ORE GENESIS AND MODELLING OF THE SADIOLA HILL GOLD MINE, MALI

GEOLOGY HONOURS PROJECT

Ramabulana Tshifularo

Student number: 462480

Supervisor: Prof Kim A.A. Hein

Acknowledgements

I would like to thank my supervisor, Prof. Kim Hein for giving me the opportunity to be part of her team and, for helping and motivating me during the course of the project. Thanks for your patience, constructive comments and encouragement.

Thanks to my family and my friends for the encouragements and support.

Table of contents

Abstract

The Sadiola Hill deposit in Western Mali is located within the Kedougou-Kéniéba Inlier (KKI) which is part of the West African Craton. The deposit is situated within the Sadiola goldfield and comprises meta-sedimentary rocks and volcanic intrusions. The meta-sedimentary rocks are meta-greywacke and marble which have been metamorphosed to hornblende-hornfels and epidote-chlorite facies. The two facies are characteristic of contact metamorphism. The volcanic intrusions are tonalite-granodiorite and quartz-feldspar porphyry dykes which cross-cut the meta-sedimentary rocks. The dykes are part of the Sekokoto pluton (2083 ± 7 Ma) and are responsible for contact metamorphism in the meta-sedimentary rocks.

Two main veins occur in the Sadiola deposit: (1) quartz-carbonate veins and (2) quartz-sulphide veins. The quartz-sulphide veins crosscut the quartz-carbonate veins forming an array of stockwork and spider veins. The host rocks contain a pervasive alteration assemblage (quartz-chlorite-carbonate-k-spar-sulphide) with a more pervasive sericite alteration which encloses veins and is associated with mineralisation. Supergene processes decomposes pyrite to marcasite after vein formation.

Mineralisation in the deposit occurs within and/or adjacent to quartz-carbonate and quartz sulphide veins. Two styles of mineralisation are present; (1) quartz-vein mineralisation were gold is concentrated in margins of pyrite and arsenopyrite, and in fractures and (2) a disseminated style were gold occurs as discrete grains in alteration zones. Gold is mainly associated with arsenopyrite, chalcopyrite and pyrite with an assemblage of arsen + gold + py + ccp.

Sulphides in the Sadiola Hill deposit become less reduced with time and temperature due to fluids in contact with the carbonaceous wall rocks. The sulphide minerals are consistent with retrograde facies. Fracturing and brecciation are part of the whole vein formation process with precipitation of fresh sulphides after every fracturing event.

Gold-sulphide mineralisation in the Sadiola Hill deposit formed during retrograde contact metamorphism and brittle deformation caused by the emplacement of the Sekokoto granodiorites (2083 ± 7Ma) at the time of the Eburmean plutonism (2150 – 2095 Ma). The Sadiola Hill deposit is characterised as an orogenic subclass intrusion-related deposit.

Chapter 1: Introduction

The Sadiola Hill gold mine is located within the Sadiola goldfield in the Kedougou-Kenieba inlier (KKI), which is part of the West African Craton (WAC) and is situated in western Mali. The Sadiola goldfield is located close to the Alamoutala-Sekokoto-Kakadian plutonic system and mineralisation has been shown to have a relationship with the tonalite-granodiorite plutons and diorite dykes. The goldfield also hosts the FE3, FE4, Timbabougouni mines, and FE2 and Tambali prospects. The relative association of mineralisation with highly deformed and metamorphosed rocks of the Birimian Supergroup makes it difficult to derive an ore genetic model. The model is important for regional and in-mine exploration, but also significant for understanding geologic evolution of the host rocks.

A number of different ore genesis models have been proposed for Sadiola Hill deposit. These have included epithermal, Carlin-type, Skarn, thermal aureole and mesothermal models. The wide variety of models was a consequence of the relative absence of fresh sulphide mineralisation for study (Boshoff et al., 1998) in the early days of mine development. However, the favoured models included the intrusion-related model proposed by Theron (1997) and Hein and Tshibubudze (2007a,b; 2008) and a structurally controlled shear zone or mesothermal genetic model proposed by Hanssen et al. (2008). The two styles can occur in similar tectonic settings but they differ in the source of mineralising fluids, minerals and metals associated with mineralisation (indicators). The intrusion related style refers to deposits that are hosted mainly within and/or in varied distances around individual intrusions in plutonic provinces (Lang and Baker, 2000). This type of deposit can be characterized by carbonic hydrothermal fluids, weak hydrothermal alteration, low sulphide content, and metal assemblages that combine gold with Bi, W, As, Mo, Te and/or Sb (Thompson et al., 1999). Ore mineral assemblages in this type of deposit typically consist of arsenopyrite, pyrrhotite and pyrite with less magnetite or hematite (Lang and Baker, 2000).

In contrast, shear hosted deposits were described by Sibson et al. (1988) as deposits that are mostly associated with Achaean greenstone belts with few younger deposits known, and appear to develop syntectonically in horizontal compression or transpressive regimes. These deposits are mainly hosted in mafic-ultramafic volcanic sequences of tholeiitic affinity, but also associated with turbidite sequences of clastic sedimentary rocks, and felsic intrusions. Generally the host rocks contain an intense carbonate alteration and have been regionally metamorphosed under low- to –mid greenschist facies conditions, but amphibolite facies assemblage occur in some areas (Zhu et al., 2006). The deposits are characterized by shear fabrics that are associated with sulphide mineralisation.

The Sadiola deposit is unique in West Africa as most of the deposits are structurally controlled (e.g. Ashanti in Ghana; Essakane in Burkina Faso; Tongon in Cote d'Ivoire, and others), but it shows similarities with the Morila gold mine in southern Mali which is an intrusion-related deposit (McFarlane et al. 2012).

The main focus of this project has therefore been to derive an ore genesis model for the Sadiola Hill gold deposit by contrasting the intrusion related style hypothesis proposed for the deposit by Theron (1997) with the shear-hosted style hypothesis proposed by Hanssen et al. (1998) using petrographic analysis. The features which will characterise the Sadiola Hill gold deposit (i.e. indicator minerals, alteration assemblage and mineral textures) will be used to contrast the two models and to establish a likely model for the deposit.

1.2 Location and Physiography

The Sadiola Hill gold mine is situated in the Sadiola goldfield, in western Mali at about 77km south of the regional capital, Kayes, near the international border of Mali with Senegal (Fig.1). Mali is a landlocked country bordered by Niger to the east, Burkina Faso to the east, Algeria to the north, and Senegal and Mauritania to the west in the West African Savannah-Sahel region (Geographia.com/Mali). The official language in Mali is French with 80% of the population speaking Bambara. Muslim is the dominant religion in Mali with a small group being Christian, with the remainder practising African religions.

The climate is subtropical-to -arid with distinct dry and rainy seasons and the dry season is warm from November to February (15˚ to 30˚C) and hot from March to June (25˚ to 45˚C) (IAMGold.com). The rainy season lasts from July to October. The dominant infrastructure in the study area is the mining operations and a mine town that includes schools, clinics and shops for the Sadiola mine employees and their dependents.

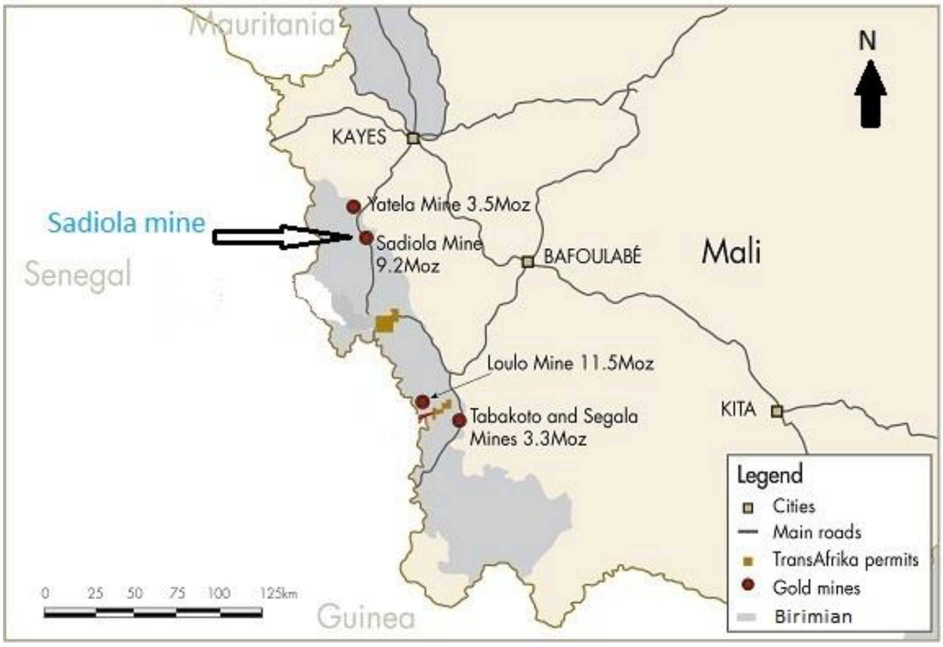


Figure 1: Locality map of Mali showing neighbouring countries, Sadiola and other gold mines with estimated reserves, and the occurrence of the Birimian rocks (IAMGold.com)

1.3. Aims and Objectives

The main aim of this research project is to derive an ore genetic model that characterizes the potential source of gold mineralization and the style of deposition at the Sadiola Hill gold deposit, by petrographical investigation of the host rocks and associated sulphides. Microscopic analyses will be used to identify any characteristic indicator minerals which characterise the Sadiola Hill gold deposit, alteration and sulphide assemblages. A detailed study of mineralogy, alteration assemblage and microstructures will be of importance in contrasting the intrusion-related style with the shear-hosted style hypotheses with which the difference will be used to establish the most likely model for the Sadiola Hill deposit.

1.4 Abbreviations and acronyms

WAC – West African Craton

KKI – Kedougou Kenieba Inlier

SMFZ – Senegalo-Malian Shear Zone

MTSZ – Main Transcurrent Shear Zone

TTG – Tonalite-Trondhjemite-Granodiorite

SFZ – Sadiola Fracture Zone

QFP – Quartz-feldspar porphyry

Chapter 2

2.1 Regional Geology

2.1.1 Geology of the West African Craton

The West African Craton (WAC) is composed of an Achaean and Palaeoproterozoic basement that is divided into two shields which are the Reguibat shield in the north and the Man shield in south (Potrel et al., 1998). These two shields are separated by the Taoudeni basin, which is Neoproterozoic to Devonian in age and are entirely surrounded by Pan African and Hercynian belts (Matthias et al. 2002). The Reguibat shield contains Palaeoproterozoic assemblages in the eastern part as well as Archean relicts which include kimberlites (Ennih and Liegeois, 2008). Large parts of the WAC in the Man Shield consist of Palaeoproterozoic rocks referred to as the Birimian Supergroup (Abouchami et al. 1990; Beziat et al., 2000). The Birimian Supergroup represents a juvenile crust without any influence of surrounding Archean continents (Abouchami et al. 1990; Pawlig et al. 2006). The Man Shield has been divided into three age provinces (Marcfarlane et al. 1981): Leonean (~ 3.0 Ga), Liberian (~ 2.7 Ga), and Eburnean (~ 2.0 Ga), but there is a debate as to whether the Leonean and Liberian are two separate events or a single event due to limited radiometric dating (Matthias et al. 2002). The Man Shield crops out in the Kedougou-Kenieba Inlier in the western part of the Birimian Supergroup.

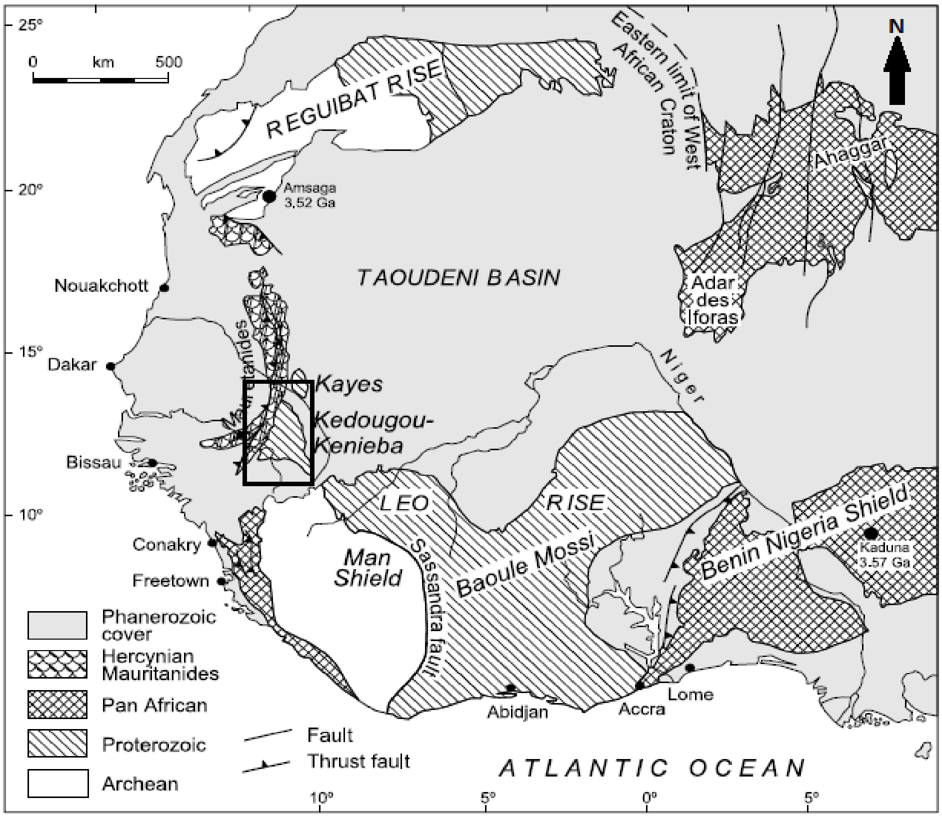


Fig. 2: Geological sketch map showing major tectonic units of the West African Craton (After Boher et al. 1992) and location of the Kedougou-Kenieba Inlier (rectangle)

2.1.1 Geology of the Kedougou-Kenieba Inlier

The Kedougou-Kenieba Inlier (KKI) is the westernmost exposed part of the WAC in eastern Senegal and western Mali (Dia et al., 1997). The KKI is a triangular-shaped area bounded by the Mauritanide Hercynian Belt on its western side and is covered to the north, east and south by Neoproterozoic and Palaeozoic formations of the Taoudeni basin (Gueye et al. 2007). The KKI consist of Birimian formations formed during the Eburnean orogeny at ca. 2.2 -2.0 Ga (Abouchami et al. 1990; Liégeois et al. 1991).

The KKI consist of volcano-sedimentary greenstone belts intruded by granites (Gueye et al 2007). The volcano-sedimentary units are separated into two lithostratigraphic supergroups, the Mako Group in the west and the Diale-Dalema Group in the east (Bassot and Cen-Vachette, 1984; Bassot, 1987).

The Mako Group was defined by Witschard (1965) and Bassot (1966) as being made up of metamorphosed and deformed volcanic and volcano-sedimentary sequences which have been intruded by granitoids of the Kakadian Batholith and smaller massifs. The Mako Group is dominated by basaltic, volcano-sedimentary and sedimentary complexes. The volcanic rocks are dated between 2160 Ma and 2200 Ma (Boher, 1992; Dia et al., 1997).

The Diale-Dalema Group consists of platform-type sediments (e.g. carbonates) which were intruded by peraluminous granites which were emplaced at synchronous to the TTG intrusive along the belts (Gueye et al. 2007; Hirdes and Davis, 2002). The Diale and the Dalema formation are separated by the Saraya Batholith (Hirdes and Davis, 2002). The Diale formation comprises basal limestones and dolomitic marbles followed by greywacke and sandstones, whereas the Dalema formation consists of interlayered quartzites, greywackes, schists and marbles that contain rare slump breccias (Gueye et al, 2007; Hirdes and Davis, 2002). The Mako and the Diale-Dalema Groups are separated by a regional crustal scale shear zone, the Main Transcurrent Shear Zone (MTZ) which trends northeast to southwest (Milési et al. 1989). The Diale-Dalema Group and the Dalema formation, also referred to as the Kofi Supergroup, are separated by the Senegalo-Malian Shear Zone (SMFZ).

During the late Eburnean, the KKI underwent transcurrent deformation along a network of ductile shear zones and almost all lithostratigraphic units were metamorphosed under greenschist-facies conditions (Ledru et al. 1991; Milési et al. 1992). Amphibolite-facies metamorphism is only observed in the contact aureoles around granitic intrusions (Gueye et al. 2007). Three deformational events have been recorded and include a compressional D_1 event related to early thrust formation and two late transcurrent deformation events (D_1-D_2), which led to the development of the MTZ and the SMFZ (Ledru et al. 1991; Dabo and Aifa, 2010,2011; Lawrence et al. 2013).

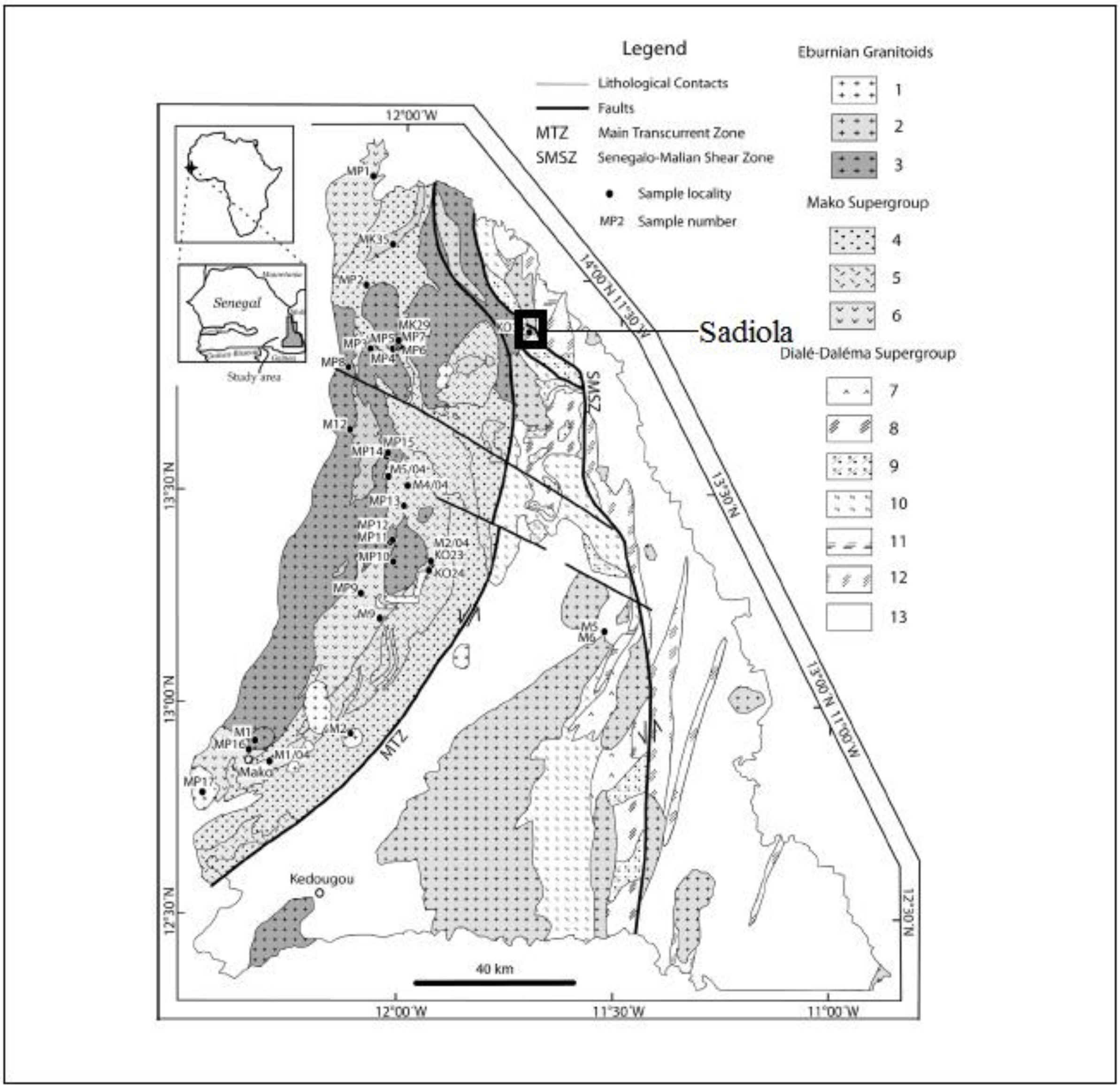


Figure 3: Geological map of the KKI located in the eastern part of Senegal (West Africa) with sample localities (modified after Ledru et al. 1991). Symbol explanation: Eburnian granitoids: 1-4 ; Mako Group: 4 = volcano-sedimentary series; 5 = intermediate to mafic volcanics; 6 = mafic volcanics; Dialé-Daléma Group: 7 = intermediate volcanics; 8 = volcanogenic sediments and tuff; 9 = intermediate volcanics; 10 = undifferentiated detrital sediments; 11 = limestone; 12 = tourmaline-bearing sediments; 13 = undifferentiated flyschic sediments.

2.2 Mine geology

The Sadiola Hill deposit is situated in the Sadiola goldfield. The goldfield is a mine camp which hosts several deposits which include the FE3 and FE4 open cast pits. These together with the Sadiola Hill mine are mined by Société D'Exploitation des Mines d'Or de Sadiola S.A (SEMOS), which is a Joint Venture between AngloGold Ashanti, IFC and the government of Mali.

The Sadiola goldfield is located within folded and altered sedimentary rocks of the Kofi Supergroup, which have been intruded by a number of felsic intrusions. The metasedimentary rocks consist of fine grained greywacke and impure carbonates with minor tuffs and acid volcanics (Hanssen et al., 1998). These lithologies show evidence of macroscopic to mesoscopic slump structures (Hein and Tshibubudze, 2007a, b). Carbonate, greywacke, quartz-feldspar-porphyry and diorite are the main host to the Sadiola deposit (Boshoff et al., 1998). The Sadiola Hill deposit is located along a diorite intruded marble-greywacke contact east of the SMFZ (Hanssen et al., 1998).

The Kofi Supergroup is obliquely cut by the N-S to NNW trending Senegalo-Malian Shear Zone, whereas the Sadiola deposit occurs along the NNE striking Sadiola Fracture Zone (SFZ) (Robins, 2006). The SFZ follows the steeply westerly dipping contact between greywacke to the west and impure carbonates to the east and its wallrock are intruded by discontinuous diorite and quartz-feldspar-porphyry dykes (Hanssen et al., 1998; Robins, 2006).

The Sadiola Hill deposit is also located at the margin of the inner and intermediate contact metamorphic aureole of the Alamoutala-Sekekoto plutonic system identified by (Hein and Tshibubudze, 2007b). Dating of the Alamoutala-Sekekoto granodiorite gave an age of 2083 ± 7 Ma and is taken as the age of gold mineralisation in the Sadiola goldfield (U-Pb zircon) (WAXI, 2013). Based on geophysical data, the plutonic system is interpreted to be situated directly below the Sadiola goldfield and is represented by projections of tonalite dykes in pits from the upper surface of the pluton, and it crops out at Alamoutala (Hein and Tshibubudze, 2007b).

Alteration assemblages identified include calc-silicate, potassic, chlorite–calcite, carbonate and silicification with gold mainly associated with both arsenic and antimony dominated sulphide assemblages including arsenopyrite, pyrrhotite, pyrite, stibnite and gudmuntite (Hanssen et al., 1998; Hein and Tshibubudze, 2007b).

Ore reserves and resources at the Sadiola Hill deposit have been estimated as of 31 December 2012, using an average of $2000/oz. gold price in accordance with JORC (IAMGold.com). In Sadiola Hill, mining is carried using conventional open-pit techniques with a carbon-in pulp processing plant (InfoMine.com). The processing plant is capable of treating 5.3 Mt of saprolite ores per year and has a 75% sulphide recovery (IAMGold.com). The table below shows the estimated ore reserves and resources from IAMGold Corp.

Category	Tonnes (10^3)	Grade (g/t)	Gold(oz)
Reserves			
Proven	2,213	1.3	101477.95
Probale	34,809	1.8	2210095.24
Resources			
Measured	7,084	0.9	224888.88
Indicated	51,519	1.8	3271047.62
Inferred	10,993	1.7	659192.239

Lithology

The steeply west dipping lithologies of the Sadiola Hill gold deposit are dominated by greywacke, carbonate, marble and volcanics as recorded by Hanssen et al. (1998). The greywacke forms the hangingwall of the deposit. Greywacke and feldspathic greywacke are biotite bearing (Hanssen et al., 1998; Hein and Tshibubudze, 2007b). These greywacke units are massive with sharp bases (to the west), show an upward gradation and cross bedding at all scales, and are best developed to the west of the SFZ (Hein and Tshibubudze, 2007b; Boshoff et al., 1998).

Carbonate rocks in the Sadiola deposit are impure marble which consists of alternating beds of dark pelite-rich carbonate and light coloured carbonate rich beds (Hanssen et al., 1998). The carbonates include a massive, grey dolomite-marble and carbonaceous greywacke, and siltstone units which occur in a number of pits within the Sadiola goldfield (Hein and Tshibubudze, 2007a, b).

The igneous rocks at the Sadiola mine include diorite, lamprophyre dykes and quartz-feldspar porphyry. The diorite is composed of alkali-rich plagioclase and hornblende, and grades into coarse biotite-rich diorite which contains sulphides (Hanssen et al., 1998; Hein, 2008). This intrusion was characterized by Theron (1997a) as having similar composition as the TTG suite rocks, which are widespread across the WAC (WAXI, 2013).

The quartz-feldspar-porphyry (QFP) dykes have been recorded in outcrop in the Sadiola opencast (Hein and Tshibubudze, 2007a).The quartz porphyry host rare tourmaline crystals (Hanssen et al., 1998). QFP dykes often intrude along steep west dipping, NNE trending faults and crosscut the diorites (Robins, 2006).

Structure

The Sadiola deposit occurs in the steeply dipping, NNE striking SFZ and NE-trending fault splays Voet (1997). Hanssen et al. (1998) stated that the SFZ crosscuts all pre-existing structures and forms a fault contact between greywacke units on the west and marbles on the east of the pit. Hanssen et al. (1998) concluded that NE and NW-trending stacking faults crosscut the orebody; in contrast Voet (1997) stated that the NE trends are due to folds cross-cutting the orebody.

Hein and Tshibubudze (2007b) recorded that the Sadiola opencast contains an N-trending zone of north and NE-trending fractures, faults, and quartz-sulphide veins which cross-cut all metasedimentary sequences, NE-trending folds in the metasedimentary sequence, and tonalite dykes. The folds are crosscut and intruded by tonalite dykes indicating that folding preceded dyke emplacement whereas the tonalite dykes are crosscut by mineralised veins suggesting that quartz-sulphide vein were formed at a later stage (Hein, 2008).

Metamorphism

The Birimian sequence in which the Sadiola Hill deposit has been affected by metamorphism associated with the Eburnean orogeny (Hasting, 1982) with regional metamorphism to greenschist facies and contact metamorphism to hornblende-hornfels and epidote-chlorite facies (Hein and Tshibubudze, 2007a, b). The low-pressure greenschist facies is indicated by the mineral assemblage muscovite, chlorite ± biotite (Ledru et al., 1991). The greenschist facies mineral assemblage is fine grained and shows a granoblastic texture, and indicates biotite-chlorite alteration (Liégeois et al., 1991).

The contact metamorphism contains two zones, the inner and the middle aureole which is a result of the emplacement of tonalite-granodiorite plutons and the tonalite dykes (Hein and Tshibubudze, 2007a, b). The carbonates in the Sadiola Hill deposit are recrystallized to marbles and attained hornblende-hornfels facies in the inner aureole (Ledru et al., 1991; Hein et al., 2004). The middle aureole is characterized by epidote-albite facies and within it, primary sedimentary features are preserved (Hein and Tshibubudze, 2007b; Hein, 2008).

Gold mineralisation and metallogenesis

Gold mineralisation has been closely associated with the steep dipping SFZ, sub-parallel structures and minor faults splaying off the SFZ (Hanssen et al. 1998). Ranson (1998) further suggested that the main zones of mineralisation underlies the large diorite sill which intruded along thrust planes of the feeder zone within the SFZ, and because the SFZ has been modelled as the principle displacement zone of the D_2 event, therefore both the diorite intrusion and mineralisation were related to the D_2 event. In both cases, mineralisation has been recorded as to have occurred as disseminated around veins in wallrock and as massive lodes in quartz veins. Sulphides recorded in the deposit include pyrite, arsenopyrite, and minor chalcopyrite, sphalerite and galena (Hanssen et al. 1998).

Two metallogenic styles have been recorded in the Sadiola Hill deposit by Hein and Tshibubudze (2007a, b). This metallogenic styles include:

1. Placer gold in palaeochannels and screes in pits at FE3-1, FE3-3, and FE4. The palaeochannels in the deposit represent the Pan African erosional surface.

2. Gold mineralisation in breccia’s and stockwork veins which formed as a consequence of dilation of thrusts and faults, and fracturing of tonalite dykes.

2.4 Previously suggested genetic models

A number of different ore genesis models have been proposed for Sadiola Hill deposit. These include epithermal, Carlin-type, Skarn, thermal aureole and mesothermal models. This wide variety of models is a consequence of the relative absence of fresh sulphide mineralization for study, and most genetic models were based on observations of oxidized lithologies only (Boshoff et al. 1998). The most probable models are described in this section.

A report by Hanssen et al. (1998) suggested that Sadiola Hill mineralisation fits a structurally controlled shear zone or mesothermal genetic model due to the systematic assemblages of the alteration and distribution of mineralization found during the IAMGold drilling project, but this model does not explain the carbonic fluids and the base metals associated with gold in the deposit.

The intrusion related gold system in Sadiola Hill was suggested by Theron (1997b) when he observed that gold mineralization is closely related to the granodioritic and trondhjemitic diorite intrusive and related quartz-feldspar porphyry dykes. This was evident by the K-enrichment and metasomatism in both the granodiorites and the diorite. The late residual magmatic and metasomatic fluids resulted in K-metasomatism and carbonization together with gold mineralization.

A gold bearing skarn model similar to intrusion related gold was suggested for the deposit. Skarn deposits are related to magmatic-hydrothermal activity associated with plutonism in orogenic belts (Einaudi and Burt, 1982) with replacement of carbonate in the wall rock with sulphide mineralisation. This is set apart from other mineral deposits by the gangue, which is a coarse grained, generally iron-rich mixture of Ca-Mg-Fe-Al silicates, formed by metasomatic processes at relatively high temperatures (Meinert, 1992). In this style, carbonate host rocks are converted to marble, calc-silicate hornfels and/or Skarn by contact metamorphism.

Furthermore to this thermal aureole gold style was reported by Hein and Tshibubudze (2007a). This gold style describes a sub-division of orogenic gold deposits that are localized in the thermal aureole of plutons and form during dilatant deformation that post-dates pluton emplacement and thermal metamorphism. They are characterized by fine grained gold in a variety of mineralisation styles and are associated with pyrite, pyrrhotite and arsenic sulphides, with lesser occurrences of other common sulphides.

Chapter 3 Methodology

This research project focused on detailed petrographic analyses of the Sadiola Hill deposit host rocks from more than 114 thin sections of diamond drill core and was preceded by literature review.

The 114 selected samples of diamond drill core and other field data were collected in 2008 by Prof Kim Hein from 5 boreholes from the Sadiola Deep Sulphide project for a total borehole meterage of 1966.02 metres. Core logging was completed after the sample collection. The boreholes intersected the Sadiola Hill deposit, and transect from the hangingwall greywacke sequence in the west to the footwall carbonate sequence in the east.

Thin sections were cut and prepared by SGS laboratories in Booysen in Johannesburg.

The petrographic study (reflected and transmitted light) was completed at the University of the Witwatersrand, Johannesburg using an Olympus BX14 Petrographic microscope with a dedicated camera in conjunction with the Stream Essentials© software. A number of thin sections were studied in detail with the main focus on the mineral assemblages, mineral textures, cross-cutting relationships, and alteration assemblage and sulphide mineralogy. The results were recorded and used to determine a paragenesis sequence for the deposit. Indicator minerals were used to characterise the type of deposit, enabling comparison and validation of ore genetic models for the deposit.

Other boreholes from the Sadiola Hill deposit were used to design a 3D model of the deposit using Gemcom Surpac 6.5.1 software from the Mining Engineering computer lab.

The petrographic study was preceded by literature review using the Sadiola mine reports by SEMOS together with other published and unpublished articles to gain an understanding of the regional and local geology of the study area.

The table presented below show the orientation of the boreholes which were used in this study which are also indicated in Figure 3.

Sadiola Grid						
DDH	**UTM**	**ELEVATION(m)**	**AZIMUTH**	**DIP**	**END OF HOLE**	**DRILL TYPES**
SD 022	E50459.21 N5650.04	127.93	100	60	508	0-29 HQ; 29-508 NQ
SD 042	E50525 N6400	125	90	60	26702	0-90 RC; 90-267.2 DD
SD 119	E50684.06 N4901.452	126.29	100	55	501	0-120 RC; 120-501 NQ
SD 129	E50625.26 N4892.795	128.25	100	55	201	0-90 RC; 90-501 NQ
SD 782	E51180 N5146	106.95	300	51	489	0-92 RC; 92-489 DD

Figure.4 Schematic of the Sadiola main pit indicating locations of boreholes (red boxes) which have been studied in this project.

Chapter 4: Host rocks in drill core

Sample descriptions included descriptions of the rock types in macroscopic (drill core) and microscopic scales (thin sections), associated alteration assemblages, and silicate and sulphide minerals. In general, the drill cores have same rock types but different mineral textures and alteration assemblages.

4.1 Drill core description

The lithologies observed from the studied boreholes are meta-greywacke and marble, the meta-greywacke generally overlies the marble. In all boreholes, the units contain slump folds which are dominated by chloritoid spots (Fig. 5a). The slump folds generally occur at depth after vein cross-cuts.

Chloritoid and/or chlorite spots are also observed in greywacke that has been hornfelsed. Both the greywacke and marble are cross-cut by quartz-carbonate and quartz-sulphide veins which in some areas form an array of stockwork veins (Fig. 5b). The marble unit are brecciated (Fig. 6a). The major alteration types observed are calc-silicate, potassic (red staining), chloritization, and silicification. The potassic alteration occurs mainly in the units west of the Sadiola Hill pit and can be clearly seen in borehole SD 042. At the scale of boreholes, the potassic alteration occurs around and within quartz-carbonate veins (Fig. 6b), the last one being only limited to marble breccia. Potassic alteration is overprinted by chlorite alteration on the western side of the pit (Fig. 6c). Other alteration types associated with veins include hornblende-biotite and chlorite-epidote alteration. Epidote hornfels occurs in the eastern side of the pit and represents the epidote-chlorite facies. Hornblende occurs on the contact of meta-greywacke and marble; this might suggest a possible transition zone of metamorphic facies from epidote-albite facies in the east of the pit to hornblende-hornfels facies in the west of the pit.

All the boreholes studied intersected tonalite dykes at depth greater that 300m before intersecting massive sulphides and hornfels. The massive sulphides make up the main portion of the Sadiola Hill orebody. Ore minerals are oxidised (e.g. pyrite) but pyrrhotite can still be recognised.

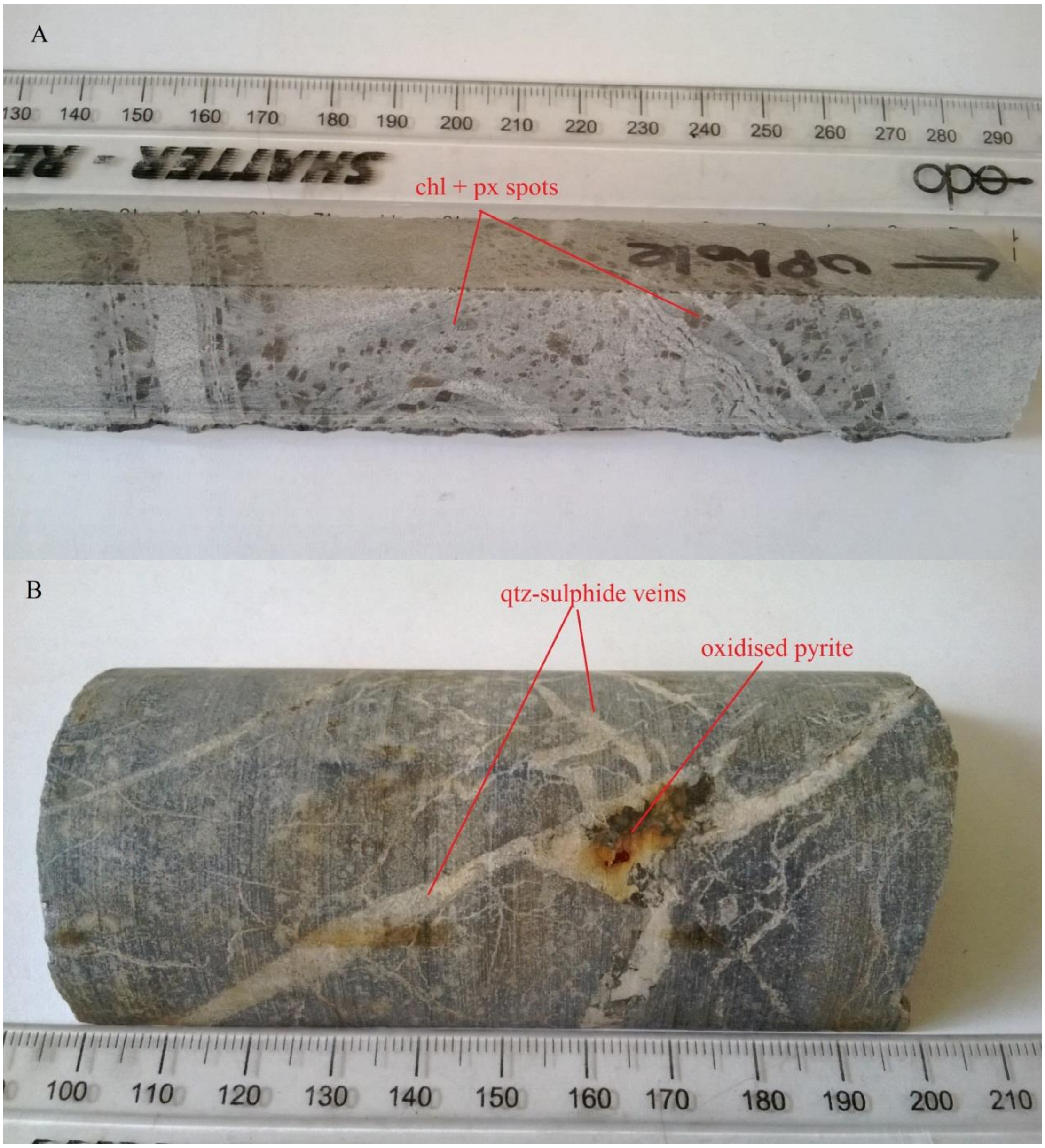


Figure 5: Drill core samples. (a) Sample SD782- 31; slump folds with chloritoid and pyroxene porphyroblasts. (b) Sample SD048- 92; quartz-sulphide veins cross cutting each other and forming an array of contraction spider veins. Pyrite in (b) has been oxidised.

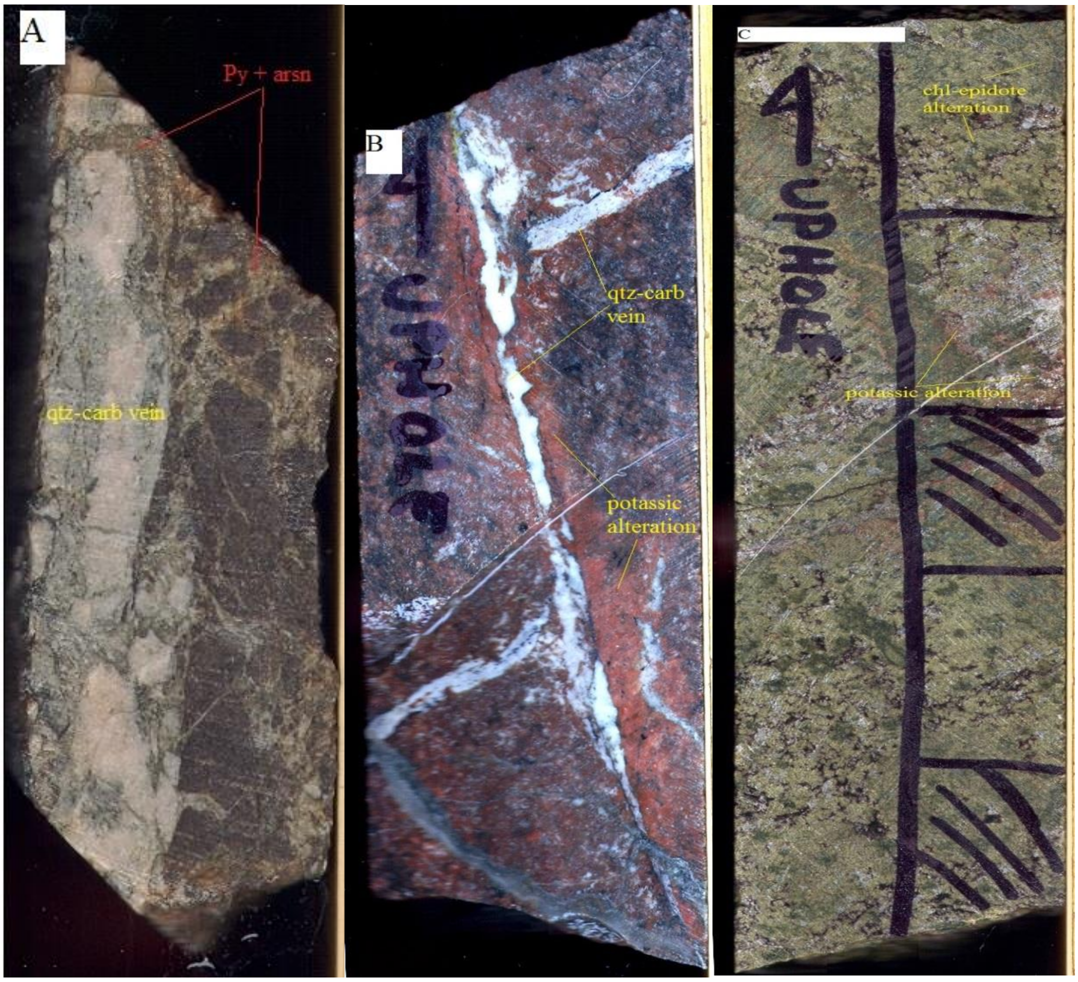


Figure 6: Drill core samples. (a) Sample SD022-49; breccia vein in marble with mineralisation in microfractures. (b) Sample SD042-86; potassic alteration (red) surrounding quartz-carbonate veins. (c) Sample SD129-74; chlorite-epidote alteration (green) overprinting potassic alteration (red).

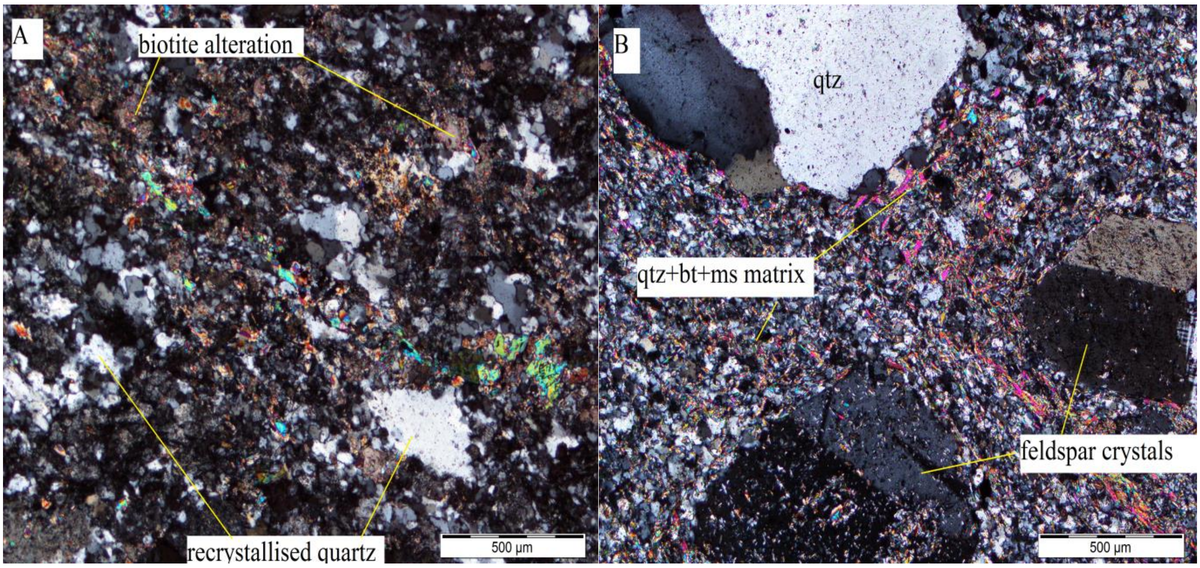
4.2 Mineral textures of host rocks

As described in Section 4.1, the lithologies intersected by the boreholes comprise metamorphosed greywacke, marble and tonalite dykes. Microscopically, the meta-greywacke consists of fine grained sub-euhedral quartz, biotite, rutile, albite and epidote crystals, which form part of the matrix and show a granoblastic polygonal texture (Fig. 7a). Albite, rutile and epidote are secondary minerals in these rocks and may indicate that metamorphism reached temperatures in the range of epidote-albite facies. The mineralogy of the meta-greywacke shows a randomly orientated mineral texture seen from the biotite crystals. In general, biotite crystals have retrogressed to chlorite and/or vermiculite. The most common alteration assemblage in this rock type is sericitic-potassic-chloritic alteration, although in most cases, potassic alteration overprints sericite alteration.

The marble mainly consists of dolomite, quartz and minor biotite (Fig. 7c). The dolomite crystals are recrystallized and contain inclusions of late stage quartz. Sulphides in marble coexist on grain boundaries and in vein-wallrock contact with biotite. Siderite, an iron carbonate mineral, coexists with adularia forming rusty stains within carbonate veins in marble breccia. A complex alteration assemblage is present, but carbonate alteration is the most common.

Tonalite dykes have intruded the meta-greywacke and marble and consist of large quartz and plagioclase crystals in a fine grained quartz-biotite matrix forming a phaneritic texture (Fig. 7b). The quartz and plagioclase contains inclusions of biotite and pinkish muscovite. Pyroxene and hornblende are common accessory minerals. Tourmaline is present in the fine grained units (slump folded), and also as large crystals together with biotite and quartz inclusions in a biotite-chlorite matrix.

The ore host rocks are completely composed of sulphide mineralisation which includes pyrite, pyrrhotite, sphalerite, galena, arsenopyrite, chalcopyrite and gold in alteration zones and in fractures. Gold is mainly associated with arsenopyrite and pyrite on sulphide boundaries although it is also found in fractures as discrete grains.



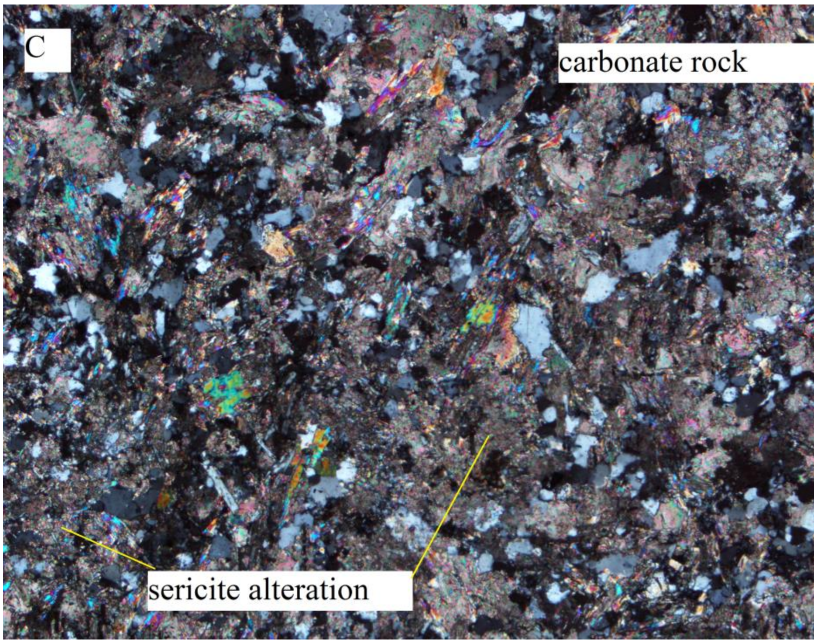


Figure 7: Microscopic images (in plane polarised light) of the host rocks. (a) Sample SD042-84b; biotite alteration in greywacke matrix. (b) Sample SD782-50a; porphyritic texture in tonalite with feldspar and quartz being the major minerals. (c) Sample SD042-83c; sericite alteration in a carbonate rock.

4.3 Mineral textures of vein system

Drill core studies revealed a number of vein systems in the Sadiola Hill deposit. The vein types include:

Type 1: quartz-carbonate veins, which are the most common in the deposit. They crosscut both the meta-greywacke and the marble units,

Type 2: quartz-epidote-chlorite veins which only occur in alteration zones; and

Type 3: quartz-sulphide veins which also occur in both host rocks and are highly mineralised compared to other vein systems.

In general, the quartz-sulphide veins form stockwork and spider veins which cross-cut the quartz-carbonate and quartz-epidote-chlorite vein systems. This texture indicates that the quartz-sulphide veins formed after the other veins.

Gold mineralisation is observed in all vein systems but also in vein-wallrock contacts, particularly in alteration zones around veins. The gold occurs on the margins of arsenopyrite and pyrite although can also be observed as discrete grains within fractures and on grain boundaries (Fig. 8c, d). The veins are composed of recrystallized quartz, calcite, albite, biotite overgrowth on quartz-carbonate veins and quartz being the only mineral in quartz-sulphide veins. The quartz-epidote-chlorite veins are mainly composed of secondary mineral that include epidote and chlorite. The main sulphides in these veins include pyrite, pyrrhotite, marcasite, chalcopyrite and minor galena and sphalerite.

Only two fill events were recorded in quartz-carbonate veins. This includes an early stage of quartz fibre fill, and a late stage sulphide fill that occurred during fracturing, i.e. episodes of fracturing had taken place throughout the development of the deposit.

The early stage of vein fill was dominated quartz and carbonate, which are also major constituents of the host rocks; these vein filled by syntaxial growth of the quartz-carbonate. The alteration zone around the veins is characterised by pervasive potassic alteration and chloritization but a zone of hornblende-biotite, epidote-chlorite, sericite and tourmaline can also be observed.

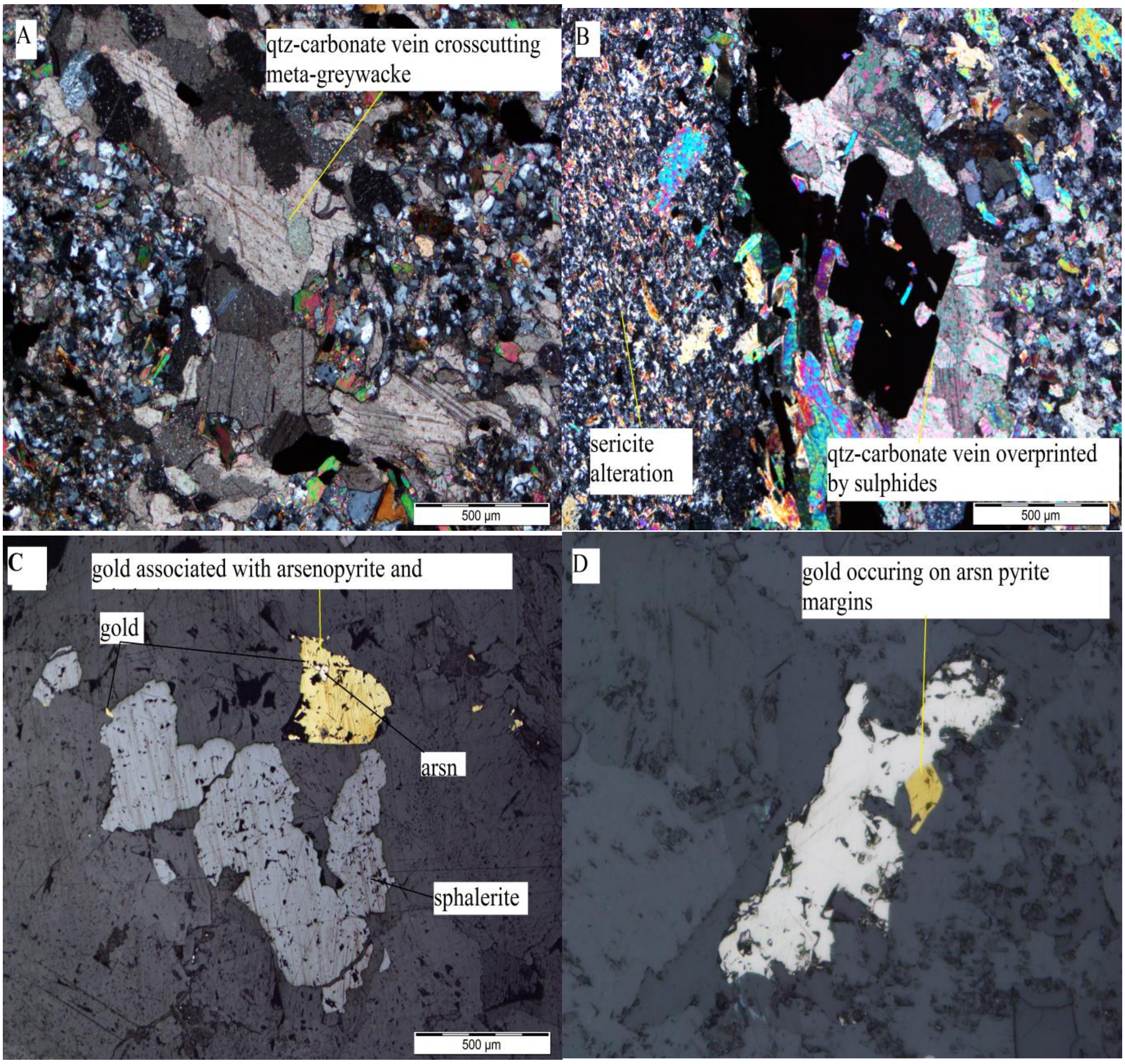


Figure 8: Quartz-carbonate veins and gold mineralisation. (a) Sample SD129-70b; quartz-carbonate crosscutting a meta-greywacke. (b) Sample SD129-69a; quartz-carbonate vein overprinted by sulphides and surrounded by a sericitic alteration. (c) Sample SD119-64; gold associated with late stage arsenopyrite and sphalerite. (d) Sample SD129-67; gold occurring in arsenopyrite margins (scale = 50µm).

Chapter 5: Petrography

A number of thin sections (~114) were studied using a reflected and transmitted light microscope with the main focus on mineral and sulphide textures, and deformation textures. These studies helped to develop a paragenesis sequence of mineralisation.

5.1 Mineral textures of quartz-carbonate veins in the Sadiola Hill deposit

The Sadiola Hill deposit has complex mineral textures in quartz-carbonate veins due to fracturing events, brecciation of the host rocks, alteration and crosscutting relationships. The quartz-carbonate sulphides are dominated by sulphides, silicate, and carbonate minerals that form an aggregate. These minerals and sulphides are not greatly affected by deformational events but are affected by supergene processes. The mineral textures of the deposit are described in four different sections which consider the following:

1. Vein mineralogy

2. Sulphide textures

3. Deformation events and textures’

4. Supergene processes and textures

5.1.1 Vein mineralogy

The vein mineralogy is dominated by silicate and carbonate minerals. The silicate is mostly dominated by quartz that is fractured. Quartz occurs in early stage vein fill and as fill to late stage fracturing events, and hosts pyrite and chalcopyrite inclusions. The occurrence of early stage and late stage quartz indicate that quartz precipitation was persistent throughout vein formation. Three quartz types were recorded during this study:

1. Quartz 1 which is highly fractured and sealed with fibres (Fig. 9a)

2. Quartz 2 is recrystallized and has irregular boundaries which suggest grain boundary migration due to deformation (Fig. 9b).

3. Quartz 3 comprises grains which overprints and forms inclusions in sulphides (Fig 9c).

In most of the thin sections studied, biotite occurs as an overgrowth in vein-wallrock contacts, and is closely associated with pyrite and pyrrhotite (Fig. 9d). This suggests that biotite was stable during the early stages of vein formation. Biotite which is in contact with sulphides forms anhedral crystals and it has regressed to chlorite (Fig. 9d), vermiculite and rutile. Chlorite and sericite minerals are the most dominant in alteration zones around the veins and in most cases, chlorite replaces biotite.

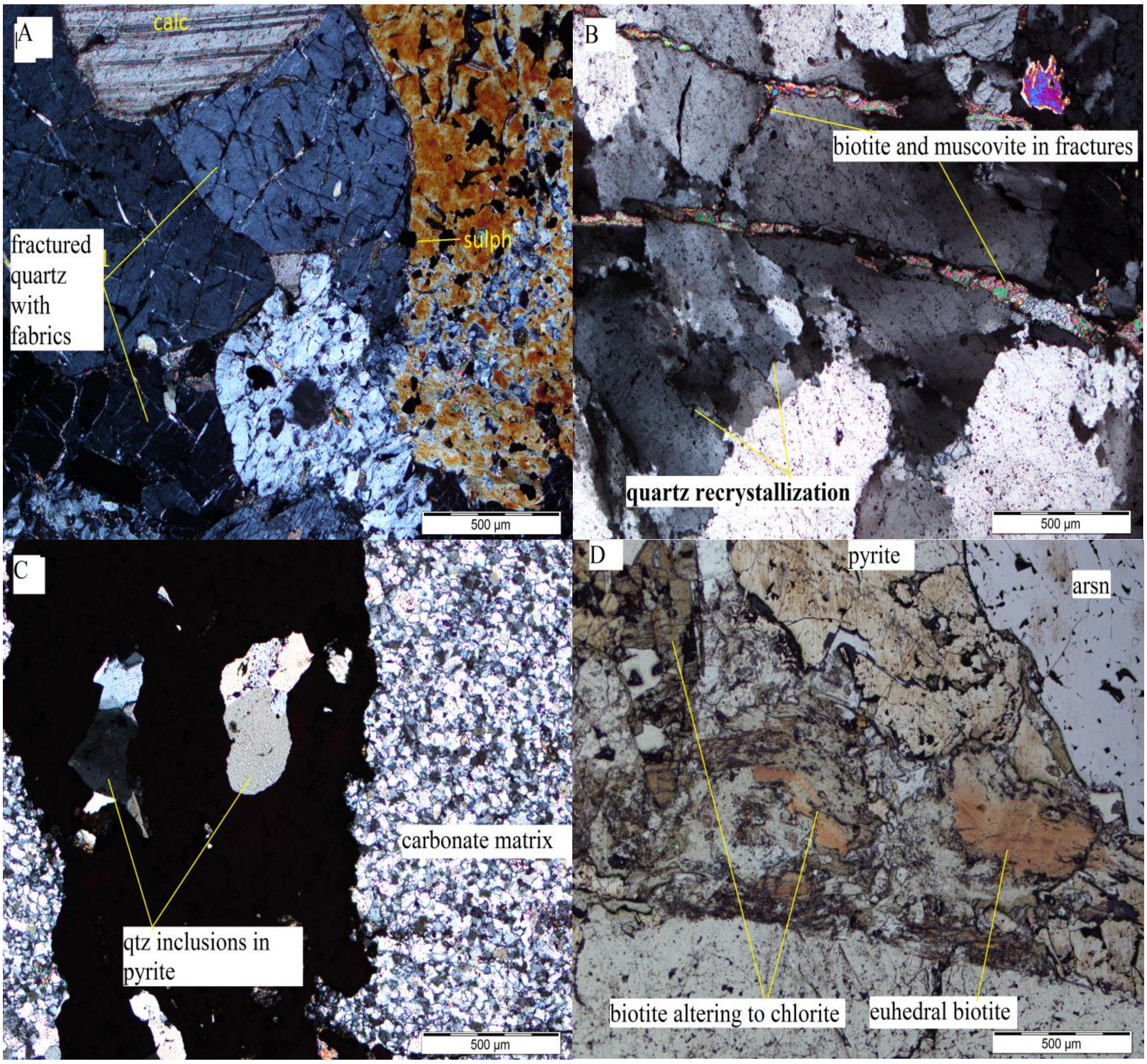


Figure 9: Quartz paragenesis in plane polarised light. (a) Sample SD022-44; highly fractured quartz with fabrics (qtz 1). (b) Sample SD782-23b; recrystallized quartz and fissural alteration (qtz 2). (c) Sample SD782-23a; quartz inclusions in pyrite (qtz 3). (d) Sample SD129-71; euhedral biotite in contact with pyrite and pyrrhotite and altering to chlorite.

5.1.2 Sulphide textures

Sulphides grains in the veins occur with silicate and carbonate minerals. Therefore are also fractured and brecciated. The sulphides also underwent supergene processes. The sulphides exhibit (1) granoblastic polygonal texture, (2) crack-seal fibre texture in quartz, (3) colliform texture, and a (4) sulphide replacement texture that is mostly common in polysulphides. Pyrite is the most abundant sulphide in the Sadiola Hill deposit and commonly alerted to marcasite. Marcasite is a supergene sulphide which forms by the decomposition of pyrite and as a replacement of pyrrhotite. In some samples, pyrite and pyrrhotite occur together with pyrite replacing pyrrhotite; this indicated that pyrite and pyrrhotite were once stable at the same time during vein formation. Three types of pyrites were recorded during this study:

1. Pyrite 1 which replaces early pyrrhotite and contains chalcopyrite inclusions.

2. Pyrite 2 which is mostly associated with marcasite and forms a colliform texture (Fig. 10a).

3. Pyrite 3 which occurs in microfractures and pore spaces which indicates late stage precipitation of pyrite (Fig. 10b).

Chalcopyrite is present in early pyrite as an inclusion suggesting that it precipitated after pyrite (Fig. 10d). Chalcopyrite also occurs with pyrite 3 in microfractures in the wall rock and with arsenopyrite. Pyrite 3 is a late stage sulphide and this suggests the same for gold and arsenopyrite as they are closely associated. Gold occurs mostly in pyrite 3 and on the margins of arsenopyrite.

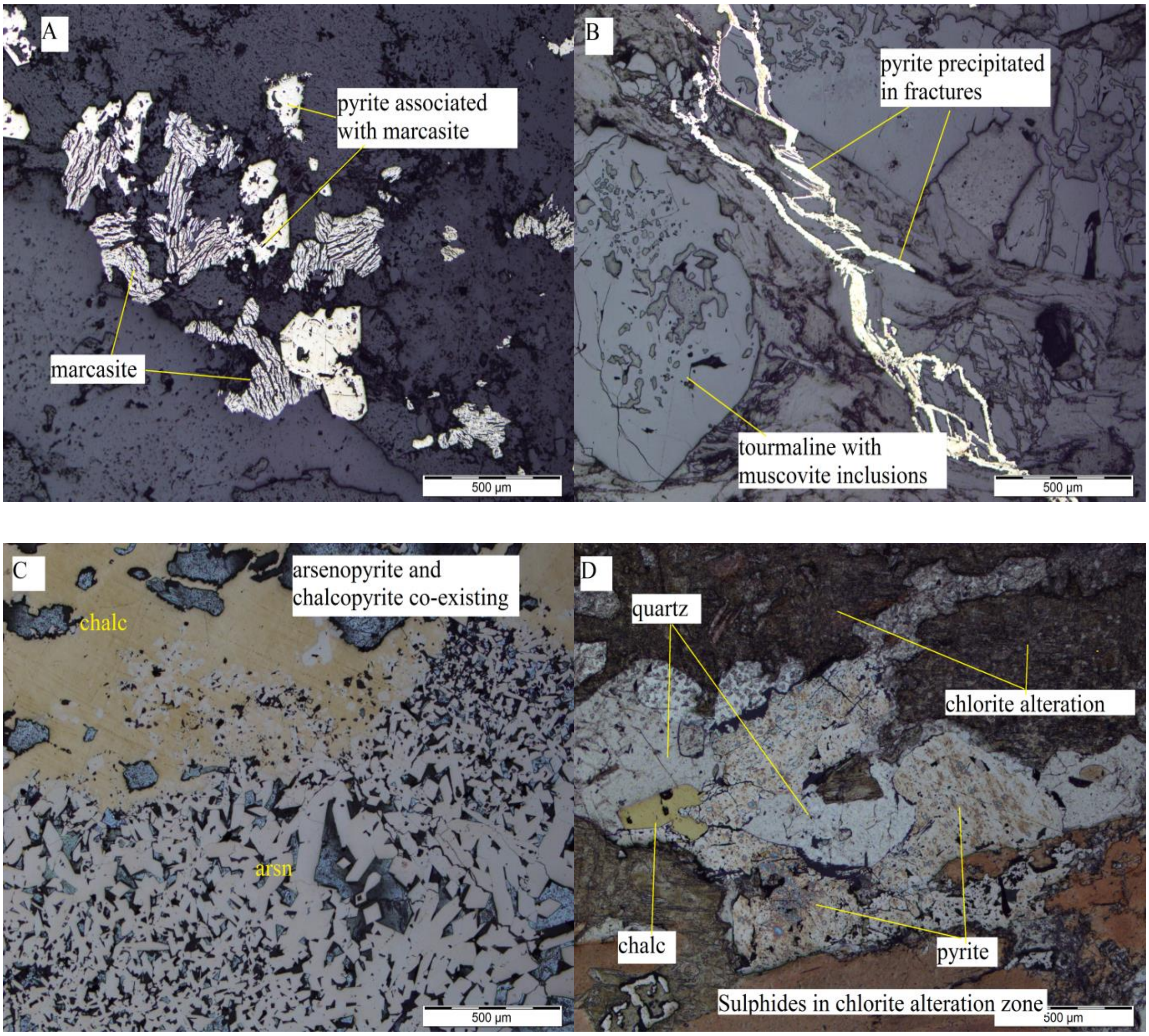


Figure 10: sulphide paragenesis. (a) Sample SD119-58a; pyrite associated with marcasite which forms a colliform texture (pyrite 2). (b) Sample SD119-60b; pyrite in fractures around tourmaline crystals

(pyrite 3). (c) Sample SD782-32a; arsenopyrite and chalcopyrite coexisting indicating that they formed at the same time. (d) Sample SD129-71b; quartz and chalcopyrite inclusions in pyrite which is surrounded by chlorite alteration.

5.1.3 Deformation events and textures

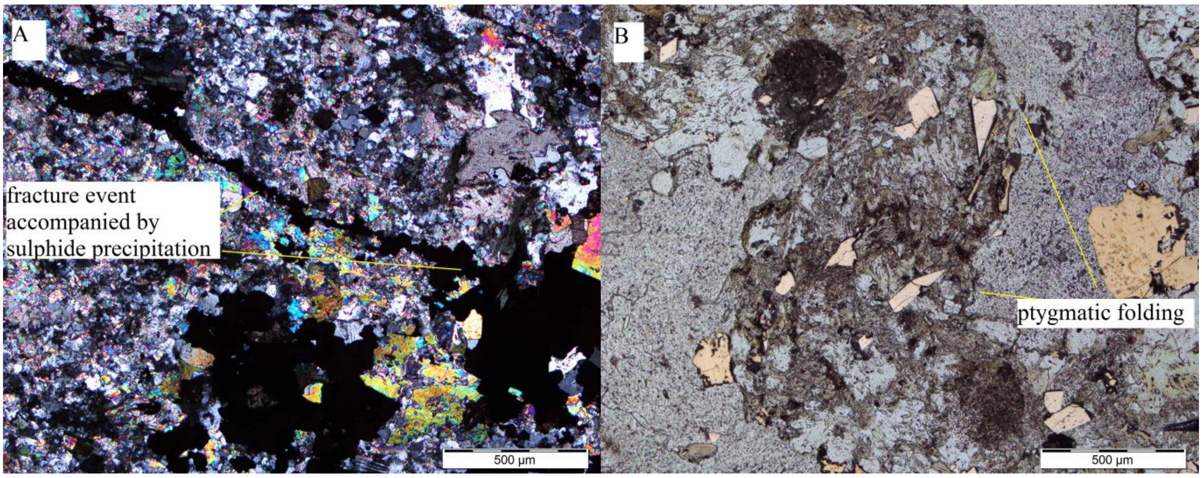
Deformation in sulphides, silicate and carbonates is not extensive. Fracturing and brecciation are the most common deformational textures recorded in this study although a micro-fold was observed in one thin section. Fracturing and brecciation are cataclasis textures and these were exhibited predominantly by quartz and pyrite. Five types of deformational events have been recorded based on crosscutting relationships:

1. Continuous fracturing which occurred during formation of crack-seal quartz-sulphide veins.

2. Fracturing which accompanied precipitation of quartz 3 which crosscuts pyrite (Fig. 11 a, c).

3. Fracturing which accompanied replacement and precipitation of pyrrhotite by chalcopyrite and quartz 3.

4. Ptygmatic folding in wall rocks suggesting small scale compression (Fig. 11b).



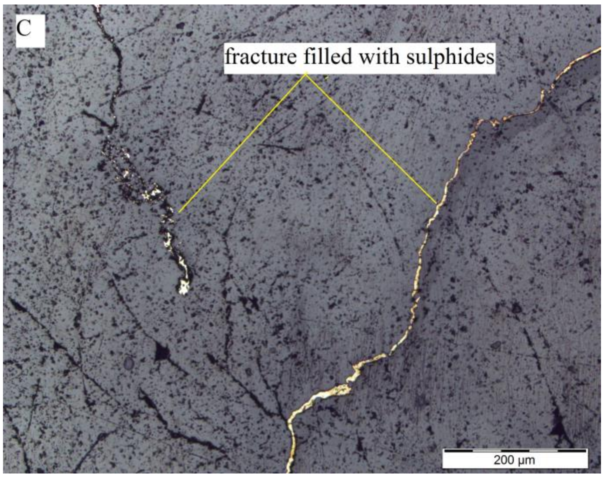


Figure 11: Deformational events. (a) Sample SD782-23a; fracture filled with sulphides. (b) Sample SD782-30 (XPL); ptygmatic folding with sulphides hosted within the fold structure. (c) Sample SD129-70; fracture filled with sulphides (reflected light).

5.1.4 Supergene processes and textures

Supergene alteration is common in the Sadiola Hill deposit because of weathering and oxidation of the host rocks. Supergene alteration is responsible for the replacement of pyrrhotite by pyrite and decomposition of pyrite to supergene marcasite. Supergene alteration in this study was evidenced by:

1. Replacement of pyrite to form a colliform texture

2. Pyrite being replaced by marcasite but retaining its appearance.

5.2 Paragenetic sequence

The paragenesis sequence is based on the crosscutting relationships outlined above. From this detailed analyses, it can be established that:

1. Pyrrhotite 1 and 2 was the first sulphide to be precipitated in the deposit.

2. A fracturing event was responsible for stopping pyrrhotite precipitation and as part of the crack-seal events; the fracture was filled by chalcopyrite and quartz 2.

3. Replacement of pyrrhotite 2 and 3 by pyrite 1

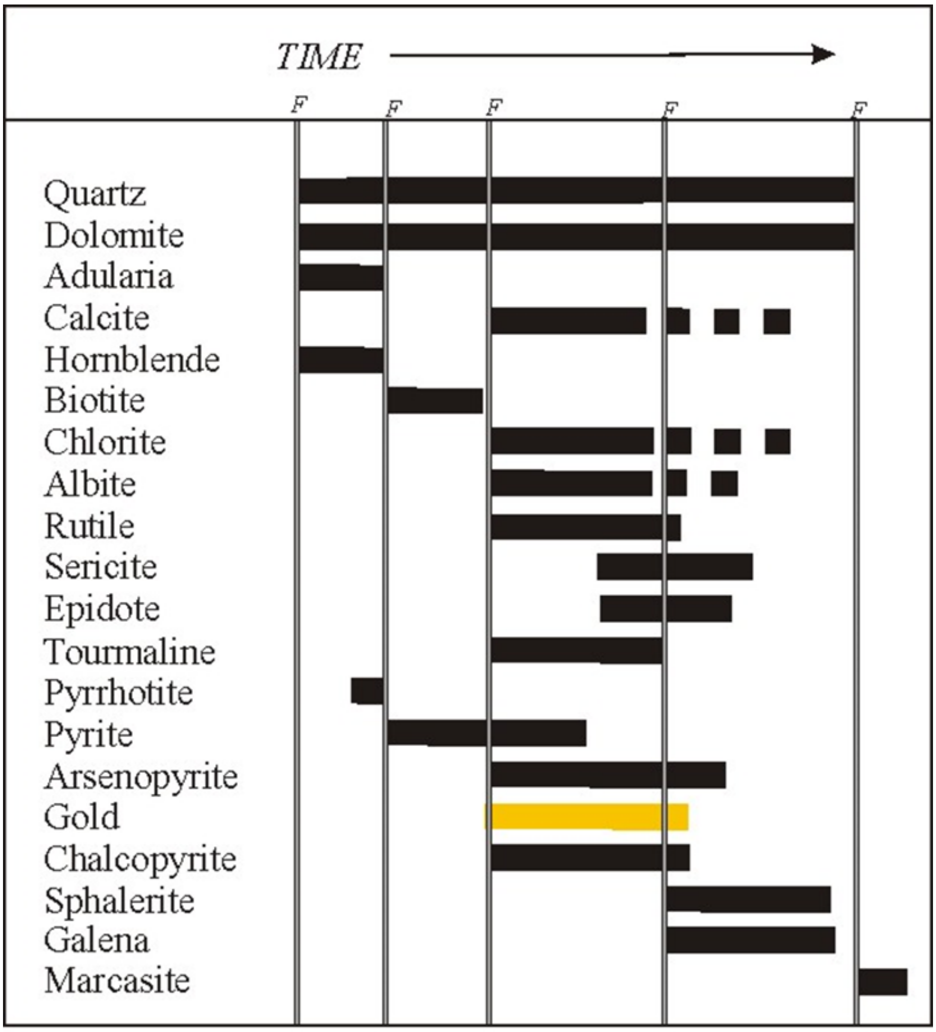
4. Fracturing event stopped precipitation of pyrite 1 and the fracture was filled by pyrite 2 and quartz 3.

5. Pyrite 2 was succeeded by formation of marcasite.

6. Precipitation of pyrite, arsenopyrite and chalcopyrite. The pyrite and arsenopyrite are associated with gold mineralisation.

7. Precipitation of sphalerite and galena immediately after precipitation of pyrite 3 and arsenopyrite.

The paragenesis of the mineralogy in the vein systems and the surrounding secondary minerals indicates that quartz precipitated throughout ore deposit formation. The fracturing event which formed the crack-seal texture in fibrous quartz 1 preceded precipitation of quartz 2, tourmaline and biotite; this was in turn preceded by quartz 3. Formation of chlorite, biotite and sericite during precipitation of pyrrhotite 1; this caused the biotite overgrowth in vein-wall rock contacts. Fresh sulphides were precipitated in all fracturing events detailed in the deformational textures section, this was continuous during vein formation. The paragenesis sequence has been summarised in the table below.



F = Fracturing Events

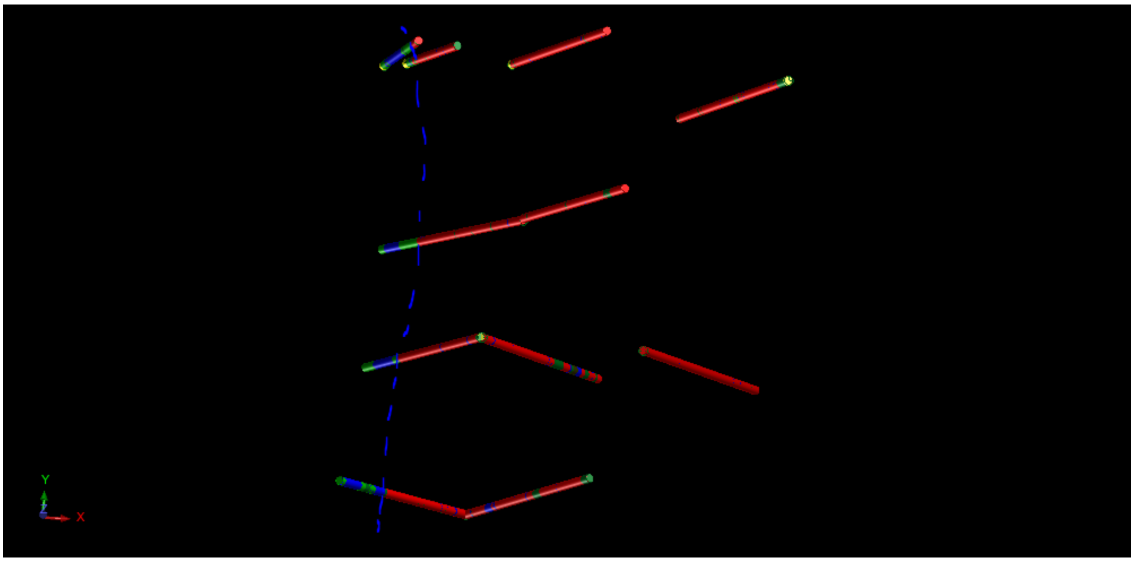
Chapter 6: Orebody modelling

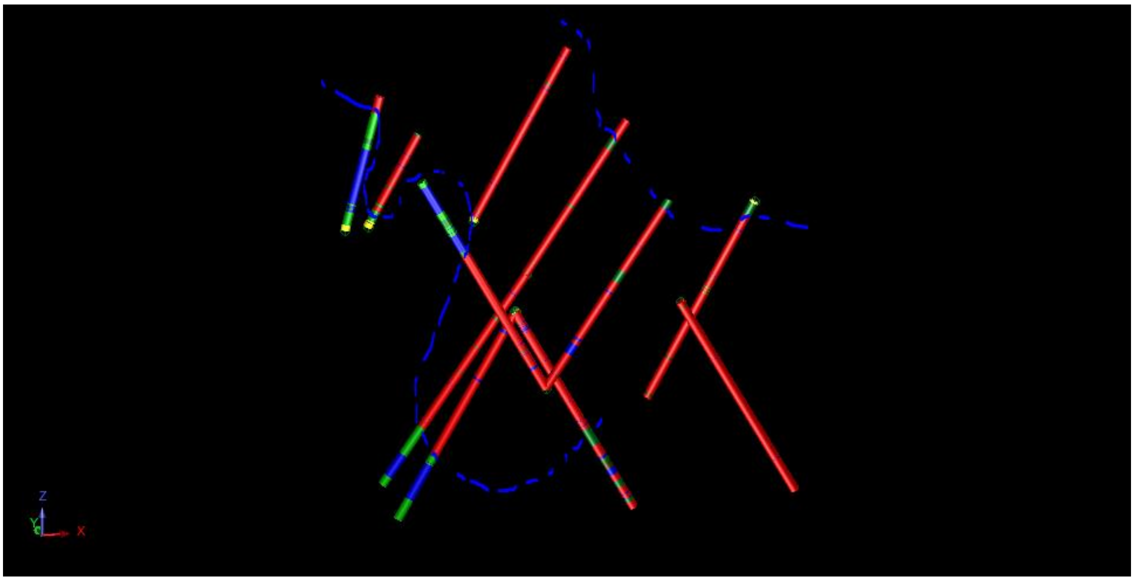
Modelling of the Sadiola Hill deposit was carried out using Gemcom Surpac software to define lithological contacts and to map alternation in the Sadiola Hill deposit, but did not prove to be useful. The software showed the contact relationship between the mineralised marbles and the overlying greywacke in boreholes in a gross way.

The software was used in an attempt to show the relationship between the meta-sedimentary rocks, granitoid intrusions and mineralisation from boreholes in the Sadiola Hill deposit.

6.1 Software Limits

Unfortunately, the software did not model the lithological contacts well and only recognises horizontal sections. As a result, all the host rocks are shown as a horizontal box, which was not ideal. Vertical granodiorite dykes were also modelled automatically as horizontal elements which was not logical; the software takes the upper and lower contacts of the element in each borehole and correlates them laterally rather than allowing in input parameters that models them as vertical. Mineralisation occurs in the marbles as massive and disseminated, but because the software cannot separate massive with disseminated sulphides, it shows that the whole pit is an orebody which is not the case in the Sadiola Hill deposit. Thus modelling of the orebody using the Gemcom Surpac was not useful.


Y
X


Z
Y
X

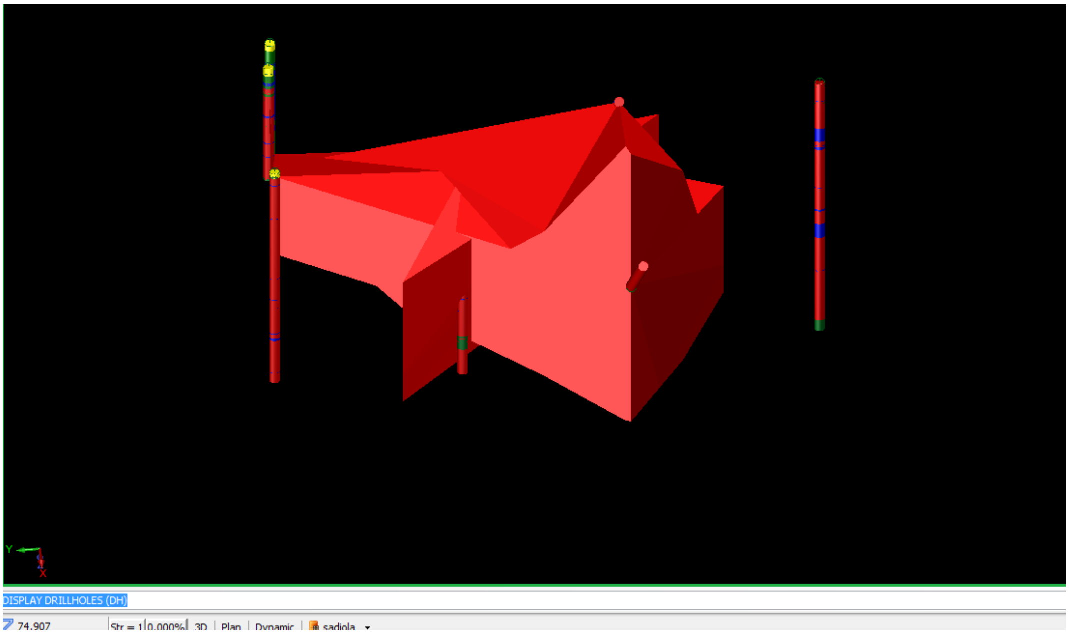

Y
X
DISPLAY DRILLHOLES (DH)
74.907
Str = 1
0.000%
3D
Plan
Dynamic
sadiola

Figure 12: The images above show the boreholes and the location of the host rocks with respect to the boreholes and each other. Diorite is marked in the boreholes, but is not modelled due to software limits which were illustrated above. In the images, marble is shown in red, and meta-greywacke in green. Image 3 and 4 contain a blue dotted line which shows the contact between the meta-greywacke (west of pit) and the marble (east of pit).

Chapter 7: Discussion

7.1 Macroscopic interpretation

The mineral assemblage observed west of the deposit is characterised by quartz-K-spar-chloritoid-hornblende-biotite, which characterises hornblende-hornblende facies metamorphism. To the east of the deposit, the mineral assemblage is characterised by epidote-chlorite-albite which characterises epidote-chlorite facies metamorphism. The two are interpreted to represent low pressure and high temperature contact metamorphism conditions and can be considered to be part of a metamorphic aureole. The gold bearing zone is situated at the contact of the two metamorphic zones.

In terms of temperature differences, it can be interpreted that cooling occurred from east to west with the source of heat situated south-west of the deposit. The transition zone is represented by hornblende which occurs on the contact of meta-greywacke and marble. The contact metamorphic facies occur in close proximity to local tonalite-granodiorite and quartz-porphyry intrusions. The occurrence of contact metamorphic facies adjacent to intrusions is interpreted to have formed during emplacement of these intrusions. Similar facies were recorded by Hein and Tshibubudze (2007a) for the deposit. In their study, they recognised that the contact boundary for the two facies is marked by a north-south trending biotite isograd; the contact boundary was also a zone of mineralisation in the deposit. The quartz-porphyry and the biotite isograd occur close together and have the same orientation which might indicate that they have a spatial relationship with mineralisation.

The recorded slump folds in the meta-sedimentary sequences which are dominated by chloritoid spots and porphyroblast pyroxene are similar to those recorded in the nearby FE3 pit by Matabane (2008). The FE3 pits are also situated within the Sadiola goldfield (Fig. 12) and contain similar host rocks to those of the Sadiola Hill deposit. The slump folds indicate a period of folding in the deposit and are interpreted to be related to the D1 tectonic phase described by Milési et al. (1989, 1992). Folding and thrusting events are typical for the Birimian formations (e.g. Kadio et al. 2010; Junner, 1935).The slump folds are crosscut by tonalite dykes, which indicates that folding occurred at an earlier stage.

Original minerals in the host rocks have been slightly and/or completely changed to new minerals. This is observed in alteration zones were plagioclase has been replaced by carbonate (dolomite ± calcite) and locally by albite, while biotite is slightly replaced by chlorite, rutile and vermiculite. Mineral replacement reactions take place primarily by dissolution-reprecipitation processes. This includes: cation exchange, chemical weathering, deuteric alteration, leaching, pseudormorphism, metasomatism and metamorphism (Putnis, 2002). The occurrence of biotite in vein-wallrock contacts in the Sadiola Hill deposit is indicative of either metasomatism and/or metamorphism reactions. Metasomatism can be seen by growth of large euhedral biotite along vein-wall rock contacts. The texture is consistent with that described by McFarlane et al. (2011) for the Morila gold mine in southeast Mali, which is classified as intrusion related gold deposit.

The brecciated units are scattered around the contact aureole of the tonalite-granodiorite (Matabane, 2008) and formed as a result of high pressure fluid circulation or by dilantacy accompanied by hydraulic fracturing during emplacement of the granodiorite dykes (e.g. Ethendge, 1983). The former correlates with skarn development described by Theron (1997a).

The hydrothermal minerals in the Sadiola Hill deposit are randomly orientated (i.e. they show no sign of preferred orientation); this suggest that there was no to low pressure involved at time of metamorphism. Low pressure metamorphism is typical to intrusion-related gold deposits (Land and Baker, 2001), and therefore conclusion that can be made is that contact metamorphism of host rocks in the Sadiola Hill deposit is associated with the adjacent tonalite-granodiorite and/or quartz-porphyry dykes. Tourmaline is a common accessory mineral in metamorphic rocks spanning a wide of bulk compositions (e.g., Henry and Dutrow, 1996), and has P-T conditions ranging from diagenesis to the granulite and eclogite facies (Henry et al. 1999, Marschall et al. 2009). This mineral is also common in the Sadiola Hill deposit.

7.1.1 Vein systems

Two vein systems occur in the Sadiola Hill deposit; quartz-carbonate and quartz-sulphide veins. The tonalite-granodiorite dykes are cross-cut by this vein which indicates that they post-date dyke emplacement. The quartz-sulphide veins cross-cut quartz-carbonate veins indicating that they formed after them. The fractures responsible for formation of quartz-sulphide veins are interpreted as to be related to dilatancy accompanied by hydraulic fracturing. The veins are surrounded by sericite alteration which indicates that it formed at the time of vein formation. The mineralised quartz-carbonate veins might be related to the quartz-feldspar porphyry intrusion which cut through the tonalite-granodiorite dykes and have an orientation similar to that of the orebody (i.e. SSE).

7.1.2 Alteration

The host rocks show pervasive hydrothermal alteration with an associated assemblage of quartz-chlorite-carbonate-k-spar-sulphide, and a more pervasive sericite alteration which encloses veins and is associated with mineralisation. This assemblage is similar to the alteration assemblage which characterises intrusion-related deposits (e.g. Thompson et al, 1999; Lang and Baker, 2000). Potassic alteration is overprinted by chlorite alteration in the far western side of the pit; this might indicate a cooling trend from east to west. The potassic alteration contains adularia (mainly in breccias) which is specific for the epithermal systems associated with volcanic rocks (Damian, 2003). Sericite grades to potassic alteration in close proximity with the high temperature hornblende-hornfels, indicating a cooling trend from the high temperature potassic alteration to the low temperature sericite alteration. Cooling features and formation of potassic alteration in high temperature zones indicate that alteration formed during retrograde metamorphism; therefore the tonalite-granodiorite dykes are responsible for alteration in the wall rocks. Evidence of fluid circulation in granodiorite dykes is represented by sericitazation and has been interpreted by Matabane, (2008) as a result of dissolution and re-precipitation related to fluid movement. Sericite alteration in granodiorite suggests that there was fluid movement after emplacement of the dykes. The fluids might be related to mineralisation as the mineralised veins cross-cut the tonalite dykes.

7.2 Petrography

The crack-seal and open space fill events recorded in the wall rocks are the result of vein growth, mostly quartz-carbonate and quartz-sulphide veins. The crack-seal textures indicate hydraulic fracturing during fluid-flow events (Goldfarb et al., 2005). Sulphide precipitation is associated with biotite in vein contacts and biotite-chlorite alteration in wall rocks surrounding the veins. These suggest that the alteration occurred at the time of sulphide precipitation (i.e. from the same hydrothermal fluid).

Pyrite and marcasite replace early pyrrhotite which is interpreted as to be a result of dissolution-re-precipitation reactions described by Putnis, (2002). Early pyrite has decomposed to marcasite showing a colliform texture suggesting a very acidic fluid (i.e. low pH). Early pyrite is crosscut by late stage euhedral arsenopyrite. Arsenopyrite, pyrite and/or pyrrhotite are both associated with gold forming an arsenopyrite+pyrite+gold±pyrrhotite assemblage which is described by Lang and Baker, (2000), as characteristic of intrusion-related gold deposits. Pyrrhotite is replaced by pyrite and marcasite. Sphalerite and galena are associated with late arsenopyrite; precipitation might have been coeval with/or preceded arsenopyrite.

The sulphides present indicate a polymetallic deposit which is characteristic of fluids derived from magmatic sources, as defined by Thompson et al. (1999). Gold, pyrite 3 and arsenopyrite were precipitated at a later stage and thus coexist. Precipitation of this assemblage is interpreted to have been coeval with potassic alteration (Boshoff et al., 1998), although in most cases they are associated with biotite-chlorite alteration in vein margins and in the wall rock matrix. The distribution of gold and sulphides in alteration zones indicates that they are of hydrothermal epigenetic origin. The biotite isograd associated with gold mineralisation marks the boundary between the inner and middle contact aureoles which occurs along the Sadiola Fracture Zone, which might have been a pathway for the gold bearing hydrothermal fluids.

7.3 Gold mineralisation

Gold mineralisation in the Sadiola Hill deposit occurs within or adjacent to quartz-carbonate veins. Therefore the deposit is interpreted to be epigenetic in origin. Two styles of mineralisation were recorded in the deposit: (1) quartz-vein mineralisation, in which gold is found in pyrite margins and in grain boundaries and (2) a disseminated mineralisation style where gold occurs as individual grains with other sulphides in alteration zones. The gold mineralisation styles correlate with the types of mineralisation in West Africa which have been distinguished by Milési et al. (1989).

Disseminated mineralisation mostly occurs in brecciated and altered zones around granodiorite dykes. This indicates that retrograde magmatic hydrothermal fluids played a major role during mineralisation. The association of gold with quartz-veins may indicate that the hydrothermal fluids were released during the late stages of granodioritic magma crystallization (e.g. Kadio et al. 2010).

7.4 Ore genesis

The main aim of this study was to derive an ore genesis model for the Sadiola deposit but at the same time contrast between the intrusion-related style hypotheses proposed by Theron (1997) with the shear-hosted style hypothesis proposed by Hanssen et al. (1998).

As described in Chapter, shear-zone related deposit develop syntectonically in horizontal compressions and the host rocks are generally regionally metamorphosed under low-to-mid greenschist facies conditions, and also the deposit is situated within and/or around a shear zone. Sulphide mineralisation is associated with shear fabrics. The mineral and sulphide textures observed in this study suggest that this is not the case for the Sadiola Hill deposit as there were no visible shear fabrics (foliation), compressional evidence and greenschist facies. However the Sadiola deposit does have few features which are similar to those of shear-hosted deposits, these are: (a) carbonate alteration, (b) sulphides hosted in and around tectonic structures and (c) host rocks are metamorphosed though in the Sadiola Hill deposit it was a result of contact metamorphism rather than regional metamorphism which generally occurs in shear-hosted deposit.

The host rocks of the Sadiola Hill deposit have been metamorphosed to hornblende-hornfels and epidote-chlorite facies which indicates high temperature and low pressure conditions during metamorphism, i.e., contact metamorphism. Contact metamorphism occurred during cooling and recrystallization of the tonalite-granodiorite and porphyry-quartz-feldspar dykes, and the Sekokoto pluton which from the alteration patterns and metamorphic facies assemblage, is suggested to be located on the south-eastern margin of the Sadiola main pit. Emplacement is suggested to have occurred at 2083 ± 7 Ma, which is the currently U-Pb zircon age for the Sekokoto granodiorite (WAXI, 2013) and the age of mineralisation in the Sadiola region, and the accepted age for Eburnean plutonism (Hein and Tshibubudze, 20076a; Leube et al., 1990; Milési et al., 1991; Bossière et al., 1996; Castaing et al., 2003a, b; Naba et al., 2004). The Sekokoto pluton is part of the Alamoutala-Sekokoto-Kakadian plutonic system first described by Hein (2007a).

Contact metamorphism was responsible for alteration in the host rocks; gold-sulphide mineralisation occurs in this alteration zone. Mineralisation consists of a polymetallic sulphide assemblage and tourmaline which are basic indicators of an intrusion-related style deposit. Plutonism was concomitant with hornblende-hornfels facies contact metamorphism of the meta-sedimentary rocks and gold mineralization throughout the Sadiola goldfield (Hein and Tshibubudze, 2007a). From the observations and interpretation made above, it is clear that mineralisation in the Sadiola Hill deposit is not shear-hosted as suggested by Hanssen et al. (1998) but rather related to emplacement of the tonalite-granodiorite and porphyry-quartz-feldspar dykes, and the Sekokoto pluton as suggested by Theron (1997).

It is interpreted that the SFZ was a pathway for magmatic related fluids which flowed from the south-eastern margin of the pit from below, causing dissolution, replacement and precipitation in the marbles within and around the SFZ and fault structures which splay off from the SFZ in marble rocks (i.e. the SFZ was the main control).

Chapter 8: Conclusion

An ore genesis model for the Sadiola Hill deposit has been a much debated topic. A number of models were suggested for the deposit but only two stood out, which included the shear-hosted model by Hanssen et al. (1998) and the intrusion related model by Theron (1997). The two models contrast in terms of style of mineralisation, alteration assemblages, mineral textures and relationship between the host rocks and mineralisation. From the study, only a few features which characterise shear-hosted deposits were present but the features can also be found in intrusion related deposit.

The Sadiola Hill deposit was metamorphosed by contact metamorphism during the emplacement of the tonalite-granodiorite and porphyry dykes, these dykes are also responsible for the fluids which altered the host rocks. Mineralisation mostly occurs in alteration zones suggesting that it was also related to the intrusions.

From the interpretations and paragenesis, it is suggested that mineralisation in the Sadiola Hill deposit formed during retrograde contact metamorphism and brittle deformation caused by the emplacement of the tonalite-granodiorite and porphyry-quartz-feldspar dykes, and the Sekokoto pluton (2083 ± 7 Ma) at the time of the Eburnean plutonism (~2150-2095 Ma). The SFZ was the main control of fluid flow during the emplacement. Mineralisation in the Sadiola Hill deposit is related to the intrusions therefore it is an orogenic subclass intrusion-related deposit as described by Theron (1997).

References

Abouchami, W., Boher, M., Michard, A., Albarède, F., 1990. A major 2.1 Ga event of mafic magmatism in West Africa: an early stage of crustal accretion. Journal of Geophysical Research B 95: 17605–17629.

Bassott, J.P., 1987. The calc-alkaline volcano-plutonic complex of Dalema (Eastern Senegal) River: Discussion of its geodynamic significance in the context of Eburnean orogeny (lower Proterozoic). Journal of African Earth Sciences 6: 505-519.

Bassot, J.-P. 1966. Etude g6ologlque du Senegal oriental et de ses conflns guin&~-maliens. MbrrL Bur. Rech. ~ Mb-u, Parts, 40, 1-322.

Bassot , J.P., Caen-Vachette, M., 1984. Geochronological data and new geochemistry on granitoids Eastern Senegal: implications for the geological history of the birimien region. In: J. Klerkx and J. Michot (Editors), African Geology. Oyal museum, Tervuren, pp. 191-1106.

Béziat, D., Bourges, F., Debat, P., Lompo, M., Martin, F., Tollon, F., 2000. Palaeoproterozoic ultramafic-mafic assemblage volcanic rocks of the Boromo greenstone belt: fractionates originating from island arc in the West African Craton. Precambrian Research 101: 25-47.

Boher, M., Abouchami, W., Michard, A., Albarede, F., Arndt, N.T., 1992. Crustal growth in West Africa at 2.1 Ga. Journal of Geophysics Research 97: 345-369.

Boshoff, F., Hanssen, E., Hill, J.V., Jones, D., Kaisin J., Traore, S., Voet, H.w., 1998. The Sadiola Hill Mine: A lower Proterozoic gold deposit in the Kinieba window-Mali, West Africa. Unpublished report to Anglo American, 6p.

Bossière, G., Bonkoungou, I., Peucat, J.J., Pupin, J.P., 1996. Origin and age of Paleoproterozoic conglomerates and sandstones of the Tarkwaian Group in Burkina Faso, West Africa. Precambrian Research 80: 153-172.

Card, K.D., Poulsen, K.H., and Robert, F., 1989. The Archean Superior province of the Canadian Shield and its lode gold deposits. Economic Geology Monograph 6: 19-36.

Castaing, C., Billa, M., Milési, J.P., Thieblemont, D., Le Mentour, J., Egal, E., Donzeau, M. (BRGM) (coordonnateurs) et Guerrot, C., Cocherie, A., Chevremont, P., Tegyey, M., Itard, Y. (BRGM), Zida, B., Ouedraogo, I., Kote, S., Kabore, B.E., Ouedraogo, C. (BUMIGEB), Ki, J.C., Zunino (ANTEA), 2003a. Notice explicative de la Carte géologique et miniére du Burkina Faso à 1/1 000 000.

Castaing, C., Le Mentour, J., Billa, M., (coordonnateurs) et Donzeau, M., Chevremont, P., Egal, E., (BRGM), Zida, B., Ouedraogo, I., Kote, S., Kabore, B.E., Ouedraogo, C. (BUMIGEB), Thieblemont, D., Guerrot, C., Cocherie, A., Tegyey, M., Milési, J.P., Itard, Y., (BRGM), 2003b. Carte géologique et miniére du Burkina Faso à 1/1 000 000.

Dabo, M., Aifa, T., 2011. Late eburnean deformation in the Kolia-Boboti sedimentary basin, Kedougou-Kenieba Inlier, Senegal. Journal of African Earth Sciences 60: 106-116.

Debat, P., Diallo, DP, Ngom, PM, Rollet, M. and Seyler, M., 1984. The series of Mako in its central and southern parts (eastern Senegal, West Africa). Information on the evolution of the volcano-sedimentary series and preliminary geochemical data on post-tectonic magmatic formations. Journal of African Earth Sciences 2 (1): 71-79.

Dia, A.N., Aquilina, L., Boulegue, J., Bourgois, J., Suess, E., and Torres, M., 1993, Origin of fluids and related barite deposits at vent sites along the Peru convergent margin. Geology 21: 1099–1102.

Dia, A., van Schmus, W.R., Kröner, A., 1997. Isotopic constraints on the age and formation of a Palaeoproterozoic volcanic arc complex in the Kedougou Inlier, eastern Senegal, West Africa. Journal of African Earth Sciences 24 (3): 197–213.

Dioh, E., Béziat, D., Debat, P., Grégoire, M., Ngom, P.M., 2006. Diversity of the Paleoproterozoic granitoids of the Kedougou Inlier (eastern Senegal): Petrographical and geochemical constraints. Journal of African Earth Sciences, 44: 351-371.

Einaudi, M.T., Burt, D.M., 1982. Introduction-Terminology, Classification, and Composition of Skarn Deposits. Economic Geology 77: 745-754.

Ennih, N., Liegeois, J.P., 2008. The boundaries of the West African craton, with special reference to the basement of the Moroccan metacratonic Anti-Atlas belt. Geological Society, London, Special Publication 297: 1-17.

Feybesse, J.L., Billa, M., Guerrot, C., Duguey, E., Lescuyer, J.L., Milési, J.P., Bouchot, V., 2006. The Palaeoproterozoic Ghanian province: Geodynamic model and ore controls, including regional stress modelling. Precambrian Research 149: 149-196.

Foster, R.P., ed., 1989. Archean gold mineralisation in Zimbabwe: Implications for metallogenesis and exploration. Economoc Geology 6: 54-70.

Gueye, M., Siegesmund, S., Wemmer, K., Pawlig, S., Drobe, M., Nolte, N., Layer, P., 2007. New evidence for an early birimien evolution in the West African Craton: An example from the Kedougou-Kéniéba Inlier, southeast Senegal. South African Journal of Geology 110: 511-534.

Gueye, M., Ngom, P.M., Diéne, M., Thiam, Y., Siegesmund, S., Wemmer, K., Pawling, S., 2008. Intrusive rocks and tectono-metamorphic evolution of the Mako Paleoproterozoic belt (Eastern Senegal, West Africa). Journal of Africa Earth Sciences 50: 88-110.

Goldfarb, R.J., Baker, T., Dubé, B., Groves., D.I., Hart, C.J.R., Gosselin, P., 2005. Distribution, Character, and Genesis of Gold Deposits in Metamorphic Terranes. Economic Geology 100: 407-450.

Groves, D.I., Goldfarb, R.J., Gebre-Mariam, M., Hangemann, S.G., Robert, F., 1998. Oregenic gold deposit: A proposed classification in the context of their crustal distribution and relationship to other gold deposit types. Ore Geology Reviews 13, 7-27.

Hanssen, E., Kaisin, J., Mounkoro, B., Hill, J., 1998. Sadiola sulphide drilling project. Unpublished, report to IAMGOLD Corporation on behalf of SEMOS, November 1998, 87p.

Hasting, D., 1982. On the tectonics and metallogenesis of West Africa: A model incorporating new geophysical data. Geoexploration 20: 295-327.

Hein, K.A.A., 2008. Geology of the Sadiola open cast and ancillary pits, Mali. Final company report to SEMOS S.A. Mali, Jan 2008, 18p.

Hein, K.A.A., Tshibubudze, A., 2007a. Sadiola Ore Genesis Model, Sadiola Mine and satellite pits, Mali. Preliminary company report to Société D'Exploitation des Mines d'Or de Sadiola S.A. (SEMOS), Mali, June 2007, 16p.

Hein, K.A.A., Tshibubudze, A., 2007b. Sadiola Ore Genesis Model, Sadiola Mine and satellite pits, Mali. Final company report to Société D'Exploitation des Mines d'Or de Sadiola S.A. (SEMOS), Mali, August 2007, 15p.

Hirdes, W., Davis, D.W., 2002. U-Pb Geochronology of Paleoproterozoic rocks in the southern part of the Kedougou-Kéniéba Inlier, Senegal, West Africa: evidence for diachronous accretionary development of the Eburnean province. Precambrian Research 118: 83–99.

Henry, D.J. & Dutrow, B.L. (1996): Metamorphic tourmaline and its petrologic applications. In Boron: Mineralogy, Petrology and Geochemistry (E.S. Grew & L.M. Anovitz, eds.). Rev. Mineral. 33: 503-557.

Henry, D.J., Kirkland, B.L. & Kirkland, D.W. (1999): Sector-zoned tourmaline from the cap rock of a salt dome. Eur. J. Mineral. 11: 263-280.

Junner, N.R., 1935. Gold in the Gold Coast. Gold Coast Geological Survey Memoir, vol. 4, 67 p.

Kadio, E., Coulibaly, Y., Allialy, M.E., Kouamelan, A.N., Pothin, K.B.K., 2010. On the occurrence of gold mineralizations in southeastern Ivory Coast. Journal of African Earth Sciences 57: 423-430.

Lang, J.R., Baker, T., (2000). Intrusion related gold systems: the present level of understanding. Mineralium Deposita 36: 477-489.

Lawrence DM, Treloar PJ, Rankin AH, Harbidge P, and Holliday J**,** 2013. The Geology and Mineralogy of the Loulo Mining District, Mali, West Africa: Evidence for Two Distinct Styles of Orogenic Gold Mineralization. Economic Geology 108: 199-227

Ledru, P., Pons, J., Mile´si, J.P., Feybesse, J.L., Johan, V., 1991. Transcurrent tectonics and polycyclic evolution in the Lower Proterozoic of Senegal-Mali. Precambrian Research 50: 337–354.

Leube, A., Hirdes, W., Mauer, R., Kesse, G.O., 1990.The early Proterozoic Birimian Supergroup of Ghana and some aspects of its associated gold mineralization. Precambrian Research 46: 139-165.

Liégeois, J.P., Claessens, W., Camara, D., Klerkx, J., 1991. Short-lived Eburnian orogeny in southern Mali. Geology, tectonics, U–Pb and Rb–Sr geochronology. Precambrian Research 50: 111–136.

Pawling, S., Gueye, M., Klischies, R., Schwarz, S., Wemmer, K., Siegesmund, S., 2006. Geochemical and Sr-Nd isotopic data on the Birimian of the Kedougou-Kenieba Inlier (eastern Senegal): Implications on the Palaeoproterozoic evolution of the West African Craton. South African Journal of Geology 109: 411-427.

Potrel, A., Peucat, J.J., Fanning, C.M., 1998. Archean crustal evolution of the West African Craton: example of the Amsaga Area, (Requibat Rise). U-Pb and Sm-Nd evidence for the crustal growth and recycling. Precambrian Research 90: 107-117.

Putnis, A., 2002. Mineral replacement reactions: from macroscopic observation to microscopic mechanisms. Mineralogical Magazine 66: 689-708.

Robins, P.S., 2006. The quantification of grade uncertainty, and associated risk, and their influence on pit optimization for the Sadiola deep sulphide prefeasibility project. MSc thesis, University of the Witwatersrand, Johannesburg, 139p.

Sibson, R.H., Poulsen, F.R.K., 1988. High-angle reverse faults, fluid-pressure cycling, and mesothermal gold-quartz deposit. Geological Society of America 16: 551-555.

Strydom, D., Repel, A.K.K., 1997. Structural investigation of the Sadiola exploitation and exploration area in the Kéniéba Kedougou window, western Mali. Preliminary summary to Anglo American Corporation of South Africa Limited, 3p.

Matabane, M., 2008. The geology of the FE3 open cast, Sadiola, Mali: Stratigraphy, structure and intrusive rocks. Honours thesis, University of the Witwatersrand, Johannesburg, 56p.

Barth, M.G., Rudnick, R.L., Carlson, R.W., Horn, I., McDonough, W.F., 2002. Re-Os and U-Pb geochronological constraints on the eclogite-tonalite connection in the Archean Man Shield, West Africa. Precambrian Research 118: 267-283.

Macfarlane, A., Crow, M.J., Arthurs, J.W., Wilkinson, A.F., Aucott, J.W., 1981. The geology and mineral resources of northern Sierra Leone. Overseas Mem. Inst. Geol. Sci. 7: 103.

Meinert, L.D., 1992. Skarns and Skarn Deposits. Jounal of the Geological Association of Canada v19: number 4.

McFarlane, C.R.M., Mavrogenes, J., Lentz, D., King, K., Allibone, A., Holcombe, R., 2011. Geology and Intrusion-Related Affinity of the Morila Gold Mine, Southern Mali. Economic Geology 106 no. 5: 727-750.

Milési, J.P., Feybesse, J.L., Ledru, P., Dommanget, A., Ouédraogo, M.F., Marcoux, E., Prost, A., Vinchon, C., Sylvain, J.P., Johan, V., Tegyey, M., Calvez, J.Y., Lagny, P., 1989. The gold mineralization in West Africa. Their relations with the Proterozoic evolution lithostructural. Chronicle of Mining Research 497, 3–98.

Milési, J.P., Ledru, P., Ankrah, P., Johan, V., Marcoux, E., Vinchon, Ch., 1991. The metallogenic relationship between Birimian and Tarkwaian gold deposits in Ghana. Mineralium Deposita 26: 228-238.

Milési, J.P., Ledru, P., Feybesse, J.L., Dommanget, A., Marcoux, E., 1992. Early proterozoic ore deposits and tectonics of the Birimian orogenic belt, West Africa. Precambrian Research 58: 305–344.

Marsrschall, H.R., Korsrsakov, A.V., Luvuvizotto, G.L., Nasdala, L. & Ludwig, T. (2009): On the occurrence and boron isotopic composition of tourmaline in (ultra)high-pressure metamorphic rocks. J. Geol. Soc. London 166: 811-823.

Naba, S., Lompo, M., Debat, P., Bouchez, J.L., Béziat, D., 2004. Structure and emplacement model for late-orogenic Paleoproterozoic granitoids: the Tenkodogo-Yamba elongate pluton (Eastern Burkina Faso). Journal of African Earth Sciences 38: 41-57.

Ranson, R.L., 1998. Structural modelling of the Sadiola Hill Gold Deposit, Mali, MSc thesis, University of Exeter, England.

Theron, S.J., 1997a. The intrusive and extrusive rocks from the Sadiola concession areas: A petrographical and geochemical study. 6 February 1997, Unpublished AARL Gold and Base Metal Unit Report No. M96X5071. p.50.

Theron, S.J., 1997b. Possible genetic model for gold mineralization within the greater Sadiola concession area. Unpublished report from Anglo America Research Laboratories (Pty) Ltd, 23 July 1997, 3p.

Thompson, J.F.H., Sillitoe, R.H., Baker, T., Lang, J.R., Mortensen, J.K., 1999. Intrusion-related gold deposits associated with tungsten-tin provinces. Miner Deposita 34: 323-334.

Voet, H.W., 1997. Cross folding at Sadiola hill mine and the possible extent of the orebody to the south. Unpublished, report to Anglo American Corporation of South Africa Limited, File 13/147/500(a), 19 November 1997, 3p.

WAXI, 2013. Confidential Final report, P934A West African Exploration Initiative, Stage 2, 924 pages with 917 pages of appendices. (part contributor in Theme 1 and Capacity Building Modules).

Witschard, F. (1965). Contribution to the geological and petrological study metallogenic granite massifs Senegal Oriental. Memories BRGM 44: 171pp.

http://www.iamgold.com/English/Operations/Operating-Mines/Sadiola-Gold-Mine/default.aspx (accessed: 20 may 2013).

Zhu, Y., Zhou, J., Zeng, Y., 2007. The Tianger (Bingdaban) shear zone hosted gold deposit, west Tianshan, NW China: Petrography and geochemical characteristics. Ore Geology Reviews 32: 337-365.

.

Appendix

Petrography

SD119

Slide 55 (hornfels)

The sample consist of a dolomite crystal which is zoned with calcite in its edges, the crystal has twinning in the long axis of the rhombohedra. The dolomites contain biotite, vermiculite and rutile as inclusions. The sample mainly consists of large crystals of dolomite and fine grained quartz crystals. All this crystals are overprinted by rutile, epidote, and biotite crystals. Few crystals of biotite are in their early stage of alteration, altering to chlorite.

Slide 56 (marble)

The sample is part of a pseudotachylite vein which is dominated by biotite crystals, also present is large dolomite crystals and fine grained quartz crystals. The biotite crystals adjacent to the vein have been highly altered to vermiculite. The biotite is randomly orientated. The biotite crystals acts as veins and they cut through the fine grained quartz crystals which in turn are eating away parts of the dolomite crystals. The sulphides overprint all the minerals in the sample, i.e. has no direct relationship with any of the minerals present. Sulphides present are pyrite, galena and minor gold.

Slide 57a (marble)

The sample mainly consists of biotite, quartz, sulphides and carbonate. Most of the sulphides co-exist with biotite crystals. The sample has been described as massive sulphide lode. The sample also contains a carbonate vein which also hosts some sulphides in the margins; the vein is responsible for a biotite zone in its contact. Most of the biotite overprints the carbonates in the vein and are associated with the sulphides.

Slide 57b (marble)

The sulphides in this section overprint the biotite. The sample also contain a very fine grained biotite band (shear fabric like) which is mineralized with galena. Gold is associated with pyrites. Sulphides also occur in grain boundaries.

Slide 58a (marble)

The sample contains a carbonate-quartz-albite vein, the surroundings of the vein are much altered and that’s where most of the sulphides are concentrated. Few sulphides occur as overprints within the vein. Pyrite is distorting to marcasite in vein contacts. Veinlets also occur in the sample.

Slide 58b (marble)

The sample contains a quartz-carbonate vein which contains biotite in its contact. The biotite bands are associated with sulphides. Most of the sulphides occur from vein contacts toward the altered host rock. Sulphides are associated with biotite growth.

Slide 59a (marble)

The sample contains a quartz-carbonate-albite vein which is mineralized. Biotite overgrowth is common throughout the sample. Biotite is altering to chlorite with most of the chlorite associated with sulphides. Sulphides are also disseminated throughout the section. Section is derived from a quartz-albite-carbonate vein. The whole section has undergone extensive alteration.

Slide 60a (marble)

Sample contains quartz-sulphide veins. Biotite, quartz, albite and pyrite are the most abundant minerals. Few discrete gold grains are present and are associated with pyrite

Slide 60b (greywacke)

The sample contains a quartz-carbonate vein. The vein contacts are dominated by bands of biotite. Sulphides occur in grain boundaries and in vein-wallrock contact. The sulphides also form veins which fills pore spaces. Biotite crystals are decomposing to chlorite.

SD 022

Sd36a (marble)

Sample is a brecciated marble which contains rusty siderite stains in the dolomites. The sample has large grains of dolomite and fine grained quartz. Mineralization is only associated with the matrix in the breccia were the sulphides are disseminated. Main sulphides are pyrite, galena and minor gold. The matrix is altered.

SD 36c (marble)

Sample is a dolomite breccia which contains siderite in its margins. The sulphide veins present crosscuts altered dolomitic rocks. The altered dolomites matrix is highly mineralized with sulphides like pyrite and pyrrhotite.

Sd37ba (marble)

The quartz-carbonate vein cuts through fresh dolomites and is surrounded by biotite crystals in its margins. The carbonates in the vein are calcites. Biotite is retrogressing to chlorite. Gold occurs in pyrite margins. Mineralization only occurs in the vein. Sample consists of rutile in its grain boundaries.

Sd38 (greywacke)

Sample consists of a quartz-carbonate vein. The vein contains biotite in grain boundaries, vein margins and overprinting the crystals. The vein is coarse grained when compared to the surrounding rock. The quartz-carbonate vein is cut by sulphide veins. Biotite occurs around the veins. Sample also contains stains of siderite adjacent to the vein. Gold and other sulphides disseminated in the vein.

Sd39 9greywacke)

Sample is a greywacke which consist of fine grained quartz and biotite matrix. The biotite is retrogressing to chlorite and vermiculite and overprint the matrix. The sample is also cut by an epidote-chlorite vein. The sample is altered. Sulphides are associated with biotite and they overprint it.

Sd40a (marble)

The sample is a marble dominated by dolomite; it is cross cut by a quartz-carbonate. The sulphide overprints the quartz-carbonate vein. Most sulphides occur in the surrounding rock type as overprints in the matrix and in vein grain boundaries. Some of the sulphides occur adjacent to the vein contacts within the vein.

Sd42a (marble)

Sample contains massive sulphides main lode. Most of the sulphides are surrounded by hornblende and are highly fractured, some are breaking. Pyrite is breaking down to marcasite. Other massive sulphides are cut by a carbonate vein.

Sd43 (marble)

Sample is highly altered marble with biotite alteration. Sulphides are abundant in this sample (massive). Most of the sulphides are associated with the biotite crystal growth. Pyrite is retrogressing to marcasite. The sulphides occur around grain boundaries but also overprint them. Biotite is breaking down to chlorite (chloritization).

Sd44a (marble)

Sample is a dolomitic marble which contains carbonate veins which are surrounded by biotite, the sample also contain chlorite and qtz. Sulphides are only present in a fracture line which might have been a pathway for fluids during precipitation. Other samples of this rock types consist mainly of an altered quartz, biotite and chlorite, the qtz is also highly fractured with filled pore spaces.

Sd48a

The sample consists of spider veins cross cutting each other, the veins contain quartz and cuts across a greywacke which consist of fine quartz grains and biotite. The sulphides are associated with biotite which they overprint.

Sd50a (tonalite)

In this sample, the greywacke is grading into a tonalite, the tonalite has a phaneritic texture with large quartz and plagioclase crystals in a fine grained qtz biotite matrix. Sulphides are present in the fine grained matrix.

Sd52 (tonalite)

Tonalite contact, most sulphides occur in the rock adjacent to the tonalite. Sample consists of very fine qtz biotite matrix and large grains of qtz and plagioclase. Few disseminated sulphides in the tonalite.

SD782

Slide 19 (tonalite)

The rock is tonalite which is being cross cut by a quartz-sulphide vein. The tonalite has a phaneritic texture and is mainly composed by a fine quartz-feldspar matrix and large biotite crystals. The cross cutting vein is composed of large quartz crystals, biotite overgrowth and sulphides. The sulphides overprint qtz and in turn are overprinted by biotite but also occur in its grain boundaries, at some point sulphides to overprint biotite

Slide 20a (tonalite)

Sample is a clotted tonalite which consist of a fine quartz matrix with biotite overgrowth. Sulphides are disseminated and are mainly associated with chloritoid. The sulphides also fill open spaces. A small quartz-carbonate vein cuts through the sample and it also contains sulphides. The sulphides do not overprint the vein minerals like in other samples.

Slide 21 (tonalite-marble)

Sample contains a contact between tonalite and marble. The marble consist of calcite and quartz. Most of the sulphides are disseminated at the tonalite but are also present at the contact. Biotite overgrowth in tonalite matrix. Sulphides are filled with fractures and they overprint the original rock mineralogy. The sulphides are associated with biotite. Main sulphide is pyrite.

<u>Sd23a (tonalite)</u>

Sample is a tonalite which consist of large quartz and plagioclase crystals in a fine quartz matrix, accessory minerals include biotite and epidote. A py-ars-chlor vein cross cut the sample and contains sulphides. Pyrite is also concentrated in open pore spaces. Sulphides overprint all the minerals in the vein and also branches out to fractures connected to the vein. Late stage quartz inclusions in the sulphides within the vein.

<u>Sd25a (marble)</u>

Sample is a marble which is cut by a quartz-carbonate vein. The veins are folded in hand sample. A crystalline mineral formed in the vein- wall rock contact, the mineral looks like biotite which has decomposed to vermiculite. Biotite crystals are also present in this vein contacts and in the wall rock. Pyrite is disseminated together with few small gold grains within the vein.

<u>Sd28 (marble)</u>

In hand sample the rock contains slump folds. The rock contains chlorite crystals in the slump folds and is a contact metamorphism wallrock (scapolite). The original rock type is marble which is cross cut by small qtz carb veins. Biotite is altering to chlorite. The chloritoid crystals occur as spits in the quartz-carbonate matrix.

<u>Sd29 (marble breccia)</u>

The sample is a breccia which consists of carbonates and quartz. The sample is highly altered and the main mineral is siderite which is also decomposing. Sample contains adularia but can only be seen in hand sample. Mineralization occurs in grain boundaries and in fractures. The carbonates are breaking down. The siderite mineral has zoning.

<u>Sd30A (marble breccia)</u>

In hand sample it contains slump fold structures which are been cut by the quartz-carbonate veins. The slumps contain chlorite spots. Pyrite is breaking down to marcasite. Most sulphides occur in the breccia matrix.

<u>SD 129</u>

<u>Slide 66 (greywacke)</u>

Sample consists of a quartz-carbonate vein with most of the gold and sulphides, and gold embedded on the carbonates and in the margins of the two minerals. The sulphides have a colliform texture and both the sulphide. The vein surroundings contain a chlorite alteration. Chalcopyrite is situated in the boundary between carbonates and pyrite.

Slide 67

Sample contains a quartz-carbonate vein. The minerals are separated by biotite which lies along the boundaries. Biotite is rotting to vermiculite. Galena and pyrite are present in grain boundaries. Pyrite and gold are also situated on top of vermiculite and biotite grains. Sulphides show a direct relationship with each other and with gold nuggets.

Slide 68a

Sample consists of sulphides which are replacing bedding. Sulphides are pyrite and galena in layers parallel to one another…predominantly within the beds. Rock type is carbonaceous. Potassic alteration is present within the bedding were the sulphides are present; sulphides are situated in the quartz and carbonate contacts. Physical evidence of chemical change in thin section scale, sulphide were dumped in a carbonate buffer due to thermodynamics…EDIT…the greywacke looks like a vein hosted in carbonates but the sulphides are all scattered through the carbonates and the greywacke…..abundant in contacts.

Slide 70a (greywacke)

Sample consists of biotite crystals which are randomly orientated in the surroundings. The sample contains quartz and chlorite alteration with fine grained late stage quartz occurring in the margins of early stage coarse quartz and carbonaceous host rock. The gold in this section is associated with pyrite grains (co-exist). Small cracks filled with sulphide and gold fluids cross cut through the mineral grains in the host rock.

Slide 72a (greywacke)

The sample is highly altered and contains crystals of quartz, biotite and sulphides. Biotite is altering to chlorite. Biotite is associated with sulphides and that's where is more abundant. The sulphides surrounded by chloritoid and biotite and all lies in a carbonate matrix.

Slide 74a (epidote hornfels)

Biotite has decomposed to vermiculite and some biotite has completely altered to chlorite. All the individual grains have increased in size due to contact metamorphism. Epidote hornfels is direct evidence of contact metamorphism.

SD042

Slide Sd83A (greywacke)

Sample consists of randomly orientated biotite crystals (~ 100μm) and sub-euhedral quartz crystals. Accessory minerals present are rutile and eclogite. The texture of the sample changes as we move up, i.e. biotite abundance decreases with respect to quartz. Sample consist of sulphides mineralization in veins which crosscut the biotite, the sulphides present are pyrite with small replacements of pyrrhotite.

Slide Sd83b (greywacke)

The sample consists of randomly orientated biotite crystals and quartz grains. Fluid inclusions present in the sample. Minor sulphides hosted in veins and are disseminated. Sulphides present include pyrite and interstitial chalcopyrite. Carbonate can be seen in reflected light. Biotite crystals are retrogressing to chlorite (chloritization) and also to vermiculite. Edenite crystals are also present in the sample.

Slide SD 84A

The rock consists of biotite, quartz and muscovite. The muscovite around the vein has a flower-like texture. The sample contains a fracture within the vein. Quartz crystal within the vein is absorbing the surrounding biotite crystals. Alteration occurs around the vein. Euhedral crystal which stands up from the quartz-biotite fine grained matrix.

Slide SD 86 (marble)

Sample consists of a quartz-carbonate vein which is surrounded by k-spar alteration. Sulphides are concentrated in the wallrock adjacent to the vein.

Orientation of boreholes used in 3D modelling.

DDH	UTM	ELEVATIO	AZIMUTH	DIP	END OF HOLE	DRILL TYPES
SD 1013	E50816.127 N6	90.531	270	-60	463	DD
SD 1014	E50812.796 N6	90.657	90	-60	468	DD
SD 1015	E51135.64 N66	93.12	90	-60	450	DD
SD 1016	E50887 N6899.8	89.81	270	-55	491	DD
SD 1017	E50887.17 N69	89.769	85	55	353	DD
SD 1018	E50849.45 N72	109.86	85	60	379	DD
SD 1019	E50640.664 N7	113.335	85	60	203	DD
SD 1020	E50595.383 N71	111.744	85	75	269	DD
SD 1021	E51399.163 N7	117.294	265	60	431	DD
SD 1022	E50799.816 N6	39.894	265	-60	500	DD
SD 1023	E50799.285 N6	39.9	85	-55	413	DD