
- (SD2) characterised by low magnetic mineral content. The SD2 includes the circular features which in this part may consist of granitoids if the basic to ultra-basic rock are not significant (Feybesse et al., 1999).
- (SD3) corresponding to the high magnetic intensity zone, which according to Feybesse et al. (1999) is composed of multiple types of rocks including Archaean granites, undifferentiated granites, granites with biotite and amphibole, diorites, micaschistes, paragneiss and basic to ultra-basic rocks.

4.2.5. Application of vertical integral on the analytical signal

The image presented in Figure 4.8 is the application of vertical integral on the analytical signal map. The attributes extracted from Figure 4.8 coincide with those extracted from the analytical signal map in Figure 4.7 but were more enhanced. The Figure 4.8 enabled the identification of:

- NE, north and NNW trending lineaments that made up the Yanfolila belt. These lineaments could be the lithological trends of Yanfolila belt.
- The Bougouni belt presents a NW trend with magmatic intrusion around.
- The Kolondieba belt (Randgold, 2007).
- Linear trend that characterized the Yanfolila-Kalana, Banifing and Fatou shear zones.
- Individualization of attributes that were interpreted as folds including the Kalana-Kodiaran, Farako and Ouelessebougou folds.

Additionally a series of regional scale faults/discontinuities can be extracted including;

- The Yanfolila Fault which trends NW.
- The Mandiana-Yanfolila Fault which trends NNE. It crosscuts the Yanfolila-Kalana shear zone and separates the Ouelessebougou and Kalana-Kodiaran fold.

- The Madina Fault trends NE. It crosscuts the Kalana-Kodiaran fold, Bougouni and Kolondieba belt and Banifing Shear Zone.
- The Menankoro Fault which crosscuts the Banifing and Yanfolila-Kalana Shear Zone, the Bougouni belt, Mandiana-Yanfolila and Madina Fault. This fault is a NW trending.
- The Kadiolo-Fourou Fault which trends NW and crosscuts the Kadiolo, Syama and Fatou Shear Zone.
- The Koumatou Morila Fault which trends NW and crosscuts the Banifing and Fatou Shear Zone.
- Farako Fault which trends NE and crosscut the Banifing and Fatou shear zones, and Bougouni belt.

The NW trend highlighted with the first derivative map of Bouguer anomalies is confirmed by Menankoro Fault (Figure 4.6).

Furthermore, Figure 4.8 enabled enhancement of as series EW trending lineaments that were extracted from the Upward Continuation of the TMI (Figure 4.3), Magnetic First Vertical Derivative (Figure 4.5) and Analytical Signal (Figure 4.7), and interpreted as dykes. The relative age of the dykes could also be established and divided into two groups. The group one was composed of dyke (1, 2, 3 and 4) and located in the northern of the area (Figure 4.8). The group two was composed of dykes (5, 6, 7, 8, 9 and 10) and located in the southern part of the area (Figure 4.8).

The dykes of group two are crosscutting the faults, folds and shear zones in the southwest of the study area. It can be established that these attributes are younger than these dykes. The dykes of group one are crosscutting the same attributes in the northern part of the study area, which mean that the dykes of group two are older than group one.

It can also be observed in Figure 4.8 that the dykes of group two are crosscutting the Banifing Shear Zone. The intersection of Banifing Shear Zone by group two dykes indicates that the Banifing Shear Zone is old relative to the Yanfolila-Kalana Shear Zone.

4.2.6. The tilt angle filter

The tilt angle filter of total magnetic field map (Figure 4.9) allowed the enhancement of dykes, Yanfolila-Kalana and Banifing Shear Zones at the expense of others attributes in the study area. It can be explained by the fact that these attribute content more magnetic mineral than other attributes in the area. The tilt angle filter enabled the confirmation of the relative age of dykes in Figure 4.8. The intersection between dykes and other structures become important for the determination of relative chronology of tectonic events in the study area.

The tilt angle of Bouguer anomaly is presented in Figure 4.10. It allowed the confirmation of Menankoto and Koumanto-Morila Faults. It confirms also certain faults described in the Figure 4.8. In additional to these faults, there is another lineament trending NE. It crosscuts the Yanfolila belt and

Yanfolila Fault. The Menankoto and the Koumanto-Morila Faults could be very deep according to their signature in Figure 4.10.

The Figure 4.10 allows the determination of dense materials trends in the study area. These trends are indicated by red line with the (Figure 41.10). These trends correspond probably to the basic lithological trends.

4.2.7. The automatic gain control (AGC)

The automatic gain control of the total magnetic field is presented in Figure 4.11. The Figure 4.11 allowed the enhancement of signal that can highlight the volcano-sedimentary belts underlined with images (Figure 4.5, 4.7 and 4.8). But the difference in this image is the fact that it presents the connexion between Bougouni belt and Kolondieba belt (Figure 4.11). The Figure 4.11 enabled the identification of others stretch features in white colour (Figure 4.11), trending NE. The automatic gain control enhances these feature (Figure 4.11) compare to Figure 4.5, 4.7 and 4.8. The Figure 4.11 allowed the enhancement of Yanfolila and Madina Faults, the Yanfolila- Kalana and Banifing Shear Zone. The Kadiola Shear Zone was highlighted with the AGC map. On the Figure 4.11 the intersection between dykes and others features were also confirmed.

The AGC of Bouguer anomaly is presented in Figure 4.12. The Figure 4.12 enable the identification of some of this image presents the same features presented with the first vertical derivative of Bouguer anomalies (Figure 4.6). The AGC of Bouguer anomalies enabled the confirmation of Bouguer anomalies first vertical derivative maps attributes (Figure 4.6). The NW trending Menankoto Fault (Figure 4.12) crosscuts the Yanfolila-Kalana and Banifing shear zone and is thus younger in relative age.

4.2.8. The attribute map from geophysical data

The attributes extracted from geophysical map were presented in Figure 4.13. These attributes extractions concerned the first and second order structures. The first and second order structures in this study were characterized by their length, wide and probably the depth. The attributes from geophysical data considered as first order in the study area included shear zone (Yanfolila-Kalana and Banifing), faults (Yanfolila, Mandiana-Yanfolila and Farako). The second orders structures were composed by folds (Kalana-Kodieran and Ouelessebougou), faults (Menankoro, Madina, Koumantou and Kadiolo) and shear zones (Siguiri, Fatou, Syama and Kadiolo). The dyke of group one were considered as the first order structures, and the group two dykes were attributed to the second order structures. These attributes coincide with some geological structures highlighted by preview study in the study area. This extraction shows that the former geological studies were limited. The attribute extracted from geophysical data show more structures that were not mentioned by the previous study. These studies were based generally on the magnetic and radiometric data interpretation with some fact data combination.

4.2.9. The potassium map

The Figure 4.14 corresponds to the potassium map of the study area. This image was used for comparison with attributes extracted from geophysical maps (Figure 4.13) to establish the confidence level of the study area. According to the similarity between Figure 4.14 with attribute maps (Figure 4.13) the attributes that can be highlighted includes:

- The Yanfolila, Mandiana-Yanfolila, Madina and Farako Faults (Figure 4.13)
- The Yanfolila belt is the only belt that can be confirmed with Figure 4.14.
- The folds were all confirmed in the potassium map (Figure 4.14).
- The shear zones were all confirmed apart from Siguiri and Kadiolo Shears Zone.

4.2.10. The thorium map

The thorium map is presented in Figure 4.15. This image enabled the confirmation of certain attributes presented in Figure 4.13. The attributes in Figure 4.13 that coincides with Figure 4.15 includes:

- Kalana-Kondiaran Fold zones and Fatou Fold zone.
- Banifing and Syama Shear zones
- Yanfolila, Menankoro, Kadiolo-Fourou Faults

4.2.11. The Uranium map

The Figure 4.16 present the Uranium maps of the study area. The image enables the confirmation of certain attributes presented in Figure 4.13. The similarity that can establish between Figure 4.13 and Figure 4.15 include:

- Yanfolila and Banifing Shear Zones in Figure 4.16. The Syama Shear Zone can be also highlighted in the Figure 4.16 but the contract in not really clear.
- Mandiana-Yanfolila, Menankoro and Koumantou-Morila Faults present the similarity with the Figure 4.16.
- Kalana-Kondiaran and Ouelessebougou Folds present the similarity with the Uranium map (Figure 4.15)

4.3. Confidence level zone of the study area

According to the comparison between the Figure 4.13 with Figure 4.14 to 4.16 the confidence level table can be established. The forward and inversion modelling area were selected according to the very high, high and moderate level of confidence structures. The dyke and belt were only considered on magnetic data. It was difficult to identify dyke and with other data than magnetic. The dykes are generally highlighted with magnetic data in applied geophysics. Using this statement, the dykes and belts are considered as high confidence level if they are highlighted by only magnetic data. The First order structures extracted included the Yanfolila and Banifing Shear Zone in term of their length and wide and there complexity. The Key areas were selected according to these two first order structures for large interpretation.

4.4. Geological fact data extraction

The geological fact data are extracted for very high to high confidence level for forward and inversion modelling. Also on the key areas geological data were extracted in additional to the petrophysics data of the study area. The Figure 4.17 present the fact data extracted for geophysical modelling and Key areas.

5. GEOPHYSICS

5.1. Geophysical characteristic of the study area

The role assigned to geophysics in this study is the detection and location of structures that have strong contrast of physical properties with respect to the host rocks, especially the identification of discontinuities at depth. The experimental models (Figures 5.1-5.2) constructed from the available geological data in forward modelling indicated that the gravimetric and magnetic potential field methods work well and can be applied throughout the study area to model geological structures. The combination of gravimetric and magnetic potential field methods is a good way to interpret, identify and determine deep structures, lateral and vertical rock variations and plutonic architectures.

However, the magnetic method is often limited, for example, in determining stratigraphic units and contact zones covered by a conductive weathering layer deeper than 100m. This was established by Wijns (2009) in a comparative study between the magnetic and electromagnetic methods as used in the Syama belt. His work showed that intrusive bodies, which are indistinct in the magnetic data, are readily resolved from electromagnetic data. The host rocks in the Syama belt are highly conductive because of graphite in the host rocks, relative to the intrusive bodies which are less conductive.

Furthermore, a study completed by Féménias (2008) of the Banifing shear zone highlighted that basement rock lineaments are well resolved in the magnetic and radiometric airborne geophysical datasets.

A limitation to interpreting magnetic data is the fact that laterite-ferricrete covers a significant portion of the study area and major parts of the Baoulé-Mossi domain (Brown et al., 1994; Blot, 2004; Beauvais et al., 2008). The presence of laterite-ferricrete can complicate the magnetic data presentation and affect interpretations, but by applying linear filters the effects of laterite-ferricrete can be minimised in the magnetic signature.

Quantitative interpretation of geophysical data is critical in terms of discovery of structures under sedimentary cover. Modelling is the stage used to achieve quantitative interpretation. It can determine stratigraphic units and contact zones covered by a conductive weathering layer deeper than 100m and/or covered by laterite-ferricrete.

This chapter presents the results of modelling and includes forward 2D and 3D inversion. The models present attributes extracted from geophysical maps, their depth, geometries and a preliminary interpretation of block displacements. The geophysical transect lines and key zones used in forward and inverse modelling were selected according to the confidence level table (Table 3.1).

5.2. Forward modelling

In this research forward modelling included three west-east transects that crosscut first-order structures and greenstone belts in the study area. The forward models were constructed using available geological fact and petrophysical data. The correspondence between observed and calculated data was performed iteratively. The forward modelling aided in the construction of models from which the geometry of structures was calculated. Transect lines selected included:

- Transect 1 (AA') from GPS coordinates 570950E and 1245150N to 616000E and 1245150N, and measures approximately 45km in length. It transects the Yanfolila belt, Yanfolila shear zone, Madiana-Yanfolila fault, and the Kalana-Kodieran fold in the west central region of the study area (Figure 4.13).
- Transect 2 (BB') from GPS coordinates 687510E and 1164475N to 721944E and 1164475N, and measures approximately 34km in length. It transects the Bougouni belt, Banifing shear zone and Menankoro fault in the southeastern region of the study area (Figure 4.13).
- Transect 3 (CC') extends from GPS coordinates 704880E and 1232696N to 751630E and 1232696N, and measures approximately 47km in length. It transects the Kolondieba belt, Madina fault, and Banifing shear zone in the east central region of the study area (Figure 4.13).

A profile of the upward continuation of magnetic data was calculated for each transect to produce three profiles (Profile 1-3). The magnetic susceptibility data used published petrophysical data to calculate the magnetic field.

5.2.1. Profile 1

Profile 1 is located in a low magnetic susceptibility and high density zone (Figure 4.13). The petrophysical data from WAXI (2013) reported that the geology along the transect line is composed of granite, coarse-grained sedimentary rocks, pegmatite, and granite with plagioclase and biotite.

The interpreted model of profile 1 presents six bodies (Figure 5.3). The parameters of the six bodies are presented in Table 5.1. According to the parameters, the top-depth of the bodies is located at approximately 1000m depth and all bodies project at depth.

According to the magnetic susceptibility and density, bodies 1, 5 and 6 are different from bodies 2, 3 and 4, reflecting different rock types. Bodies 2, 3 and 4, which are located in the Yanfolila shear zone, report high susceptibility that corresponds to the low magnetic field. Bodies 1, 5 and 6 report a low susceptibility.

The profile shows similarities between body 1 and 6 in terms of parameters (dip, top depth and depth projection) (Table 5.1). Bodies 2, 3, 4 and 5 with approximately the same parameters (Table 5.1) are situated between bodies 1 and 6 (Figure 5.3) and correspond with the positon of the Yanfolila shear zone which crosscuts the region. Body 5 is slightly different than bodies 2, 3 and 4 and corresponds with the position of the Kalana-Kodiaran fold. Bodies 1 and 6 are located respectively to the west and east of the fold. (Figure 5.3)

5.2.2. Profile 2

Profile 2 which transects the Bougouni belt, is located in a moderate to high magnetic susceptibility and low density zone (Figure 4.13). The petrophysical data from WAXI (2013) reported that the geology along the transect line is composed of orthogranite, sediments, pegmatites and quartz veins.

The interpreted model of profile 2 presents five bodies (Figure 5.4). The parameters of the five bodies are presented in Table 5.1. According to the parameters, the top-depth of the bodies is located at approximately 750m depth and all bodies project at depth.

According to the magnetic susceptibility and density, bodies 2, 3 and 5 are different from bodies 1 and 4, reflecting different rock types. Bodies 2, 3 and 5 report a low susceptibility corresponding to a high magnetic field. Bodies 1 and 4 shows similarities in term of parameters (dip, top depth and depth projection) (Table 5.1) and report a high magnetic susceptibility. The bodies 2, 3 and 5 correspond with the Banifing shear zone and are possibly west-dipping splay shears. Consequently the Banifing shear zone is interpreted as complex structure. The high susceptibility and low density of bodies 1 and 4 could indicate granitoid intrusions.

5.2.3. Profile 3

Profile 3 transects the Kolondieba belt, and is located in a low to moderate susceptibility and low density zone (Figure 4.13). The petrophysical data from WAXI (2013) reported that the geology along the transect line is composed feldspathic sand, gneiss and gneiss-granitoid.

The interpreted model of profile 3 presents six bodies (Figure 5.5). The parameters of the six bodies are presented in Table 5.1. According to the parameters, the top-depth of the bodies is located at approximately 800m depth and all bodies project at depth.

According to the magnetic susceptibility and density, bodies 1, 2 and 4 are classified as different from bodies 3, 5 and 6, reflecting different rock types. Bodies 2 and 4 report low susceptibility and are interpreted as splay shears of the Banifing shear zone. Bodies 3, 5 and 6 report a high susceptibility.

The profile resolves similarities between bodies 3, 5 and 6 in term of parameters (dip, top depth and depth projection) (Table 5.1). The bodies 2 and 4 are similar in parameters, and different from body 1. However, bodies 2, 3, 4, 5, 6 are located in the Banifing shear zone. Consequently, the Banifing shear zone can be considered as a complex structure formed by a main shear and several secondary splay shears that resolve differences in dip and trend.

5.2.4. Synthesis of forward modelling

The forward modelling of the three transects shows that:

1. Transect 1 crosscuts the Yanfolila shear zone and resolves its complexity. The trends are subvertical to east-dipping for body 3, and east-dipping for bodies 2 and 3; they are interpreted as

splay shears to the main Yanfolila shear zone. The Yanfolila shear zone crosscuts the Yanfolila belt according to the similarity of bodies 1 and 6. The Kalana-Kodieran fold also is identified in transect 1.

2. Transect 2 and 3 is located to the Banifing shear zone which is also a complex structure composed of several shear trends and secondary splay shears.

The forward modelling of three profiles across the Yanfolila and Banifing shear zones (Figure 4.13) facilitated the characterization and geometry of the first-order structures, in terms of trend and dip. The models enabled the determination of magnetic anomalies. The depth of the anomalies is greater for the Yanfolila shear zone than the Banifing shear zone. The difference of source depth is due to the presence of sedimentary cover rocks along transect 1 to 1100m, and 850m for transect 2 and 3. Importantly the data shows that the cover sequences postdate activity on the shear zones suggesting that the shear zones were truncated and unconformably overlain by younger sedimentary cover rocks. The low magnetic susceptibility and high density along transect 1 is interpreted to be related to the thickness of the sedimentary cover rocks. The higher density may be due to compaction effects. The rocks types are likely to be siltstone, shale and/or volcaniclastic sediments.

5.3. Inverse modelling

The inversion was performed on six (6) key zones according to high levels of confidence established in Table 4.1, and available fact and petrophysical data (Figure 4.17). The location of the key zones is presented in Figure *** and are situated on the first-order crustal scale Yanfolila and Banifing shear zones, and certain second-order structures and dykes (Figure 5.6). The selection of second-order structures was based on proximity to the first-order crustal scale structures. The inversions were performed using magnetic and gravity data in addition to the forward modelling of transects to produce a consistence model of the selected zone. The results of the inversions enabled the determination of the form, volume and the geometries of rock volumes and structures. The trend, depth, dip, and the crosscutting relationship between rock volumes and structures were calculated to develop an architectural model of the study area.

5.3.1. Key zone 1

The inversion model of key zone 1 is presented in Figure 5.6; zone 3 is located *****. The inversion model of key zone 1 included the Yanfolila shear zone, Kalana-Kodiaran fold, Mandiana-Yanfolila fault, and dykes. According to the magnetic and gravity maps (Figure 4.13), the area is located in a low susceptibility, and low to high density region.

Comment [KH1]: Not correct figure number for gravity and magnetic maps

The inversion of magnetic and gravity data (Figure 5.6) resolves the Yanfolila shear zone and specific rock volumes that trend north and north-northeast. These can be divided into two susceptibility groups, namely (1) a high susceptibility rock volumes, and (2) moderate to low susceptibility north-northeast trending rock volumes values.

A low density rock volume in the southeastern corner of the inversion could be due granitoids in that region. North-northeast trend rock volumes in the magnetic data resolve high density values in the north and south of the inversion (Figure 5.6) that probably correspond with basalt andesite rocks. The Yanfolila shear zone is characterised by two parallel trends and the presence of a close upright symmetric fold in the south on the inversion. A number of southeast trending splay shears are also evident.

Geometric elements such as dip, depth of structures and rocks volumes were determined for the magmatic and gravity inversion sections of zone 1 (Figures 5.7-5.8). The Yanfolila shear zone dips steeply west in the south of the inversion, steeply east in the centre and north of the inversion. Secondary southwest trending splay shears dip subvertical to steeply west. The shears bound high susceptibility rock volumes, and in the centre of the inversion form a left-handed (anticlockwise) sigmoid that is consistent with sinistral displacement in the plane of the Yanfolila shear zone (Figure 5.6).

5.3.2. Key Zone 2

The inverse model of key zone 2 is presented in Figure 5.9; zone 3 is located ****. Zone 2 includes the Yanfolila shear zone; Kalana-Kodiaran fold and Madiana-Yanfolila fault. According to the petrophysical data, Zone 2 is composed of granite, sedimentary rocks, pegmatite and weathered granite. Zone 2 is characterised by low magnetic susceptibility (Figure 4.13).

The inversion of magnetic and gravity data resolves rock volumes and structures that trend north-northeast (Figure 5.9). According to the gravity data inversion, high density rock volumes are located in the western region of the inversion adjacent to the Yanfolila shear zone (Figure 5.9). High susceptibility rock volumes generally trend north-northeast across zone 2 and are bounded by shears.

Geometric elements such as dip, depth of structures and width were determined for the magmatic and gravity inversion sections of zone 2 (Figures 5.10-5.11). The majority of high susceptibility rocks dip steeply to the east, as do their bounding shear zones. The inversion section of gravity data presented in Figure 5.11 resolves high densities rock volumes at depth in the region of the Yanfolila shear zone, but these are (apparently) not crosscut by the shear. The high density rocks could be due to intrusion at depth that is younger than the Yanfolila shear zone. Low density rocks occur in the extreme west of zone 2, and to the east of the Yanfolila shear zone (Figure 5.11). These low density rocks are interpreted as unconsolidated sediment and/or deeply weathered granite.

5.3.3. Key Zone 3

The inversion model of key zone 3 is presented in Figure 5.12; zone 3 is located in the northwest of the study and includes the Yanfolila fault and Yanfolila belt. The area is characterised by low magnetic and high density rocks. According to published petrophysical data, the area is composed of felsic intrusions.

The inversion model of magnetic data is presented in Figure 5.12 resolves generally north to north-northeast rock volumes. The north trending rock volume in the east of zone 3 correspond with the position of the Yanfolila belt. The north-northeast trending rock volume in the west of zone 3 corresponds with the position of the Yanfolila fault. The Yanfolila fault is arcuate and is north trending in the south of zone 3 and north-northeast trending in the north of zone 3. An east-west trending dolerite dyke is clearly evident in the inversion model and corresponds with dyke 1 marked in Figure 4.13; the dyke crosscuts the Yanfolila fault and Yanfolila belt. East-west trending linear intrusions have been mapped as dolerite dykes across the study are a (Reference)

According to the gravity data inversion, high density rocks are located in the northwest of zone 3 (Figure 5.14). The high density coincides with a north-northeast trending susceptibility volume. The coincidence may indicate basaltic rocks.

Geometric elements such as dip, depth of structures and rocks volumes were determined for the magmatic and gravity inversion sections of zone 3 (Figures 5.13-5.14). The Yanfolila fault dips steeply west.

The parameters of the east-west trending dyke that crosscuts the Yanfolila fault and Yanfolila belt and the high density (basaltic) rocks in the northwest of zone 3 are presented in Figure 5.15 with sections. From this data it is clear that the dyke dips steeply to south in the east of zone 3, and rolls over the dip steeply north in the west of Zone 3. High susceptibilities are located at approximately 300m depth for the dyke and at 600m depth for the basalt. Thick sedimentary cover above the dyke and basalt is attributed to low susceptibility values at surface.

5.3.4. Key Zone 4

The inversion of key zone 4 is presented in Figure 5.16. Key zone 4 is located in the southeast of the study area on the Banifing shear zone (Figure 4.13). It includes the Bougouni volcanic belt, Menankoro fault, and group two dykes. Zone 4 is composed of low to high magnetic susceptibility, and low density rocks. According to petrophysical measurement of surface rocks, the geology of the region includes ortho-granite, sediment, ortho-gneiss and pegmatite.

Comment [KH2]: Confusion. Is group 2 number 2, or is their another way of grouping the dykes.

The inversion of magnetic data of key zone 4 presents many rock volume and structural trends (Figure 5.16). The trends include northwest to north trending rock volumes in the west of the inversion, and northeast trending rock volumes in the east of the inversion. An east-west trending dyke is evident in the inversion model and corresponds with dolerite dyke ***** marked in Figure 4.13.

The northwest to north trending rock volumes correspond with the Bougouni volcano-sedimentary belt. Segments of the northwest trending Menankoro fault crosscut this belt. The northeast trending rock volumes in the east of the inversion are located adjacent to the Banifing shear zone and could also be related to granitoid as the susceptibility is high and density low, perhaps as a result of a high content of silica. Additionally, a high density high susceptibility zone is located in the northwest corner of zone 4 which could be related to gneissic rocks in the Bougouni belt.

The inversion sections from magnetic and gravity data of zone 4 are presented in Figures 5.17-5.18. In Figure 5.17, northwest trending rock volumes in Bougouni belt dip sub-vertically to steeply west, while north trending rock volumes trending dip steeply east.

In contrast, northeast trending rock volumes in the region of the Banifing shear zone dip steeply east and are bound by it and secondary splay shears that trend north to north-northeasterly. According to the inversion sections, the Banifing shear zone is characterised by low density and low susceptibility which could be due to the volcaniclastic sediments in the region because *****.

Comment [KH3]: Why specifically volcaniclastic and not sedimentary

The parameters of the east-west trending dyke that crosscuts zone 4 are presented in Figure 5.19 with sections. From this data the dyke dips steeply to north to vertical. Thick sedimentary cover above the dyke is attributed to low susceptibility values at surface.

5.3.5. Key Zone 5

The inversion of key zone 5 is presented in Figure 5.20. Key zone 5 is located in the central east of the study area on the widest part of the Banifing shear zone and includes the Madina fault and the southern extension of the Kolondieba belt (Figure 4.13). According to the petrophysical measurements of surface rocks (WAXI, 2013) lithologies include granitoid gneiss, various metasedimentary rocks, feldspathic sand, and pegmatite veins. The low susceptibility of the zone 5 model is related to sedimentary cover.

The zone 5 is composed of low to high susceptibility and the low density volumes, that trend north to northeast. Some rock volumes are arcuate in shape (Figure 5.20).

Northeasterly and north-northeasterly trending rocks volumes dominate the centre and east of the zone 5 model and correspond to high magnetic susceptibility values in and adjacent to the Banifing shear zone (Figure 5.20). The overall shear trend can be defined as northeasterly but internal north-northeast trending rock volumes form right-handed (clockwise) sigmoids that are consistent with dextral displacement in the plane of the Banifing shear zone

Northerly trending rocks volumes occur in the Kolondieba belt in the west of zone 5, and in the east and are arcuate in form. This may suggest folding of the rock units they represent.

Two areas of high densities are resolved in the zone 5 inversion model (Figure 5.20). Area 1 is located in the Kolondieba belt, where the high density coincides to the high susceptibility. The coincidence of high susceptibility and high density corresponds to gneissic rocks identified with the surface rock petrophysics measurements. Area 2 is located in the Banifing shear zone and is also interpreted as a gneissic rock volume.

The magnetic and gravity inversion sections of model 5 are presented in Figures 5.21-5.22. The inversion sections demonstrate that the Banifing shear zone is steeply dipping to the west and east. According to the magnetic section, the rock volumes are located at approximately 500-700m depth.

According to gravity sections (Figure 5.22), high density rocks are located in the northern part of model 5 at depth; they are not crosscut by the Banifing shear zone and may represent younger intrusions. A high density region in the northwest of zone 5 in the Kolondieba belt could be due to the basalt and gneiss.

5.3.6. Key Zone 6

Magnetic and gravity inversion of key zone 6 are presented in Figure 5.23. The zone 6 is located in the northern part of Banifing shear zone in the northeast of the study area. Zone 6 includes the Madina fault and Koumantou-Morila fault (Figure 4.13). The geology includes andesite and highly metamorphosed sediment with biotite and muscovite according to the surface petrophysical measurements. Zone 6 is characterized by low, moderate and high susceptibility. The density values of zone 6 vary from low to moderate.

In the magnetic data inversion for key zone 6, north to north-northeast trending rock volumes are readily identified. They correspond to the high susceptibility values of the rocks. In the north of zone 6, high susceptibility values coincide with high density values and could indicate the presence of andesite in that region.

The magnetic and gravity inversion sections of model 5 are presented in Figures 5.24-5.25. The inversion sections demonstrate that north trending rock volume dip steeply east, while north-northeast trending rock volume dip steeply west.

5.3.7. Geological synthesis of inverse modelling

Inverse modelling was performed on the two first-order crustal-scale structures, namely, the Yanfolila shear zone and Banifing shear zone. The inversions modelling resolved the geometry of the shear zone geometries using the surface petrophysical and fact data available. The inversion showed:-

1. There is a difference in thicknesses of sedimentary cover at approximately 1200m for the Yanfolila shear zone and approximately 700m for Banifing shear zone.
2. First-order scale shear zones are steeply dipping to the west or east and are complex structures, with numerous second order splay shear.
3. The Yanfolila shear zone is characterised by parallel shear trends. A number of southwest trending second order splay shears are also evident. The shears bound high susceptibility rock volumes that internal to the Yanfolila shear zone form left-handed (anticlockwise) sigmoids that are consistent with sinistral displacement in the plane of the shear zone. The high density rocks at depth could be intrusions that are younger than the Yanfolila shear zone.

4. The Yanfolila fault to the west of the Yanfolila belt is arcuate and dips steeply west.
5. The Banifing shear zone is also characterised by parallel shear trends. A number of southeast trending splay shears are also evident. The shears bound high susceptibility rock volumes that internal to the Banifing shear zone form right handed (clockwise) sigmoids that are consistent with dextral displacement in the plane of the shear zone, respectively.
6. It is possible to resolve the geometry of dolerite dykes and establish their crosscutting relationship. Thick sedimentary cover above dykes is attributed to low susceptibility values at surface.