Artisanal mining in the Dem region, Burkina Faso: the mining, processing and production of iron ore

By
Todani Advice Funyufunyu
(520347)

A dissertation submitted to the Faculty of Science, University of the Witwatersrand Johannesburg in partial fulfilment of the requirements for the degree of Master of Science

Johannesburg, 2013

FRONTISPIECE

"*Wherefore smelting is necessary, for by this means earths, solidified juices, and stones are separated from the metals so that they obtain their proper colour and become pure, and may be of great use to mankind in many ways. When the ore is smelted, those things which were mixed with the metal before it was melted are driven forth, because the metal is perfected by fire in this manner. Since metalliferous ores differ greatly amongst themselves, first as to the metals which they contain, then as to the quantity of the metal which is in them, and then by the fact that some are rapidly melted by fire and others slowly, there are, therefore, many methods of smelting."* (Agricola, 1556)

DECLARATION

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

…………………………………....

(Signature of Candidate)

……….day of………...……2013

TABLE OF CONTENTS

Frontispiece....................*ii*
Declaration....................*iii*
Table of Contents....................*iv*
Acknowledgements....................*vi*
Dedication....................*vii*
List of Figures....................*viii*
List of Tables....................*xii*
Abstract....................*xiii*

1.0 INTRODUCTION

1.1. Nature of Artisanal mining.................... *14*
1.2. Location and physiography.................... *18*
1.3. Geology of the study area.................... *19*
1.4. Project aims.................... *20*
1.5. Thesis organisation.................... *20*
1.6. Conventions and acronyms.................... *21*

2.0 LITERATURE REVIEW

2.1. Artisanal and Small-scale Mining.................... *22*
2.2. Artisanal mining, processing and production of iron.................... *23*
2.3. Laterite-Ferricrete in the WAC.................... *27*
2.4. Iron ore deposits in the WAC.................... *28*

3.0 METHODOLOGY

3.1. Introduction.................... *30*
3.2. Ethnographic research.................... *30*
3.3. Fieldwork and geological mapping.................... *33*
3.4. Petrography.................... *34*
3.5. Pilot study - AMS radiocarbon dating.................... *35*

4.0 THE MINE SITE AT DEM

4.1. Introduction.................... *40*
4.2. Ore body.................... *40*
4.3. Mines.................... *42*
4.4. Ore Dressing and Processing.................... *44*
4.5. The greater mining footprint.................... *48*

5.0 PETROGRAPHY OF ORE BEARING ROCKS AND SLAG

5.1. Introduction.................... *52*
5.2. Petrography of the host rocks.................... *52*
5.3. Petrography of the ore bearing rocks.................... *54*
5.4. Slag geology and petrology.................... *54*
5.5. Summary.................... *59*

6.0 RADIOCARBON PILOT STUDY

6.1. Introduction.. *60*
6.2. Interpretation of the results of carbon dating……... *64*

7.0 DISCUSSION *66*

8.0 CONCLUSIONS *68*

REFERENCES... *70*

APPENDIX-1: LITHOLOGICAL DATA.. *78*
APPENDIX-2: SAMPLING... *90*
APPENDIX-3: SELECTED SAMPLES FOR PETROGRAPHIC STUDIES............................. *94*
APPENDIX-4: CARBON SAMPLES.. *95*

ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to my supervisor, Prof. Kim A.A. Ncube-Hein for her time, constructive criticism, editorial comments, mentorship skills, and patience in supervising this work. However, I would like to thank her for introducing me to the field of artisanal and small-scale mining, geochronology and iron ore smelting. Her encouragement, understanding, financial support and valuable contribution to this research report is highly appreciated.

Many thanks go to the museum of Kaya and villagers of Liligomde (Pèrè Continwagre, Grampre Conviba, and Arvère Grapère Yonka) for their help on the insight on historic artisanal mining of iron ore in Burkina Faso.

Acknowledgement is also given to everyone who has provided valuable guidance, suggestions and help for this project. I am grateful to Dakalo Emmanuel Nethavhanani for his understanding and never ending motivational support. Many thanks go to my family for their moral support, encouragement and believing in me while I was doing this research.

Above all, I would like to thank the almighty God for giving me the energy and wisdom to finish this research.

DEDICATED

To my wonderful son, Gundo Nethavhanani,
the one who motivates me to be a responsible mother and
encourages me to work to my very best.

LIST OF FIGURES

Frontispiece "Wherefore smelting is necessary, for by this means earths, solidified juices, and stones are separated from the metals so that they obtain their proper colour and become pure, and may be of great use to mankind in many ways. When the ore is smelted, those things which were mixed with the metal before it was melted are driven forth, because the metal is perfected by fire in this manner. Since metalliferous ores differ greatly amongst themselves, first as to the metals which they contain, then as to the quantity of the metal which is in them, and then by the fact that some are rapidly melted by fire and others slowly, there are, therefore, many methods of smelting." (Agricola, 1556)

Figure 1.1: Photograph of a typical modern day artisanal forge that is operated by one man, with a single pump and a number of small crucibles. The tuyere is clearly visible. A goat skin bellows would have been placed over the bellows hole to pump air into the tuyere. This particular working forge is on exhibition at the Museum of Kaya and is presented with the permission of the Museum.

Figure 1.2: Location of the study area in Burkina Faso, northeast of the capital city of Ouagadougou and 17 km northwest of the regional centre of Kaya. The study area is located near the village of Dem and west of the Lac (Lake) Dem in the Goren greenstone belt.

Figure 1.3: Photographs of the elders of the village of Liligomde who provided the ethnographic background to this study (a, b, e). Their information indicated that no artisanal mining for iron had taken place at Dem in their lifetimes. The senior elders ranged in age from 75-104 and they were the senior blacksmiths of the Chief Naba of the Mossi people. Consequently, it can be reasonably assumed that the Dem site is older than 80 years. Artisanal mining for iron is conducted west of the village of Liligomde (c) with smelting in the village on small crucibles. Iron rich spongy ferricrete is used for smelting (d) which makes tools for local agricultural use. The elderly gentleman in (e) made his own gun from smelting local iron. Photographs are reproduced with permission of the village elders. (f) Ethnographic data was collected by interview and data was recorded in a notebook with translations from Mossi to French and English as facilitated by Mr Bamogo Makido of the Museum of Kaya (squatting).

Figure 2.1: Schematic of furnace, showing temperatures and reactions during smelting (Cleere. 1981, Figure 6). I = Roasting zone, II = Indirect reduction zone, II = Oxidation zone, IV = Direct reduction in hearth, V = Slag bath and outlet.

Figure 2.2: A Fe-FeO–Fe_2O_3–SiO_2 slag phase diagram at varying temperatures redrawn from Schuhmann et al. (1953), the temperatures is in degrees centigrade.

Figure 3.1: Photographic mosaic of the Dem site constructed from GoogleEarth images. Location of the town of Dem along the main road to Kaya is shown. Sites of Opencast (OC) mining, underground (UG) mines and forges/ furnaces are also presented. The mine site is wholly located east of the major ridge on an alluvial plain. Lac Dem is located east of the town of Dem.

Figure 3.2: Geology and layout of the Dem site. Open cast mines 1-3 are located on the eastern side of a ridge of ferricrete duricrust and immediately east of ferricrete scree in Fe-Mn rich metasedimentary rocks, and adit to UG 1-2 underground mines is located above the open casts. Forges/Furnaces 1-11 are situated on the alluvium plain blow the open cast mines. Waste dumps are situated proximal to the furnace sites.

Figure 4.1: Photographs of vein-hosted iron ore from adits in the underground mines of the Dem iron site. A. Massive siltstone hosting hosting zones of iron staining. Numerous fine vein rich veinlets crosscut the host rock. B. Interlocking network of iron rich veinlets. C. Quartz vein cataclasite veins surrounded by a wide alteration zone of iron enriched siltstone. D. A complex zone of alteration in massive siltstone.

Figure 4.2: Laterite-ferricrete plateau and outcrops occur across the Dem region. A. Photograph of recemented ferricrete in the foreground with ferricrete plateau in the back ground. B. Ferricrete overlying massive siltstone unit in the Dem region. C. Ferricrete plateau in the background is composed of the profile in photograph D. Several layers of ferricrete development can be interpreted from the profile.

Figure 4.3: The two surface mines consist of bowl-shaped opencast pits that are approximately 500-600m in diameter. The most significant is pit 1 which has worked a considerable volume of primary ore dislodged from outcrops above the opencast, in a natural valley. Iron rich cataclasite veins also crop out across the floor of the open cast. Underground workings (UG 1) occur between the two open casts with adit/entrance located high on a rock face (as marked). Open cast pit 2 worked mainly ferricrete scree that roll down from the laterite plateau above.

Figure 4.4: Underground Mine 1 (UG1) consists of a series of drifts, galleries, adits and tunnels that accessed primary in-situ iron ore from the selvedge of quartz cataclasite veins. The galleries were too dangerous to enter but the workings were considerable.

Figure 4.5: Iron smelting at the Dem site is evidenced from the remains of at least 11 furnace (furnace wall and floor fragments), and hundreds of fragments of tuyeres, crucible, burnt clay and iron slag. A. Burnt clay of the furnace wall. B. Furnace 2 which is representative of all furnace in the Dem mine site. They are typically round with flat or bowl shaped floors. C and D. Tuyeres are scattered around many of the furnaces or welded into the floor of the furnaces with slag. E and F. Crucibles made of clay-sand are also found proximal to the furnace site of welded together with slag.

Figure 4.6: Processing sites at the Dem site. A and B. Numerous processing and slag dump sites are located near the mines and adjacent to furnaces and scattered throughout the area. They indicated that the ore was beneficiated before use in the furnace, or that slag was removed from the ore after smelting. C. Section through a slag dump site next to a furnace 8. It is clear that a significant amount of forging had taken place at Furnace 8.

Figure 4.7: Photographs of the different types of slag in found at the Dem mine site. A. Fragment of glassy slag resembling obsidian found throughout the Dem site at all furnaces is consequent of rapid cooling. B. Flow type slag from Furnace 5 which is forms during slow cooling from a high temperature melt. C. Coarse grained slag from Furnace 5 formed by slow cooling rate at a relatively constant temperature. D. a dense black-grey flowing type that resulted from a slow cooling rate in cow-pat form, E. Spinifex texture which forms due to quenching at high temperature. F. Vesicular slag with vugs that formed due to the release of gas bubbles in the melt.

Figure 4.8: A number of stone tools (A B) litter the Dem site specifically long old tracks (C, D) which link the furnace sites and the mine sites, and around furnaces site. By and large, the purpose or use of these artefacts is not known.

Figure 5.1: A. Transmitted light photomicrographs of siltstone from sample LD001 SN-114. Siltstone units are composed of quartz (light grey) and goethite (black), with accessory epidote and sericite. B. Transmitted light photomicrographs of iron rich carbonaceous shale from sample LD003 SN-116. Iron oxides are made up of hematite-goethite ± sericite (black). Carbonate-quartz makes up the remainder of the matrix (white). C. Transmitted light photograph of chloritized basalt (Sample LD002 SN115). The basalt is composed of chlorite (after pyroxene), sericite, epidote and quartz, with minor relict plagioclase. Opaque minerals are goethite ± hematite (black). D. Transmitted light photomicrograph of ferruginous silicrete (Sample LD 016, SN121). The silicrete is made up of nodules of goethite and chalcedonic quartz enclosing rock fragments particularly around pisoliths. The rock fragments are also cemented with goethite and chalcedonic quartz.

Figure 5.2: A. Photomicrograph of Fe-rich ore bearing siltstone in transmitted light (cross-polars) which is dominated by goethite-hematite (Sample LD 013, SN-118). B. Quartz cataclasite vein at the base of the valley in open pit 1. Fe-rich fractures and micro-faults crosscut the quartz veins and wall rock indicating they formed after the quartz vein. Photomicrographs from Sample LD 013, SN-118 in transmitted (C.), transmitted crossed polars (D.) and reflected light of quartz cataclasite demonstrating that hematite-goethite dominate veins and fractures which crosscut quartz in quartz veins.

Figure 5.3: Type 1 dense black glassy slag with flow texture from Furnace 5. B. Type 2 vesicular green-black blocky slag from Furnace 10.

Figure 5.4: Photomicrographs of slag from the Dem mine site. A. Fine to coarse skeletal hematite with spinifex in a hematite matrix from Furnace 4. B. Herringbone textured hematite-wüstite (Wu) with ocelli of fayalite (Fa) and quartz (Qtz), and vesicles (V) in a hematite matrix. C. Intergrown massive hematite and semplectic hematite. D. Beautiful skeletal structure of hematite spinifex in hematite matrix. E. Cross-formed wüstite (Wu) in subhedral to anhedral hematite in a hematite matrix. F. Skeletal herringbone texture hematite in a hematite matrix. F1, F2, F4, F5 = Furnace 1, 2, 4 or 5.

Figure 5.5: Photomicrographs and sketch from Furnace 9 of fayalite in a hematite spinifex (A, B) and as ocelli, as fill or the lining of vesicles (as amygdules), and fill to fractures that crosscut the hematite matrix of the slag.

Figure 5.6: Photomicrograph of micro-fault, fractures and hematite veinlets crosscut the spinifex and herringbone textured hematite.

Figure 6.1: Sampling points from different furnaces. a. Sampling points for furnace 2 from furnace walls. b.-c. Sampling points for furnace 5 from furnace and tuyere fragments. d. Sampling points for furnace 6 from the exposed stratigraphy of the furnace. e. Sampling points for furnace 8 from the exposed layers of the furnace. F. Sampling point for furnace 11 from the furnace walls.

Figure 6.2: Radiocarbon calibration curve organic material extracted from Furnace 6 (Sample FOR06 02CAR). Radiocarbon age (BP) is plotted against calendar years (AD). White bars correspond to 68% and grey bars correspond to 95% confidence levels, respectively. The 95% confidence level gives an age 1438-1458 AD.

Figure 6.3: Radiocarbon calibration curve organic material extracted from Furnace 6 (Sample FOR08 02CAR). Radiocarbon age (BP) is plotted against calendar years (AD). White bars correspond to 68% and grey bars correspond to 95% confidence levels, respectively. The 95% confidence level gives ages (1438-1458, 1651-1600, 1756-1759, and 1949-1951) AD.

LIST OF TABLES

Table 3.1: The characteristics of selected samples that were sent to the laboratory for AMS radiocarbon dating.

Table 6.1: Results of samples processed and calibrated by Beta Analytic using the Pretoria Calibration Procedure program (Talma and Vogel, 1993).

Table 6.2: Radiocarbon ages from the study area, the dates have been calibrated with the INTCAL04 Radiocarbon Age Calibration after Talma and Vogel (1993).

ABSTRACT

Artisanal and small-scale mining (ASM) has been a crucial industry in Africa for centuries. In Burkina Faso approximately 95 kms northeast of the capital city Ouagadougou near the village of Dem and on a ferricrete capped ridge to the west of the village, it is possible to find a number of opencast workings and underground mines that show evidence of extensive artisanal mining for iron. Iron mining worked quartz-vein hosted and lateritic ore. Nearby, waste piles, processing sites and at least eleven (11) Bloomery furnaces are exposed on the alluvial plain. Petrographically the ore bearing rocks consist of goethite-hematite as the dominant oxides with silica. Geological and ethnographic studies conducted in 2011 focussed on detailing and mapping the mine site and host rocks (including ore rocks), and establishing the age of mining, processing and forging of ore. Selected charcoal samples were collected from furnaces sites. Limited AMS radiocarbon dating of six (6) samples was performed at Beta Analytic laboratory in Miami, Florida, USA and suggested that iron forging may have begun in the 15th century, which could also be the age of mining and processing of ore. The site has characteristics such as impure slag, eleven (11) large furnaces, hundreds of tuyeres, and crucibles, and clay fragments. Remnant slag samples were collected for petrographic and mineralogical study to deduce the mineral composition of the slag. The slag samples contained high concentration of fayalite, quartz, magnetite and hematite and low concentration of iron metal and ulvospinel suggesting an iron silicate slag of low melt temperature was formed in the furnaces.

1. INTRODUCTION

1.1. Nature of Artisanal Mining

Artisanal mining is the extraction of economic minerals from the ground in the form of surface and underground mining, legally or illegally. Artisanal and small-scale mining (ASM) activities are conducted on ore bodies or deposits by persons using traditional techniques and/or low mechanisation levels (Anonymous, 1999). Artisanal mining involves extraction and processing of minerals by intensive selective manual labour. Hilson (2002a, b) stated that in the most advanced case, ASM is semi-mechanised and utilises slightly advanced processing techniques to highly rudimentary. In recent years, the ASM sector has experienced significant growth worldwide, predominantly in remote rural areas of the developing world (Hentschel et al., 2003). Hentschel et al. (op. cit.) stated that this has occurred mainly in response to widespread unemployment in African, Latin-American and Asian countries in which ASM takes place.

ASM is informal to formal and is an alternative and often seasonal form of income for the rural sector (Hein, 2007). It is highly selective mining and is linked to poverty in a complex way. ASM is practiced by millions around the world (in 2009 the United Nations Environment Programme estimated 10-15 million artisanal and small-scale miners globally in approximately 70 countries) and concerns every mineral and petroleum resource. ASM communities comprise individuals, families, groups or cooperatives (often with illegal status). ASM covers activities involving as little as two or three part-time miners working in a region, or tens of thousands of miners at a site working shifts to produce as much ore as possible (Telmer, 2006).

ASM in Africa is typically regulated but legislation is not consistently implemented and controlled by the relevant authorities. However ASM communities have a complex system of internal checks and balances (Hein, 2007). It often involves large numbers of women and children. ASM is normally associated with significant to insignificant production of ore, poor or low-level mining, processing and extraction practices, illegal trading and access (Cameroon, 2002), conflict, corruption, violence, exploitation and human rights violations (Bower, 1987; ICMM, 2010), poor health (HIV/AIDS, mental health, prostitution, high mortality and sanitation), poor safety (high worker morality, child versus adult), low levels of education and skill, environmental degradation (Hentschel et al., 2002), pollution and regolith bioturbation, and/or an absence of security of tenure (Hein, 2007).

Generally, ASM is practiced as an alternative economic activity in times of economic stress (Hoadley and Limpitlaw, 2004). ASM in Burkina Faso, where this study is located, extracts iron for the production of agricultural tools, and gold and silver in exchange for money and food. Hentschel et al. (2003) divided ASM into the following categories; (a) gold rush or influx (ICMM, 2010); (b) temporary operations fuelled by economic recession; (c) isolated and remote operations with little or no involvement with nearby communities; (d) seasonal ASM activities within an agricultural cycle; and (e) traditional year-around activities that are generally associated with stable communities (or 'permanent cohabitation' of ICMM, 2010). ASM is ultimately maintained by the demand for a commodity in question (e.g., gold, tantalum, iron, diamonds and sand).

ASM of iron in the Sahelian-Saharan rural sector is often characterised by one man with one small furnace, one pump and one crucible (Figure 1.1 and Frontispiece), although increasingly ASM of iron recycles steel. However, the Dem site which covers an area in access of 2 km^2 presents a significant scale of mining, with 11 large furnaces and hundreds of crucibles, and a large mining footprint. Importantly, the site is not modern as evidenced by small grassed fossil dunes of sand which cover forging sites and are presently undergoing erosion to expose aspects of the mining area.

Figure 1.1: *Photograph of a typical modern day artisanal forge that is operated by one man, with a single pump and a number of small crucibles. The tuyere is clearly visible. A goat skin bellows would have been placed over the bellows hole to pump air into the tuyere. This particular working forge is on exhibition at the Museum of Kaya and is presented with the permission of the Museum.*

The Dem region is situated 17 km north-northwest of the town of Kaya in Burkina Faso (Figure 1.2). Burkina Faso's rural economy is dependent on agriculture, and seasonal artisanal small and medium-scale mining (ASM) for livelihoods. According to the National Museum of Burkina Faso there have been no studies of ASM for iron in Burkina Faso, and there are no records of iron mining and processing for the Dem region. Consultations with senior elders in the village of Liligomde near Kaya (Figure 1.3), who were the chief blacksmiths of the Chief Naba of the Mossi people (the Chief Naba's residence is in the village of Boussouma, 19 km southeast of Kaya), clearly argued that mining of iron in the Dem region, or for any metal commodity, or any artisanal mining in the Dem region, had not occurred in the last 80 years, i.e., mining in the Dem region is not recorded in oral tradition of significant elders of the Mossi people. The Dem site is thus an archaeological curiosity and may provide a link with the historic mining history of the people of West Africa.

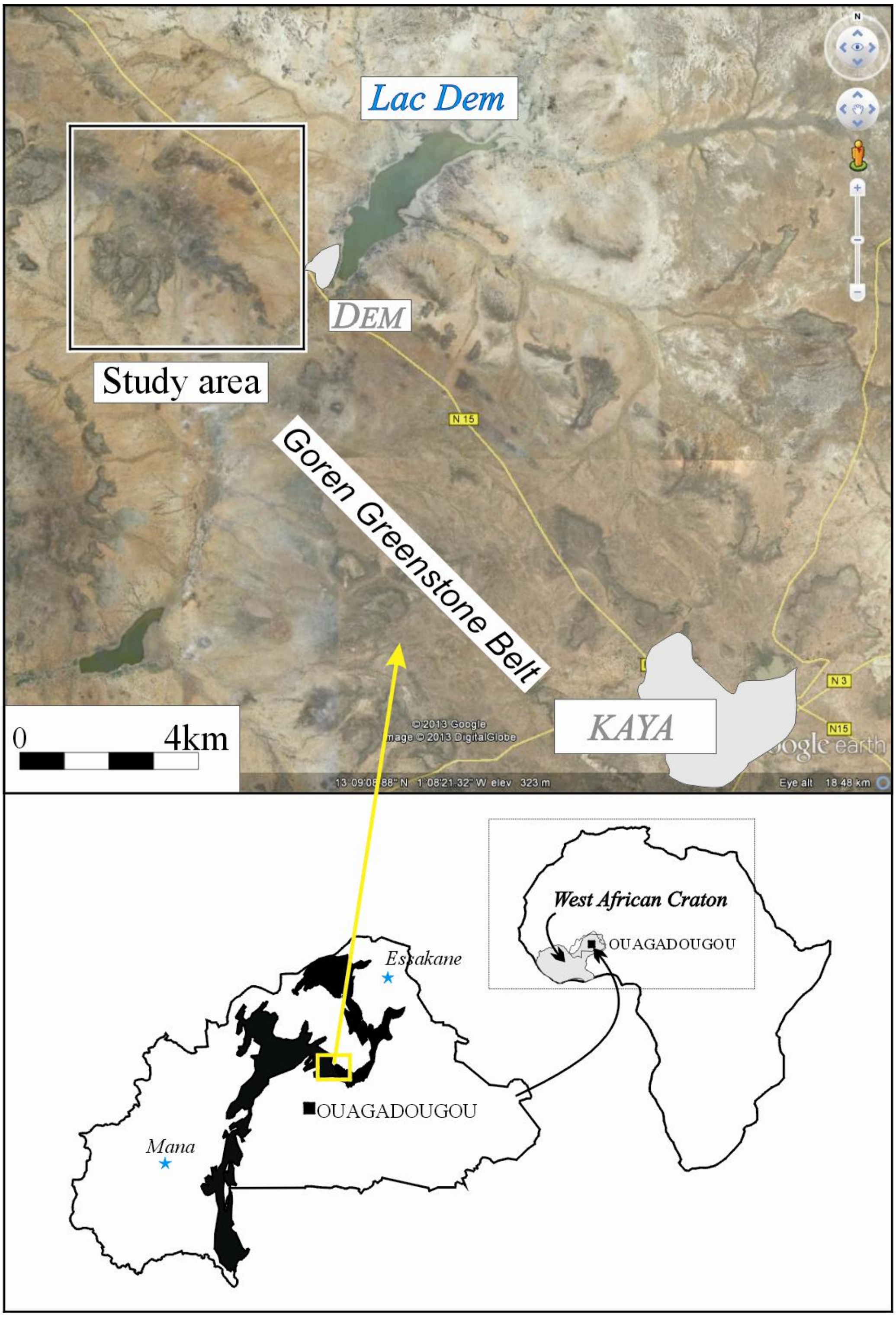

Figure 1.2: *Location of the study area in Burkina Faso, northeast of the capital city of Ouagadougou and 17 km northwest of the regional centre of Kaya. The study area is located near the village of Dem and west of the Lac (Lake) Dem in the Goren greenstone belt.*

Figure 1.3: *Photographs of the elders of the village of Liligomde who provided the ethnographic background to this study (a, b, e). Their information indicated that no artisanal mining for iron had taken place at Dem in their lifetimes. The senior elders ranged in age from 75-104 and they were the senior blacksmiths of the Chief Naba of the Mossi people. Consequently, it can be reasonably assumed that the Dem site is older than 80 years. Artisanal mining for iron is conducted west of the village of Liligomde (c) with smelting in the village on small crucibles. Iron rich spongy ferricrete is used for smelting (d) which makes tools for local agricultural use. The elderly gentleman in (e) made his own gun from smelting local iron. Photographs are reproduced with permission of the village elders. (f) Ethnographic data was collected by interview and data was recorded in a notebook with translations from Mossi to French and English as facilitated by Mr Bamogo Makido of the Museum of Kaya (squatting).*

Importantly, although the Museum of Kaya has a single ASM furnace on display to preserve the techniques of iron forging, the museum indicated that no research has ever been undertaken on iron mining, processing and production anywhere in Burkina Faso and certainly not in the Dem region.

With this in mind, this study focuses on the historic mining, processing and production of iron ore in the Dem region of Burkina Faso. Because the history is arguably lost, the techniques are not known, the reasons for production are forgotten and the age of mine workings is no longer known, this study records the size and dimensions of the mine sites, waste sites, orebody and furnaces. It records the techniques used as best can be interpreted from the site. It looks at the metallurgy of the processed ore, and type of the ore deposit. Oral tradition has suggested that the age of iron workings in the Dem region may predate the time of the Mogho Naabas (i.e., Kings of the Mossi people) and could thus be as old as the foundation of the Mossi Empire, whose inception was in the 15th century. Alternatively, the Dem iron site may be associated with French industrialisation as numerous mineral resources were mined during the period of French colonisation in the 1800's. Regardless, this research attempts to recover that lost history.

Elemental iron has atomic number of 26 and is one of the transition elements of the periodic table. Metallic iron is magnetic, malleable, and silvery-white in colour. Its physical properties make it an outstanding material for the production of tools and industrial steel. Iron is found in different forms including magnetite (Fe_3O_4), hematite (Fe_2O_3), limonite ($FeO(OH).n(H_2O)$), goethite ($FeO(OH)$), and/or siderite ($FeCO_3$). Metallic iron was used for decorative purposes and weapons in prehistoric times (Bahn et al., 1994). The most primitive sample is a cluster of oxidized iron beads found in Egypt that date from 4000 BC.

Historically, there was virtually no use of metals in sub-Saharan Africa before 500 BC, when both iron and copper came into use in the savannah and forest regions of West Africa (Smith et al., 1993). Large amounts of iron were smelted in the Nile Valley. Iron reached eastern Africa by 200 BC, and by 200 AD had been carried to the south by ancestors of the modern Bantu peoples, together with farming. However, the age of iron in the Dem region is not known and establishing its age may be important to the mining history and heritage of the African continent.

1.2. Location and physiography

The Dem study area is located in the Sanmatenga District of northeast Burkina Faso. Burkina Faso is a landlocked country that covers 274 300 km^2 (Bierschenk, 1968) and shares its borders with Mali, Togo, Benin, Ghana, Niger and Côte d’Ivoire. The capital city is Ouagadougou and is located in the geographic centre of the country. The average daily temperature is recorded as 32°C and the average annual rainfall is less than 25 centimetres in the north and northeast (McFarland et al., 1998). Vegetation in Burkina Faso is predominantly sparse savannah grasslands, dry forest with occasional shrub vegetation, or acacia forest. The country has a subtropical Sahelian climate with two distinct seasons, i.e., rainy season and dry season.

The dry season lasts for eight to nine months with a rainy season from June to September (Bierschenk, 1968). Burkina Faso is characterised by low hills and alluvial plains, and is covered by an extensive laterite plateau which is locally mined as a source for iron ore, or for alluvial gold.

Land use can be divided into (1) land that includes pastures, woodland, forest, built-up areas, barren lands and roads, and which total 82% of all land in Burkina Faso; (2) arable land that is mainly cultivated for crops that are replanted after each harvest (e.g., rice, maize, wheat) and which only total 17% of all land; and (3) permanent cultivated land that cannot be replanted after harvest (e.g. coffee, rubber) and which makes up 1% of all land (Bierschenk, op. cit.). Gold mining has recently become an important economic aspect of development in Burkina Faso, with gold producing mines in the northeast and southwest at Essakane gold mining (Tshibubudze and Hein, 2013) and Mana gold mining districts, respectively.

1.3. Geology of the study area

Burkina Faso lies on the West African Craton (WAC). Burkina Faso is generally characterized by granitic gneiss, and also north to northeast-trending belts of metasedimentary and meta-volcanic rocks of the Palaeoproterozoic Birimian Supergroup (ca. 2.3 Ga) that are intruded by trondjemite-tonalite-granodiorite plutons (ca. 2.1 Ga).

The Birimian Supergroup metasedimentary and metavolcanic rocks were deformed during the Tangaean Event that is dated at 2170-2130 Ma (Hein, 2010; Tshibubudze and Hein, 2013) and Eburnean Orogeny (2130-1980 Ma) (Feybesse, 2006; Tshibubudze et al., 2009). They were subsequently deformed during the Wabo-Tampelse Event which is currently not dated (Hein, 2010; Baratoux et al., 2011). The supracrustal rocks host economic concentrations of gold in quartz veins in shear zones, in stockwork veins or as placer gold deposits (Beziat et al., 2008). Other valuable minerals hosted by the supracrustal rocks include iron which is mined by artisanal processes in Burkina Faso for agricultural purposes, with modern exploration for manganese, diamond, zinc, lead and silver being restricted to small-scale short-term mining entrepreneurs (Klemd et al., 1997; Milési et al., 1992).

According to Cole et al. (2009), the geology of the WAC can be subdivided into three major litho-tectonic domains namely, (1) Archaean-Palaeoproterozoic basement making up the WAC, (2) NeoProterozoic sedimentary cover rocks that are developed along the western, northern and southeastern portions of the WAC, and (3) a Cenozoic mobile belt forming small inliers in the north-western and extreme eastern regions of the WAC. The WAC is generally characterized by granitic gneiss and north to northeast-trending greenstone belts of metamorphosed sedimentary and volcanic rocks.

The Dem study area is situated in the Goren greenstone belt (GGB) which comprises meta-volcanic and pyroclastic units that are interbedded with meta-sedimentary rocks (Hein et al., 2004; 2010). Carbonaceous manganese-rich shale beds and tholeiitic dacitic rocks are interbedded with volcanic units (Kříbek et al., 2008).

Based on a reconnaissance geological survey conducted in November-December 2010, the Dem region consists of metamorphosed basalt, siltstone, iron formations and shale units that are unconformably overlain by a 10 m thick silcrete-laterite-ferricrete duricrust. The Dem mine site is hosted in shale and manganiferous ironstone units. An iron-rich laterite-ferricrete duricrust formed during the Cretaceous and Miocene (Dequincey et al., 2006) and is a local source of iron ore.

1.4. Project aims

The aims of this project include:

- To map the Dem mine site footprint, its geology and geography.
- To identify the characteristics of the Dem ore deposit including its mineralogy and host rocks.
- Determine the methods of mining, processing and production of iron ore as reasonably can be reconstructed.
- To establish the mineralogy and metallurgy of the slag.
- To provide a first pass estimate of the absolute age of iron mining and the age of the furnaces.
- To reconstruct the mining history of iron mining in the Dem region.

1.5. Theses organisation

This thesis is divided into text and appendices the latter containing the database on which the text is based. The text is subdivided into nine chapters excluding the Introduction.

Chapter Two provides a Literature Review of the artisanal and small-scale mining. The Literature Review also provides an overview on the historic mining, processing and production of iron ore. The chapter presents an overview on the geology of laterite-ferricrete and iron ore deposits in the WAC.

Chapter Three presents the Methodology used in this research; it also describes in detail the different techniques used for data acquisition, data analysis, interpretation and the final product of every stage. Some of the methods included GIS evaluation, petrography, ore petrology and dating. GIS evaluation involved the use CorelDraw® and GoogleEarth® for data processing and interpretation. This helped establish the location of mine sites, furnaces, artefacts, river profiles and contacts.

Chapter Four describes the Mine Site at Dem, its mining footprint and the layout of the mine sites, processing sites, mines, and waste dumps.

Chapter Five presents petrography and metallurgy of selected samples of host rock and slag.

Chapter Six presents the results of a pilot radiocarbon study of the limited absolute geochronology which were conducted on a selected number of furnace samples. Geochronology was conducted at Beta Analytic laboratory in Miami Florida USA.

Chapter Seven Discussion, summary and interpretation.

Chapter Eight presents conclusions.

1.6. Conventions and acronyms

The conventions and acronyms used in this thesis include:

ASM - Artisanal and small-scale mining

BIF - Banded Iron Formation

BP - Before Present

Ga - Billion years

GGB - Goren Greenstone Belt

GIS - Geographical Information System

ICMM - International Council on Mining and Metals

Ma - Million years

pMC - Percent Modern Carbon

WAC - West African Craton

2. LITERATURE REVIEW

2.1. Artisanal and Small-scale Mining

Artisanal and Small-scale Mining is the oldest form of mining known in Africa and Europe (c.f., Agricola, 1556). To date, there is no internationally acceptable definition of Artisanal and Small-scale Mining (ASM). The United Nations uses the volume of material mined as a base criterion to establish the difference between small and large-scale mining (ICMM, 2010), but summarily, artisanal mining involves mining activities conducted on ore bodies or deposits by persons using traditional techniques and/or low mechanisation levels (Anonymous, 1999) using extraction and processing of minerals by intensive selective manual labour. ASM mostly occurs in rural areas by artisanal miners with inadequate (1) necessary education, (2) management skills, (3) training and (4) essential tools.

There are a range of criteria that are generally applied to categorize ASM practices. Chaparro (2000) classified ASM on production, depth of workings, capital investment, mineral type, size of concessions, number of workers, quantity of reserves, sales volume, operational continuity, operational reliability, duration of the mining cycle, use of machinery and explosives. In contrast, Hilson (2002b) divided ASM activities into two categories that included (1) high value mineral extraction including iron ore, gold, silver, precious stones and quarry mining, or (2) the mining of industrial minerals and construction materials. In the first category, as an example, iron ore requires mining, furnacing, smelting and production where the final product can be used to manufacture the rudimentary tools such as handpicks and hoes. In the case of gold, similar processes are used but chemical reagents are utilized such as mercury amalgamation or cyanidisation to liberate the gold from the mined ore (Hilson, 2002a). The mining of industrial minerals and construction materials such as sand generally do not require any form of processing technique (although mining of quartz for gravel in Burkina Faso requires considerable processing and hand-crushing).

Lovitz (2006) attempted to classify ASM practices in terms of modern mining techniques, markets, and productivity drivers and included categories that involved investment costs, mine output, labour, productivity, size of concessions, reserves and annual sales. However, these categories were less significant for ASM when compared to large-scale mining, and were often difficult to quantify. In fact they relied on considerable amounts of qualitative data. For example, production is considerably less in ASM operations relative to large-scale mining operations and productivity from day to day is difficult to quantify in an ASM operation. Regardless, in terms of ore reserves, ASM is often characterized by small and poorly defined reserves and thus produces small concessions.

In general, artisanal operators use simple methods and processes to extract in excess of more than 30 different mineral substances world-wide and there is a huge variation in the amount of success. Mining practices vary according to the type of the deposit being mined and the location

(Aryee et al., 2002), but the majority of ASM miners rely on manual methods of mining using simple equipment such as shovels, pans, chisels, pick-axes and hammers. This manual aspect of ASM methodology has probably not changed for hundreds, if not thousands of years in Africa and around the world and is probably how iron ore was mined at Dem.

The more sophisticated ASM miners currently purchase small, cheap, readily mobile machines to speed production, or use forms of ventilation, such as wind assisted plastic ventilation tubes to bring air to depth, so that extraction can proceed to up to 60 metres or more. Torches strapped to the heads of the miner to aid with vision underground, plastic ropes and metal pulleys, or bucket hauling systems, are all modernisations, but extraction is typically manual.

Furthermore, ASM mining is characterised by simple and sometimes illicit marketing arrangements mainly due to poor government policing (Sinding, 2005; Hoadley and Limpitlaw, 2004). Funds for the allocation of proper market research are limited by low or no investment capital and this encourages effective illegal trading and smuggling (Mutemeri et al., 2002). The process of finding adequate markets for minerals in the ASM sector is also difficult and may be disorganized (United Nations, 2002) and trade tends to follow along traditional or informal trade routes, or occurs within the same country.

ASM sites are also associated with health, safety and environmental problems. Lovitz (2006) stated that poor health and safety, and the use of environmentally destructive mining and processing practices draw criticism to the sector. The health, safety and environmental problems are often aggravated by inadequate regulatory frameworks governing ASM in many developing countries, especially in Africa. Nonetheless, although ASM may be associated with negative impacts, it provides a means of livelihood, jobs and business opportunities to millions of people across the world. This includes ASM in Burkina Faso both in a modern and historic context.

2.2. Artisanal mining, processing and production of iron

Africa is abundantly supplied with ores of differing qualities such as iron and copper. Iron is found in nature as iron ore but iron oxides are the most abundant. Iron is the sixth most abundant element and metal in the universe and fourth most abundant in the Earth's crust after O, Si, and Al at 5% by weight (César et al., 2002). It is a key ingredient for structural material such as steel due to its availability, low cost and strength. Iron ore is used mainly for making pig iron and sponge iron, and rusts easily when combined with oxygen through the process of oxidation (Guilbert et al., 1975).

Historically, iron was a resource that was more common than bronze and easier as a metal to work with, much as the historic improvement that bronze provided over copper (Phillipson, 1975). However, the use of iron was limited by furnace design which could not achieve sufficiently high enough temperatures to melt iron ore into workable material (Cleere, 1972). From the 19th century onwards, furnace design improved and temperature of 1540 ºC could be achieved which was sufficient to completely melt the iron ore into a workable material (Tylecote, 1976).

According to the radiocarbon dating results of Todd (1979) there was a rapid expansion of iron technology from 1400-1600 AD in West Africa but Pleiner (2000) indicated that iron workings may have reached West Africa as early as 1300 AD. In the southeast part of Burkina Faso and southwest of Niger, the Iron Age civilizations were demonstrated by the Bura culture that practiced smelting and forging of tools and weapons in 1200 AD (Miller et al., 1994).

Charcoal was a primary fuel in sub-Saharan Africa for smelting, and successful smelting required resilient woods that would burn slowly at high temperature (Childs, 1991). Ore preparation involved picking of the leanest ores followed by washing and crushing to remove the matrix and gross impurities (Kense, 1983). The ore was frequently pounded to concentrate the mineral although the nature of the pounding tools is generally not known. Ore was also roasted to eliminate excess moisture and increase rock permeability (Avery et al., 1970). Studies by Friede et al. (1986) showed that the ore was sometimes made into balls that could be fed into the furnace. Fluxes were added in form of old slag.

The chemistry of the slag is important to the smelting process as well as the chemistry of the iron ore. Smelting in Africa depended exclusively on the Bloomery process (Childs, 1991). The Bloomery process removes or extracts Fe from its ore, i.e., separating Fe and O in Fe_2O_3 to isolate Fe. Herbert (1993) on explaining the concept of smelting summarised that smelting requires three sources which are (1) source of iron which is the iron ore, (2) source of fuel to produce high temperatures which is charcoal from wood and/or coke from coal, and (3) carbon to reduce iron by combining with oxygen in iron ore to form CO_2 (Figure 2.1). The characteristics of the slag are dependent on the carbon (Scott-Garrett, 1956). In smelting, other elements are needed to remove impurities such as silica (Si). Limestone or calcium carbonate, ($CaCO_3$) is typically added to remove silica from the iron ore.

The process of removing iron from its ore is known as smelting. As described by the curator at the Museum of Kaya in Burkina Faso, in smelting of iron ore in artisanal iron workings, the furnace is loaded with charcoal and iron ore. Air is directed into the furnace from below with a tuyere (blow pipe). During the process, iron oxides in the ore are reduced to iron within the furnace and the reduced iron particles fall into a melt of slag formed near the air inlet.

Three vital chemical reactions inside the furnace occur during smelting, (1) carbon monoxide (CO) that is formed by reaction of oxygen in the air and carbon present in the fuel, (2) the reduction of iron oxide to metallic iron, and (3) the formation of slag. In the process of smelting roasted ore, flux (carbonates and/or quartz), and fuel (charcoal) are required (Herbert, 1993).

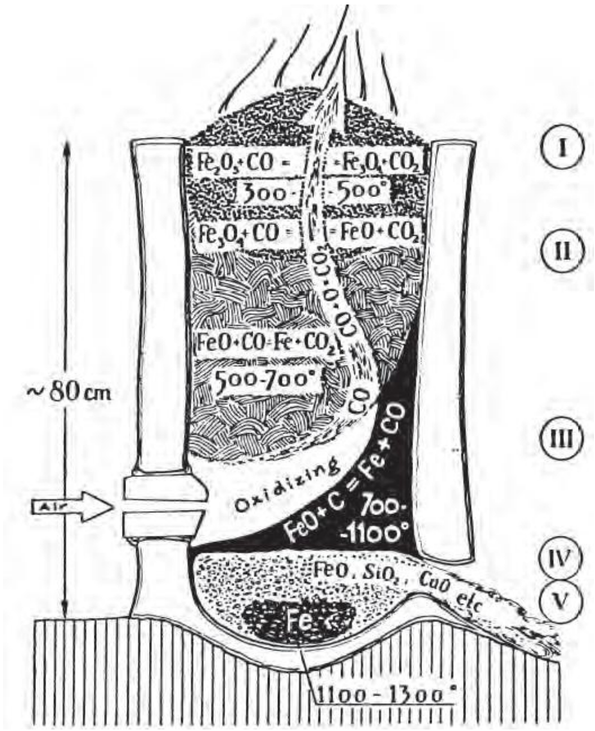

Figure 2.1: *Schematic of furnace, showing temperatures and reactions during smelting (Cleere. 1981, Figure 6). I = Roasting zone, II = Indirect reduction zone, II = Oxidation zone, IV = Direct reduction in hearth, V = Slag bath and outlet.*

The chemical reaction in which carbon monoxide (CO) is formed takes place when the furnace is packed with crucibles and preheated by burning of grass and wood, and when air is blown into the furnace. Charcoal is added to bring the furnace to approximately 1400 °C. In the reaction, the heat oxidises carbon to CO_2 through an endothermic reaction that cause the temperature to rise drastically. As carbon dioxide is transferred throughout the furnace, it combines with the charcoal to form CO through an endothermic reaction that reduces the temperature.

The second chemical reaction that reduces the iron oxide to metallic iron takes place when iron oxides combine with carbon in the furnace to form iron metal, which is the main purpose of iron smelting. The extraction process deals with the separation of Fe and O in Fe_2O_3 (hematite) and Fe_3O_4 (magnetite), and probably goethite (FeO(OH)), to isolate Fe for subsequent use. The iron melt then settles at the bottom of the furnace where it is tapped off for smithing.

The third reaction, the formation of slag, occurs between the flux and impurities in the iron ore. The slag floats on top of the iron melt due to its lower density. The purpose of the flux is to assist in the removal of impurities. The slag is drained through a temporarily opening on the lower side of the furnace (Herbert, op. cit).

The chemical reactions in the smelting process include:

$$C + O_2 \rightarrow CO_2 + \text{furnace heat (1200 °C)}$$
$$CO_2 + C \rightarrow 2CO + \text{furnace heat (1200 °C)}$$

$$\Downarrow$$

$$3Fe_2O_3(s) \mathbf{+ 3C \rightarrow 2Fe\ (iron\ metal)} + 3CO$$
$$Fe_3O_4 + 4CO \rightarrow \mathbf{3Fe\ (iron\ metal) +} 4CO_2$$
$$CO_2 + C \rightarrow 2CO$$

$$\Downarrow$$

$$Fe_2O_3 + 3CO \rightarrow \mathbf{2Fe\ (iron\ metal) +} 3CO_2$$

$$\Downarrow$$

$$CaCO_3 \rightarrow CaO + CO_2$$
$$CaO + SiO_2 \rightarrow CaSiO_3\ \mathbf{(slag)}$$

During the reducing conditions, iron oxides changes from hematite to magnetite, from magnetite to wüstite (FeO) and from wüstite to metal iron (Tylecote et al., 1971, Doherty et al., 1985). Ulvospinel (Fe_2TiO_4) may also be formed by the reaction between magnetite and titanium in the host rocks at high temperature under reducing conditions (Verhoogen, 1962; Ivanyuk et al., 2012).

At high temperature, any silica present in the furnace is likely to combine with some of the iron oxide to form fayalite (Fe_2SiO_4). Fayalite and the oxides combine to form slag with a melting temperature below 1400 °C (Paynter, 2006).

$$Fe_3O_4 + TiO_2 \rightarrow FeTiO_3 + Fe_2O_3$$
$$2FeO + SiO_2 \rightarrow Fe_2SiO_4\ \mathbf{(Fayalite)}$$

Based on the conditions inside the furnace, the reduction of iron oxide may take place in stages within the slag, or independently within the individual ore particles.

The phase relations and the thermodynamics properties have been studied by Schuhmann et al. (1953). The stability of the phases depends on temperature, pressure and oxygen activity (Figure 2.2). At high pressure fayalite transforms to spinels. At normal pressure fayalite is the only stable compound within the Fe-O-SiO_2 system. The iron-saturated section is characterized by a liquid miscibility gap, which was investigated by Greig (1937).

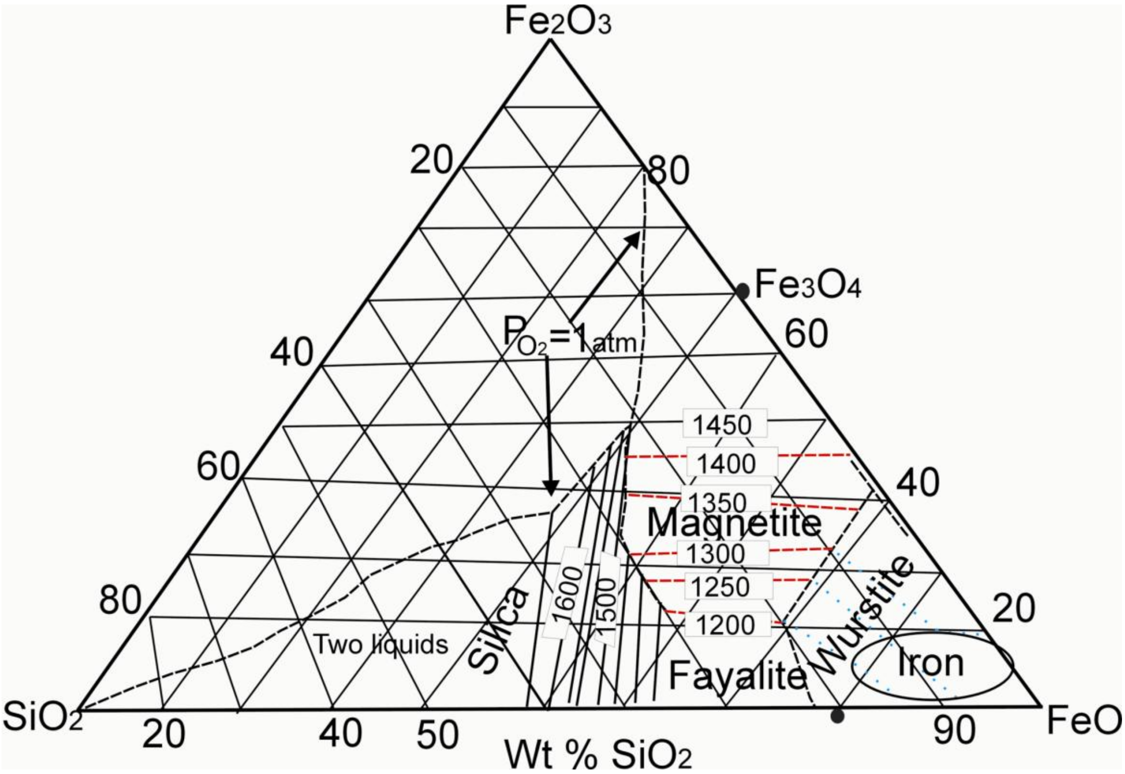

Figure 2.2: *A Fe-FeO–Fe_2O_3–SiO_2 slag phase diagram at varying temperatures redrawn from Schuhmann et al. (1953), the temperatures is in degrees centigrade.*

2.3. Laterite-Ferricrete in the WAC

In West Africa, the volcano-sedimentary rocks of the Birimian Supergroup contain iron (Milési et al., 1989; Bamba et al., 2002). These rocks are often overlain by an extensive lateritic weathering profile that provide laterite mantles and screes to younger ferricrust (Beauvais and Chardon, 2013; WAXI, 2013). Lateritization processes regulate the weathering products through extreme leaching of the silica and alkaline-earth elements of the bed rock, which results in a mineralogical reorganization of iron oxide, silica and alumina (Nahon 1991; Tardy 1993). According to Pryce et al. (2010), laterites result from the decomposition of rock within a dynamic leaching environment.

Beauvais et al. (2008) stated that most laterite deposits in the northeast Burkina Faso were formed by long-term meteoric weathering. Formation probably took place in a tectonically stable, slowly eroding, tropical environment (Brown et al., 1994; ^{10}Be and ^{26}Al isotopic depletion ratios of ferricrete) in the Cretaceous period and during breakup of Gondwanaland, with reworking of the laterite during the Miocene-Eocene (Beauvais et al., 2008; Beauvais and Chardon, 2013; WAXI, 2013). Although Burkina Faso is currently in a sub-tropical to Sahelian climatic zone, geographically it was positioned in a tropical climatic zone during the Cretaceous when the equator was located just north of Burkina Faso, the repositioning being the result of continental drift and the slow march northward of the African plate.

According to Taylor et al. (2001), laterite is a regolith mass that is cemented by Fe-oxides, with composition that is characterised by SiO_2, Al_2O_3, Fe_2O_3, H_2O and accessory elements, including Cr, V, Zr and Ti. However, laterites exhibit a vertical zonality of their characteristics and components (Blot, 2004) but are typically a weathering profile consisting of some, or all of the soil profile, ferruginous crust and bedrock. Laterites in the northeast of Burkina Faso are similar but some are developed from weathering of tuffaceous schist and calc-alkaline granites (Brown et al., 1994).

In general, iron laterites are low in iron and not of economic interest (Read, 1937). However, laterites derived from weathering of basic or ultra-basic rocks, or host rocks that are enriched in iron, such as iron-rich shales and siltstones, may be sufficiently rich in iron (and/or other elements such as nickel) to be minable. This is the case in the Dem study area, where iron-rich laterite overlies iron-rich shale host rocks of the Birimian Supergroup.

In contrast to laterite, ferricrete is the iron-cemented duricrust that is formed by various processes particularly pedogenesis (McFarlane, 1976). Generally it overlies the laterite profile in Burkina Faso but is still regarded as part of the laterite weathering profile (Schwartz, 1994). The mineralogy of ferricrete is typically composed of goethite, limonite, lepicrocite, hematite in varying proportions, sometimes with minor amounts of manganese oxides, and residual base metal sulfides (Craig and Vaughan, 1994). The profile typically presents indurated strata rich in kaolinite and hematite (Nahon and Tardy, 1992).

Further to this, in Burkina Faso, the general outcrop distribution of ferricrete indicates that the surfaces have also been eroded, redeposited and cemented several times such that the current profile is representative of several phases of ferricrete formation (Middleton et al., 1997). In fact, ferricrete may overlie one, or more of three gently inclined laterite pediments that formed as erosional surfaces between 45 Ma and 2 Ma (Beauvais et al., 2008).

2.4. Iron ore deposits in the WAC

The WAC hosts iron ore reserves that are hosted in large Palaeoproterozoic BIF (banded iron formation) deposits (>6000 mt) of iron ore in the Man and Reguibat shields (Bronner et al., 1990). The BIF in greenstone belts are also a local source of iron (Milési et al., 1989).

BIF's are fine bedded chemical sedimentary rocks composed of chert (amorphous silica) and iron-bearing minerals with an iron content of greater than 30 wt% (USGS, 2000). BIF’s are formed in shallow marine conditions from iron transported to the oceans in solution (Drever, 1974), as the result of free oxygen released by photosynthetic cyanobacteria combining with the iron in solution, insoluble iron oxides formed, which precipitated to form thin layers on the seafloor. Consequently, BIF deposits normally occur as horizontally and vertically widespread sequences.

Some BIF deposits are formed from metal-rich brines that are expelled at active rift zones by hydrothermal activity. This is case for the Faléme iron ore deposits which are the largest Palaeoproterozoic iron ore deposits in the WAC (Combes, 1980; Milési et al., 1992). They are spatially associated with hydrothermal mineralisation associated with tourmalinisation, carbonisation, chloritisation and albitisation of the host metasedimentary and volcanic rocks (Bassot, 1997).

Fe-Ti-V mineralization occurs in Tin Edia deposit of the Oudalan province in Burkina Faso (Neyberg et al., 1980). The Fe-Ti-V mineralization occurs in veins which crosscut gabbro, gabbro-norite and norite intrusions as magnetite and ilmenite, with accessory pyrrhotite, pentlandite and arsenopyrite (Castaing et al., 2003). Iron-titanium ores mostly consist of titaniferous-magnetite in association with ulvospinel and ilmenite.

The volcano-sedimentary formation in the northeast portion of the WAC contains stratiform deposits of iron-rich shale, manganese and manganese-iron-carbonate deposits particularly in the northeast of Burkina Faso at Tambão (Kimberly, 1989; Beauvais et al., 2008) and Billiata (Tshibubudze and Hein, 2013). Manganiferous iron ore deposits are formed by the leaching of silica, carbon dioxide, magnesia and minor amounts of other constituents. In addition, some manganiferous deposits are formed by the local migration of iron and manganese that produced space filling and replacement of silica. Manganese iron ore deposits are formed on the seafloor and build-up as chemical sediments together with additional sedimentary or volcanic detritus (Dasgupta et al., 1999; Mücke, 2005 suggesting that perhaps the formation of the iron and manganese deposits is related to seafloor exhalite processes.

In the Goren greenstone belt, in which the Dem site is located, Fe-rich siltstone shale and siltstone are sometimes manganiferous and intercalated with volcaniclastic meta-greywacke, meta-siltstone with minor resedimented pyroclastic deposits (Peters and Hein, 2013). However, repetitious successions of Fe-rich low grade metamorphosed siltstones, fine-grained, carbonaceous, Fe-rich exhalative and volcaniclastic units are typically intercalated with the basalt units.

3. METHODOLOGY

3.1 Introduction

The overall project carried out in the Dem study area encompassed five aspects including mapping, sampling, database development, laboratory studies and analysis of the results. Once the methodology was established, the next stage involved the accumulation and analysis of required data. In general;

- **A reconnaissance survey** was undertaken to establish traverse lines.
- **Ethnographic research** on historical mining, processing and production of iron ore.
- **Field mapping** of the study area was completed in November-December 2010. At each station point, lithological data was recorded and the GPS coordinates were established (UTM; WGS 84). Also, where appropriate, a photographic record was made and samples were collected for petrographic study. An aerial photographic mosaic map of the Dem site is presented in Figure 3.1 and a geology map of the same region is presented in Figure 3.2. Lithological data recorded in the field is presented in Appendix 1.
- **Sampling** included; (1) lithological, (2) furnace, (3) ore body and (4) host rocks. The sampling was done at normal surface temperatures 35° to 37°C with about eight hours of day light. A list of samples is presented in Appendix 2.
- **Petrographic and mineralogical studies**: selected samples of the lithologies, host rocks, ore body and slag were investigated to establish the lithological type and slag characteristics. The list of selected samples for petrography is given in Appendix 3.
- **Carbon isotopes and AMS radiocarbon dating**: A total of six carbon samples were dated using radiometric and accelerator mass spectrometry (AMS) at Beta Analytic Laboratories in Miami, Florida, USA.

3.2. Ethnographic research

This study used ethnographic methods and research as a first pass to establish the history of artisanal mining of iron in the Kaya region, and specifically the Dem region. The recording of ethnographic data was considered important to develop a base historical perspective and perhaps constrain the age of activity at the iron artisan mine site. Interviews with significant elders (Fig 1.3) of the Mossi peoples where arranged with the assistance of staff from the Museum of Kaya.

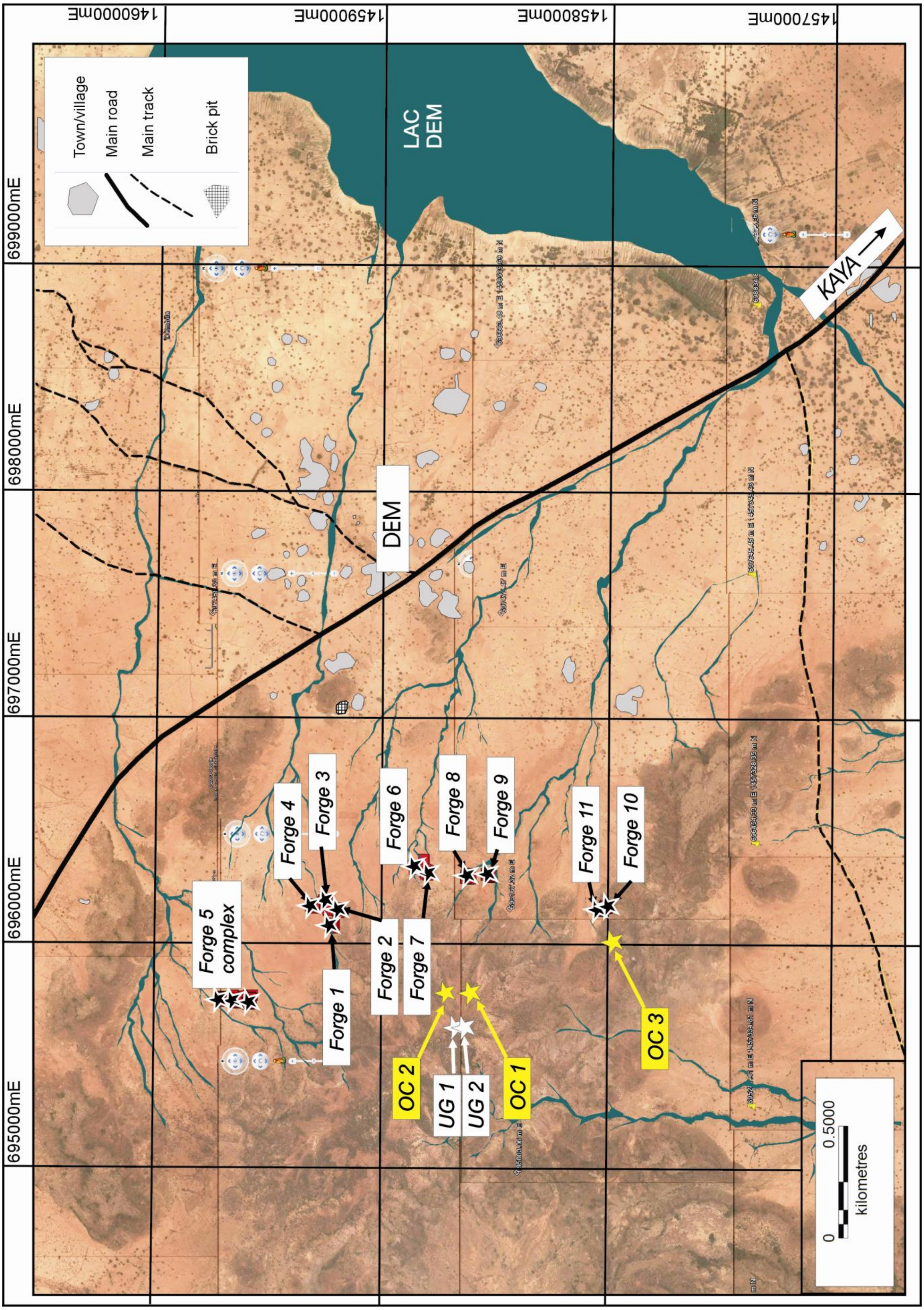

Figure 3.1: *Photographic mosaic of the Dem site constructed from GoogleEarth images. Location of the town of Dem along the main road to Kaya is shown. Sites of Opencast (OC) mining, underground (UG) mines and forges/ furnaces are also presented. The mine site is wholly located east of the major ridge on an alluvial plain. Lac Dem is located east of the town of Dem.*

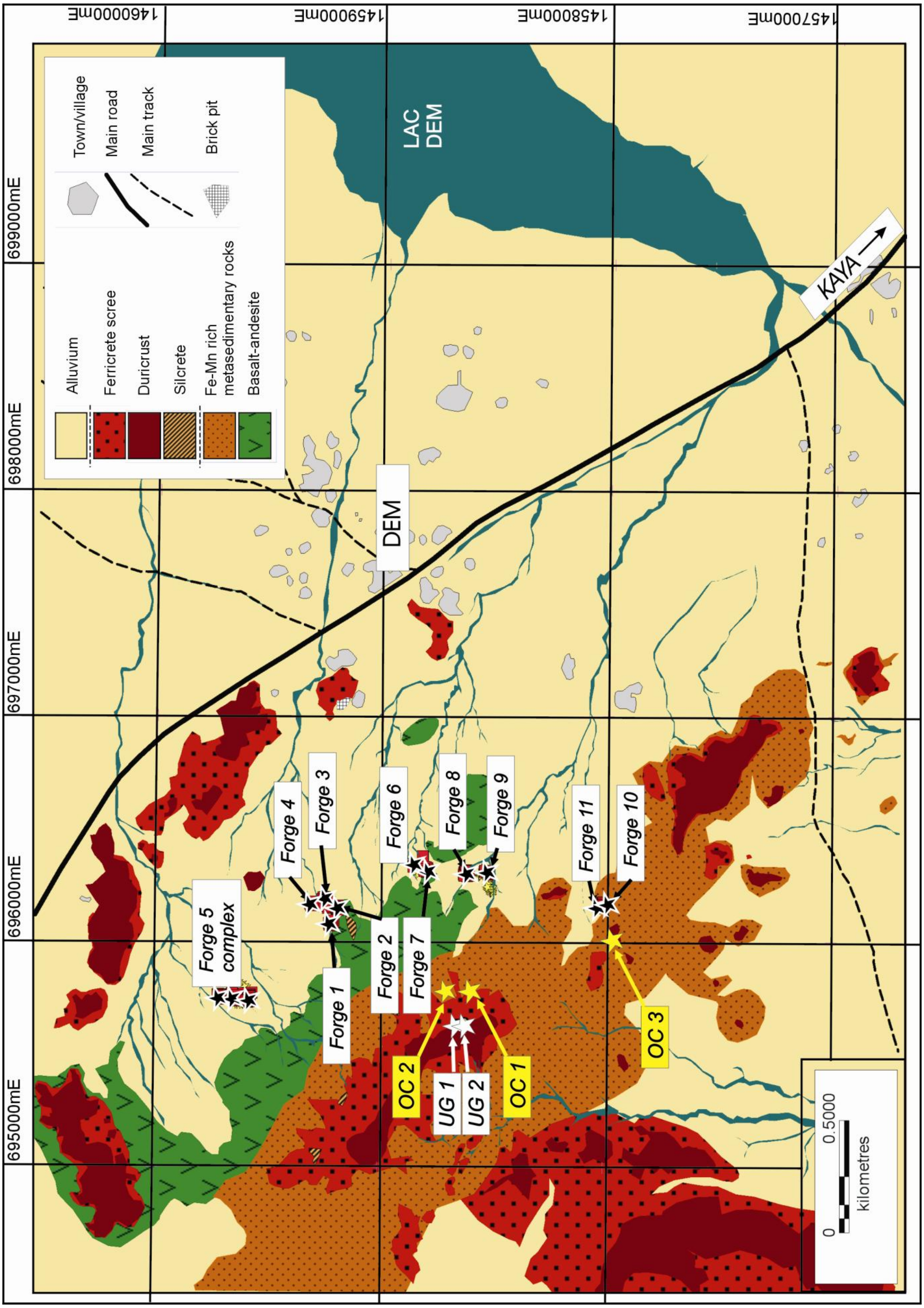

Figure 3.2: *Geology and layout of the Dem site. Open cast mines 1-3 are located on the eastern side of a ridge of ferricrete duricrust and immediately east of ferricrete scree in Fe-Mn rich metasedimentary rocks, and adit to UG 1-2 underground mines is located above the open casts. Forges/Furnaces 1-11 are situated on the alluvium plain blow the open cast mines. Waste dumps are situated proximal to the furnace sites.*

Interviews were conducted with community members of the towns of Liligomde and Kaya, which are the two local centres of artisanal mining for iron and gold. No interviews were held without the expressed permission of the senior elders of the villages. Data was recorded in a notebook; translations from Mossi to French and English where facilitated by Mr Bamogo Makido of the Museum of Kaya and all notes were recorded in English.

Several consultations were specifically conducted with two groups of senior elders (ages ranged from 75 to 101 years of age) of the village of Liligomde near Kaya (Figure 1.3), who were the former chief blacksmiths of the Chief Naba of the Mossi people. The results of the consultations clearly argued that mining of iron in the Dem region, or any significant artisanal mining in the Dem region for any metal commodity, had not occurred in the last 80-90 years, i.e., mining in the Dem region is not recorded in oral tradition of the significant elders of the Mossi people. In fact, the consultations recorded that mining for iron for primarily agricultural purposes only took place at a site immediately west of the village of Liligomde and not at Dem. The presence of iron in the Dem region was known but the iron was not used for fabrication purposes.

The Museum of Kaya also supported the ethnographic evidence and added that research has not been undertaken on iron mining, processing and production anywhere in Burkina Faso and certainly not in the Dem region. There was a record that research had been undertaken in the village of Liligomde, but the results of that work does not appear in the published works or reports held by the Museum of Kaya.

Interestingly, consultations with the significant elders about the history of iron mining in the Kaya region quickly recounted that iron mining and working as having arrived from the north through the village of Aribindi in the Oudalan province (northeast Burkina Faso) by Chief Abukonde. Ethnographic research also revealed that iron technology was brought to Burkina Faso by the Dogon people of Mali before the Mossi Kingdom was established in 1543 in Burkina Faso (Brunner-Robion et al., 2003). There was no ethnographic evidence of iron mining, processing and production in the Dem region; iron mining in the Dem region took place before the senior elders became blacksmiths, or before 1920-1930 AD.

3.3. Fieldwork and geological mapping

This research is based on one phase of fieldwork. The fieldwork took place in November-December 2010 over a period of 17 days and recorded the geology of the iron orebody that was mined, the type and number of mines, ore dressing and processing techniques (as reasonably could be established) and the greater mining footprint; the results of field studies is presented in Chapter Four.

A total of 93 rock, mine site, carbon and metallurgical samples were collected in the study area and transported to the University of Witwatersrand Johannesburg. Geological surface mapping was conducted throughout the Dem study area which is located in the Goren Greenstone Belt of Burkina

Faso (Figure 1.2). Field studies focussed on furnace sites, mine sites, waste sites and also accessible outcrops (see Figures 3.1, 3.2).

Geographical features such as dry river profiles, sand dunes and the geomorphology of the terrain were recorded and if necessary, traversed using a GPS (Garmin) instrument (WGS84, UTM), for example, the trace of the edge of dry river profiles was mapped in this way. Selected photographs were also taken of sample sites and geographical features. Artefacts were photographed whenever they were found and their GPS location recorded. All geographical and geological data were recorded on Excel® spread sheets for map creation using MapInfo® and Coreldraw®. Maps of furnace sites, establishing a photographic record, and site sampling were also completed.

The selected samples collected in the field represent a cross-section of the iron ore deposit, mine site locations, furnace locations, and waste materials (host rock, slag and chimney). Host rock lithologies were studied for thickness, orientation and rock character. Underground mine sampling was limited because the adits and drives of the underground mine site were considered unsafe and unstable to access. All samples were photographed, wrapped, bagged and labelled to keep in their water content as of date of sampling.

Carbon samples from chimneys and furnace materials were collected from the 11 furnaces that were found across the site, and their location was accurately recorded using GPS (Appendix 4). The furnace materials included charcoal on fragments of broken furnace bricks and samples of slag.

All samples were transported to the University of the Witwatersrand Johannesburg for laboratory work. At the university, the lithology samples were catalogued and sent to the School of Geosciences thin-section laboratory for preparation, while metallurgical and ore body samples were sent to the SGS Laboratory in Booysens for polished block preparation. Carbon samples were packaged and shipped to the Beta Analytic laboratory in Miami, Florida, USA.

3.4. Petrography

A total of 59 samples were collected (Appendix 3) from sites of interest at Dem including host rocks, ore bearing rocks and slag and petrographic sections were made. Host rock and ore bearing rock samples were collected from the mine sites. Samples of the metallurgical slags were collected from 11 furnaces and in the waste areas, and ore blocks were made from eight (8) samples. Metallurgical polished blocks and rock thin-sections were studied using reflected light and transmitted light microscope under an Olympus BX51 microscope with a CC12 imaging system; the results of petrography and metallurgy are outlined in Chapter Five.

Petrographic studies documented the mineralogy, texture, and alteration mineralogies of the host rocks. Petrographic data of the bulk rock and individual mineral attributes were recorded on a spread sheet before describing characteristic features of each mineral. These petrographic data were used to determine the main rock types in the study area, and also ore minerals that might be suitable for determining the grade of iron ore before and after the smelting.

3.5. Pilot study - AMS radiocarbon dating

The main aim of dating the charcoal samples using limited AMS radiocarbon dating was to constrain the age of forging as a proxy for artisanal mining activity at the Dem region through dating of forge charcoal which was assumed to have formed at the same time as mining and processing took place. The sampling of furnaces was undertaken as a pilot study in 2011, with a view to a focussed comprehensive study if the pilot study was successful, but limited funding has meant that a comprehensive study has not been possible to date.

There are three primary carbon isotopes that are ^{12}C, ^{13}C and ^{14}C. ^{14}C is radioactive whereas isotopes ^{12}C and ^{13}C are stable (Vogel et al., 1993). Radiocarbon dating is used to establish the ages of samples younger than 55 000 years. According to Anderson et al. (1950), the radiocarbon method is based on the rate of decay of the unstable carbon isotope ^{14}C. Bowman (1990) showed that the ^{14}C isotope rapidly oxidizes to form CO_2, which is absorbed by all living organisms through the process of photosynthesis. Subsequent to death and burial of an organism, the material loses ^{14}C as it converts to ^{14}N by radioactive decay.

Based on the studies by Taylor (1987) and Libby (1952), the method used in radiocarbon dating is the Libby-half life ($t½$) of 5570 ± 30 years and assumes that (1) the ^{14}C production in the atmosphere has been constant through time, (2) the concentration of ^{14}C is homogeneous for all parts of the system, (3) the half-life is accurately known and (4) there is only decay of ^{14}C after the organism's death. All of these are the sources of errors that need to be taken into consideration when analysing and interpreting the ^{14}C ages.

Accelerator Mass Spectrometry (AMS) radiocarbon dating is a technique that is based on detecting and counting the amount of beta radiation emitted in a unit time by radiocarbon atoms in a sample of known weight (Guo et al., 2000). This technique usually provides reliable results and is also based on counting the relative amount of radiocarbon to stable carbon isotopes in a sample with a mass spectrometer (Oda et al., 2000). The technique requires very small samples (usually below one gram in weight) and the time necessary to measure the amount of radiocarbon in each sample is only a few minutes.

For pilot AMS radiocarbon dating, six samples with a wide range of carbon content were selected from different furnace sites in the Dem study area including samples FOR02-01CAR, FOR05-02CAR, FOR06-02CAR, FOR08-01CAR, FOR09-01CAR, and FOR11-01CAR. The characteristics of the selected samples are presented in Table 3.1.

Sample no	Sample code	Description	Weight(g)
1	FOR02-01CAR	Furnace burnings	34.92
2	FOR05-02CAR	Furnace burnings	28.51
3	FOR06-02CAR	Furnace burnings	32.22
4	FOR08-01CAR	Furnace burnings	34.80
5	FOR09-01CAR	chimney	11.43
6	FOR11-01CAR	chimney	24.95

***Table 3.1**: The characteristics of selected samples that were sent to the laboratory for AMS radiocarbon dating.*

The samples were placed into individually labelled beakers; they were also placed on water and then a hydrochloric acid solution of 1N. The samples were heated to about 150 to 200ºC for several hours to remove any carbonates. The samples were then rinsed to neutral acidity with de-ionized water and dried in a low temperature oven. This process of laboratory pre-treatment was done to remove possible age contaminants.

The second step after pre-treatment was also performed at the sample preparation laboratory where the pre-treated sample was placed under optical microscopy to identify whether they contained carbon and also if they showed evidence of physical contaminates. No contaminants were seen.

Carbon identification was followed by chemical cleaning by acid or alkali acid to isolate carbon from the sample, but in this case acid washes were used. The samples were not exposed to alkali washes to ensure the absence of secondary organic acids.

The final step in the sample preparation laboratory was the conversion of carbon to graphite in which CO_2 and hydrogen (H_2), which acts as a reducing agent, was combined with iron powder that acts as a catalyst. This reaction takes place in a graphite reaction cell under vacuum that is composed of Vycor glass, Pyrex glass and Stainless Steel. The CO_2 generated was cryogenically purified by removing water vapour and any non-combustible gases by passing it through a series of dry-ice methanol water. The CO_2 was then measured.

When the reactants were heated to a high temperature, H_2 removed C from the CO_2 and combined with O_2 to form H_2O and lastly deposited the elemental carbon in the form of graphite. This process was achieved following the Bosch reaction (Manning, 1977).

(550 to 650°C)

$$CO_2\,(g) + 2\,H2\,(g) \rightarrow C(s) + 2\,H_2O\,(l)$$

Fe catalyst

The graphitization cell was then placed into a 550°C to 650°C oven for a period of 10-12 hours. The graphitization tube was then removed from the graphitization cell and capped with an Al-foil cover and placed in a test-tube rack ready to be loaded into a cathode for AMS counting.

Prepared samples were taken to the AMS room for AMS radiocarbon dating. The graphite was pressed into an aluminium (Al) target holder, or cathode, which was placed into a wheel that had 40 positions. Forty cathode targets were loaded in a 40-position source. From the 40 cathodes, 25 of them were test/standard samples and the remaining ones were of graphite. Modern oxalic acids standards (OXI and OXII) that allow the determination of quality assurance and radiocarbon age calculation were used.

The wheel was placed into the ion source which is the CCM beam that blasted the carbon out of the cathode into the accelerator. AMS counting is performed by converting the atoms in the graphite sample into a beam of fast moving ions (charged atoms). The stream of the carbon ions went to the accelerator being burnt and separated at certain places by the application of magnetic and electric fields and measured by nuclear particle detection techniques. The fields separated ^{12}C, ^{13}C and ^{14}C; the ^{14}C continued through the accelerator where it was detected. Finally the filtered ^{14}C ions enter the detector where their velocity and energy are checked so that the number of ^{14}C ions in the sample could be counted.

Once the data was analysed on the accelerator, the radiocarbon age was calculated. The information coming off the accelerator was the ratio between ^{14}C to ^{13}C. The conventional radiocarbon age (CRA) before present (BP) was obtained by using the following equation (Stuiver and Polach, 1977).

$$\mathbf{t = -8033 \ln (Asn/Aon)}$$

where *-8033* represents the mean life time of ^{14}C; *Aon* is the activity in counts per minute of the modern standard, *Asn* is the equivalent counts per minute (cpm) for the sample. *ln* represents the natural logarithm. The age is reported with a ± error meaning that the age can fall anywhere within that radiocarbon age span (Taylor, 1987).

With respect to contaminates there are broadly two types; natural and artificial. Natural contaminants are introduced to the carbon containing material by the surrounding substances such as soil. Hogg (1992) categorised the natural contaminants into (1) carbonates, (2) plant rootlets, and (3) humic acids (Cresswell, 1992).

Carbonates make the sample to appear older than its true age due to its older geological age, and although there are no carbonates in the Dem area, the iron-rich shales are carbonaceous. Consequently, it became imperative that $CaCO_3$ be removed from the sample during the pre-treatment stage as described in Section 3.5, and as a precaution.

Plant rootlets growing in the material of interest can also introduce additional carbon. It is possible that plants grew in the study area at some time because the Dem region grows Sahelian grass, but it should be noted that growth fluctuates dramatically according to intensity and duration of rainfall. In this context, humic acids may have circulated through the sample by the process known as adsorption and the sample may liberate a younger or older age depending on the age of growth of the plant material (Hogg, 1992). There are no records of vegetation growth for Burkina Faso, but rainfall statistics that would help to ascertain if plant growth could be important might were considered useful.

With respect to age calculations, the conventional radiocarbon ages of the selected samples were calculated using the Pretoria Calibration Procedure program after Vogel et al. (1993). The measured radiocarbon dates are presented in two ways: (1) pMC, which refers to percent Modern Carbon, and (2) BP, which is Before Present or 1950 AD. There are factors that influence the pMC while affecting the ^{14}C activity. According to Bowman (1990), the factors include (1) contamination, (2) isotopic ($^{13}C/^{12}C$) fractionation or alteration effects, (3) processes affecting the global concentration of ^{14}C in the atmosphere, and (4) reservoir effects. These factors affect the accuracy and precision of radiocarbon age.

Isotopic fractionation refers to the variation in the carbon isotope ratios as a result of natural biochemical processes as a function of their atomic mass (Taylor, 1987). Isotopic fractionation is important in presenting radiocarbon dates that are accurate and precise. Certain biochemical processes such as photosynthesis change the stability between the carbon isotopes. They favour one isotope over another (Craig, 1953). The amount of isotopic fractionation on the $^{14}C/^{12}C$ ratio, which must be measured precisely, is approximately twice that for the measured $^{13}C/^{12}C$ ratio. If isotopic fractionation occurs in natural processes, a correction can be made by measuring the ratio of the isotope ^{13}C to the isotope ^{12}C in the sample being dated (Aitken, 1990).

It is important to measure the ratio of ^{13}C to ^{12}C. According to Gowlett et al. (1986), the ratio of ^{13}C to ^{12}C is measured in an AMS with a low resolution. This is done by extracting a small amount of the CO_2 generated during the combustion and measuring the $^{13}C/^{12}C$ ratio relative to the mass-spectrometry standard. This ratio is used later in the calculation of the radiocarbon age and error to correct for the nature's isotopic fractionation. The C^{13} concentration ratio is then expressed as.

$$\delta^{13}C = \left(\frac{\left(^{13}C/^{12}C\right)_S - \left(^{13}C/^{12}C\right)_{VPDB}}{\left(^{13}C/^{12}C\right)_{VPDB}} \right) \cdot 1000‰$$

The composition of isotopes in the sample that were measured is expressed as $\delta^{13}C$, which represents the parts per thousand difference (‰, per mill) between the sample ^{13}C content and the content of the international PDB standard carbonate which refers to the Cretaceous belemnite formation at Peedee in South Carolina, USA (Coplen, 1994). The carbon dating results are calculated after normalising the $\delta^{13}C$ values to -25‰.

Calibration was made using IntCal04 after Talma and Vogel (1993) and Reimer et al (2004), and the calibrated ages were calculated using atmospheric calibration curves. The conventional radiocarbon ages were converted into Roman calendar years. For calendar years conversion, conventional radiocarbon age was applied to the calibration curve. The radiocarbon ages intercept the calibration curve at two different locations. The calibration database designs a curve for the probability of the calibrated ages. Each curve was studied to make sure the best interval was selected, and the arithmetic mean was used for the 2 sigma (2σ) age interval of highest probability of 95% and 1σ with 68% probability. In this study only 95% confidence level is considered as it is accurate, precise and reliable whereas the 1σ gives errors and means there is a 68.3% chance that the true result will lie within $\pm 1\sigma$ of the experimental result, a 95.4 % within $\pm 2\sigma$ and 99.7% within $\pm 3\sigma$ (Bowman, 1990).

4. THE MINE SITE AT DEM

4.1. Introduction

The mining of iron ore in the Dem study area produced a limited number of underground workings and surface open pits. These mine workings show no modern mechanised mining method of operating. The surveyed ASM site covers 1.9 km by 1.3 km. About four ore extraction areas and eleven smelting sites were located during field studies but a broader study of the Dem region is warranted.

The mining proximal footprint is characterised by two underground mine openings and two semi-circular open casts which are 500-600 metres in diameter. The underground mines include galleries, ventilation shafts and adits.

The underground mine workings and opencasts were mined by selective mining methods, where mineralised iron-rich fractures and quartz veins were extracted. The mineralisation generally comprised ore of magnetite, hematite and laterite.

The mined ore was (apparently) transferred to a number of nearby processing sites which are located within 500 m of the mines. Waste rocks were dumped next to both the surface and underground mine excavations. Slag was dumped near the smelting sites (furnaces) and also close to the ore sources. The layout of the Dem ASM site is presented in Figures 3.1 and 3.2.

The host rocks to the iron ore deposits included metamorphosed shale, siltstone, low grade laterite-ferricrete and mineralised quartz cataclasite veins. At least one mine site, the host rock was mangacrete.

4.2. Ore body

The Dem study area is situated in the Goren greenstone belt and hosted in rocks of the Birimian Supergroup (Hein et al., 2004; Hein 2010). The lithologies of the study area include metamorphosed basalt, shale and interbedded carbonaceous, manganifereous, sulphurous and ferruginous shale and siltstone beds, which are unconformably overlain by laterite, silicrete and ferricrete duricrust, and rarely as mangacrete which is Tertiary in age (Beauvais et al., 2008; WAXI , 2013). The western half of the study area is characterised by fine grained siltstone and shale. The eastern half of the study area is composed of metamorphosed basalt. The geology is unconformably overlain by deposits of orange aeolian sand that is interbedded with rare stream conglomerate beds. The sand and conglomerate beds are incised by ephemeral streams.

The study area is crosscut by buck quartz cataclasite veins, which in the carbonaceous, manganifereous, sulphurous and ferruginous shale and siltstone beds are surrounded by an alteration zones, veins and interlocking veinlets that are rich in iron in the form of magnetite and hematite. The veins were selectively mined by gallery methods. Magnetite-rich ore is black in colour and dominantly hosted in massive siltstone. It may present as stratified ore that extends over a strike length of 30-100 cm and width of 10 cm. The vein-hosted iron was a primary source of high grade iron ore (Figures 4.1a-d).

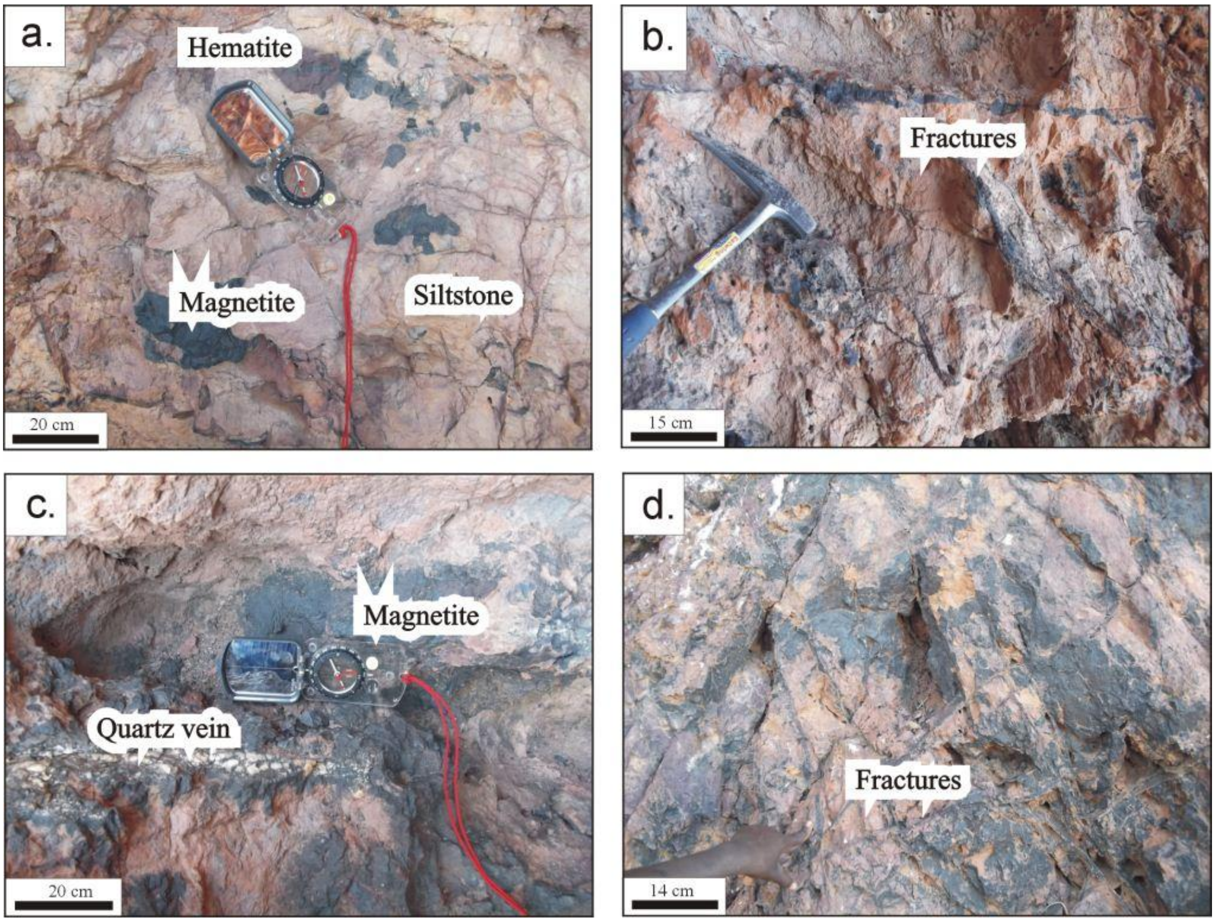

Figure 4.1*: Photographs of vein-hosted iron ore from adits in the underground mines of the Dem iron site. A. Massive siltstone hosting zones of iron staining. Numerous fine iron-rich veinlets crosscut the host rock. B. Interlocking network of iron rich veinlets. C. Quartz vein cataclasite veins surrounded by a wide alteration zone of iron enriched siltstone. D. A complex zone of alteration in massive siltstone.*

Across the West African Craton, an extensive laterite-ferricrete plateau is locally mined as a source for iron ore for the agricultural industry (Figure 4.2), such as near the village of Liligomde near Kaya). In the Dem region, ferricrete overlying iron-rich shale was clearly mined artisanally as a source of iron, along with primary iron in the alteration selvages around buck quartz veins that crosscut the iron-rich shale.

Laterite-ferricrete type iron ores are derived from the sub-aerial alteration of rocks (Beukes et al., 2002). Laterite-ferricrete ore deposits in the study area are 6-20 m thick, but usually less than 6 m, and consist of nodular red, yellow and brown hematite and/or goethite. The laterite ores are concentrated on the upper surface of the regolith as a supergene product of the iron-bearing host rocks. It consists of oxidised and insoluble rock constituents.

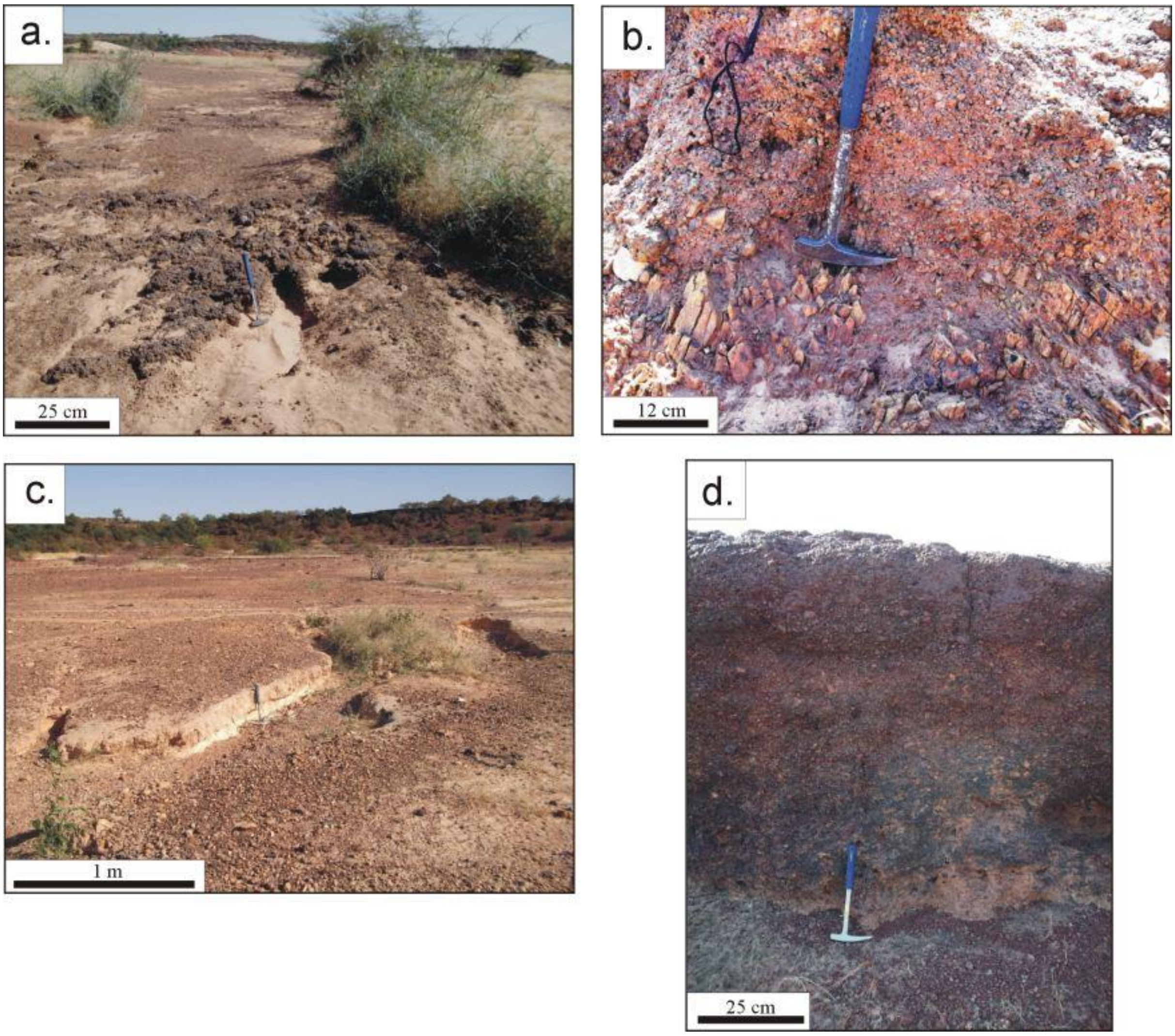

Figure 4.2: *Laterite-ferricrete plateau and outcrops occur across the Dem region. A. Photograph of recemented ferricrete in the foreground with ferricrete plateau in the back ground. B. Ferricrete overlying massive siltstone unit in the Dem region. C. Ferricrete plateau in the background is composed of the profile in photograph D. Several layers of ferricrete development can be interpreted from the profile.*

In summary, there are two types of ore deposits in the study area; vein hosted and laterite-ferricrete hosted. The range of ore types mined was extensive and varied from high grade magnetite to low grade laterite.

4.3. Mines

The surface mines consist of two bowl-shaped open cast pits (OC 1, OC 2) that are approximately 500-600m in diameter, with small galleries running a short distance into the sides of the pit following the iron-rich vein-type ore. A third site (OC3) is situated approximately 650 metres south-southeast of these two opencast. OC1 is situated at UTM 695780.98 mE, 1458597.50 mN, OC2 at UTM 695778.71, 1458705.0 mN, and OC3 at 696020.66 mE, 1457969.2 mN. Iron ore supply that came from these sites comprised mostly laterite ore that was at or near surface. The open cast mines are shown in Figure 4.3 as pit 1 and pit 2. Underground Mine 1 (UG1) is located between OC 1 and OC 2. OC 1 mined scree rocks that rolled down the hill from outcrops of shale-siltstone above. OC 2 mined ferricrete scree that rolled down the hill from the ferricrete plateau above. This both in-situ and scree was mined at Dem.

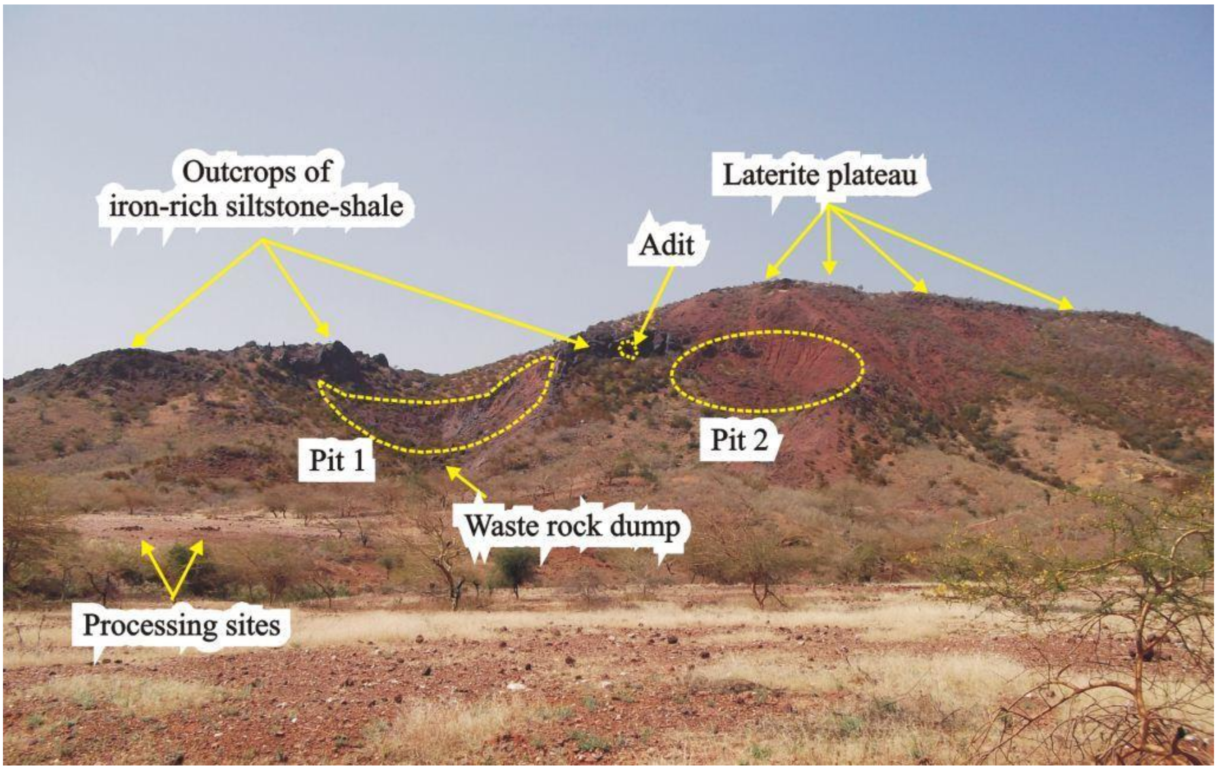

Figure 4.3: *The two surface mines consist of bowl-shaped opencast pits that are approximately 500-600m in diameter. The most significant is pit 1 which has worked a considerable volume of primary ore dislodged from outcrops above the opencast, in a natural valley. Iron rich cataclasite veins also crop out across the floor of the open cast. Underground workings (UG 1) occur between the two open casts with adit/entrance located high on a rock face (as marked). Open cast pit 2 worked mainly ferricrete scree that roll down from the laterite plateau above.*

The site also has two underground mines, which are characterised by drifts, galleries, adits and tunnels (Figure 4.4). These openings were developed along and perpendicular to the mineralised vein type ore. Underground mine 1 (UG1) is situated at latitude 13°11'15.137" N, longitude 1°11'36.017" W and is characterised by two adits that are 3m apart. The opening of each adit is 1 to 2 metres in diameter. Underground mine 2 (UG2) is situated 67m SSE of UG1 at latitude 13° 10' 55.107" N, longitude 1° 11' 28.759" W. These two underground mines are characterised by quartz vein-hosted iron ore with-magnetite and hematite hosted in shale and siltstone units.

After the ore was extracted from the open cast and underground mines, it is likely that the ore was transported to the processing sites nearby the mines, with ore being dumped proximal to mining operation, as occurs at ASM sites around the world today. The ore might have been man-hauled to the surface in bags or sacks particularly because there is no evidence at the Dem site of mechanical aids for hoisting and hauling ore. It is possible that the open cast operations were mined by women, children and aged persons, as can be witnessed at ASM site throughout Burkina Faso and West Africa, with the underground operations being the domain of men.

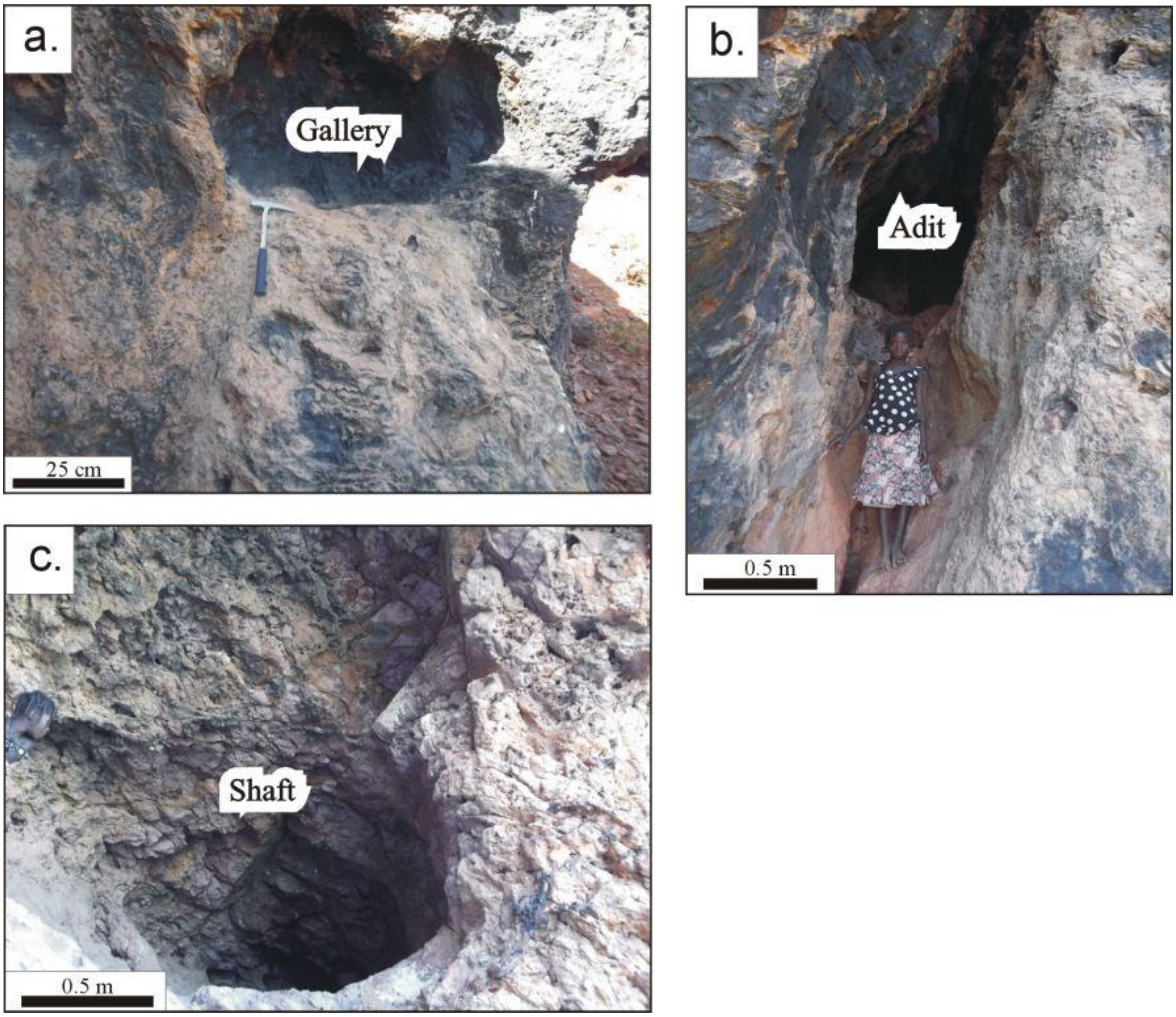

Figure 4.4: *Underground Mine 1 (UG1) consists of a series of drifts, galleries, adits and tunnels that accessed primary in-situ iron ore from the selvedge of quartz cataclasite veins. The galleries were too dangerous to enter but the workings were considerable.*

4.4. Ore Dressing and Processing

After mining, the material containing the ore was likely separated from the waste material by handpicking, sorting and crushing as occurs at ASM sites today and around the world, and particularly because there are small ore stockpiles near to the mines. The locations of stockpiles are presented in Appendix 2. The waste rocks included quartz, silicrete and iron-poor laterite.

After the removal of most of the waste rock, the ore was transferred to the forging sites. The means of transport is not known, but we can speculate that the ore was transported by man-labour or perhaps on livestock such as donkeys, as this is the technique that remains in use today in ASM sites. Well defined paths (which currently stand proud of the eroding land surface) lead between the mine sites and the forges.

Assuming that the ore was transported by man power in baskets, sacks and bags, the transportation from the sorting site and ultimately to the furnaces would have been across short distances as the processing and furnace sites are not far from the mine sites (1 km). After beneficiating the ore at the processing (again by hand with rudimentary tools for liberating the high grade ore from the waste), the ore would have been transported to the furnaces. Stockpiles of high grade ore were not found in the study area and it is assumed that ore was passed directly into the furnaces as needed from the processing sites.

The evidence of iron smelting in the study area includes the remains of at least 11 furnace (furnace wall and floor fragments), and hundreds of fragments of tuyeres, crucible, burnt clay and iron slag (Figure 4.5). The furnaces remains are circular in shape with a maximum diameter of 2 m. The furnaces designs were bowl-shaped and/or dome-shaped, as interpreted from the remains at the furnace sites. The bowl-shaped furnaces formed a hollow in the ground which was lined with clay and filled with iron ore and charcoal. The dome-shaped furnaces comprised a circular hearth that was flat at the base and covered by a brick dome. A list of the different types of furnaces in the study area with their geographic locations, are presented in Appendix 3.

The furnaces were filled with a number of tuyeres, fragments of burnt clay and small slag fragments. Except for their size, both the bowl and dome furnaces were the same in most characteristics. Furnace 1 and 5 are the only processing sites that are far from the mine sites at 1.6 and 1.7 km distance, respectively. The relationship between the individual furnaces is not known, and it is not clear if they worked as entities across the mine-processing sites, or together.

Tuyere fragments were found in all the furnaces and sometimes hold slag on their ends. The average tuyere size found in the study area was 7 cm long. Tuyeres are clay nozzles used to allow air into the furnace through forced bellows (Childs, 1989). A bellow is used to cover the furnace and is normally made of goat skin. The tuyere provides oxygen into the furnace and increases the pressure of the furnace temperature. It can be interpreted that a bellows system was used to allow air into the furnaces in order to increase the temperature achieved in the furnace.

Hundreds of crucibles were also found in the study area in association with the tuyeres and furnaces. A crucible is a heat resistant bowl-like structure made of clay and organic material used in the smelting process. The source of the material used to make the tuyeres, crucibles and furnace bricks can only be speculated; however, they are made of orange aeolian sand similar to that which unconformably overlies the Birimian Supergroup and Tertiary rocks of the study area. It is interpreted to mean that the local sand was mined or harvested in the production of crucibles (probably made by hand).

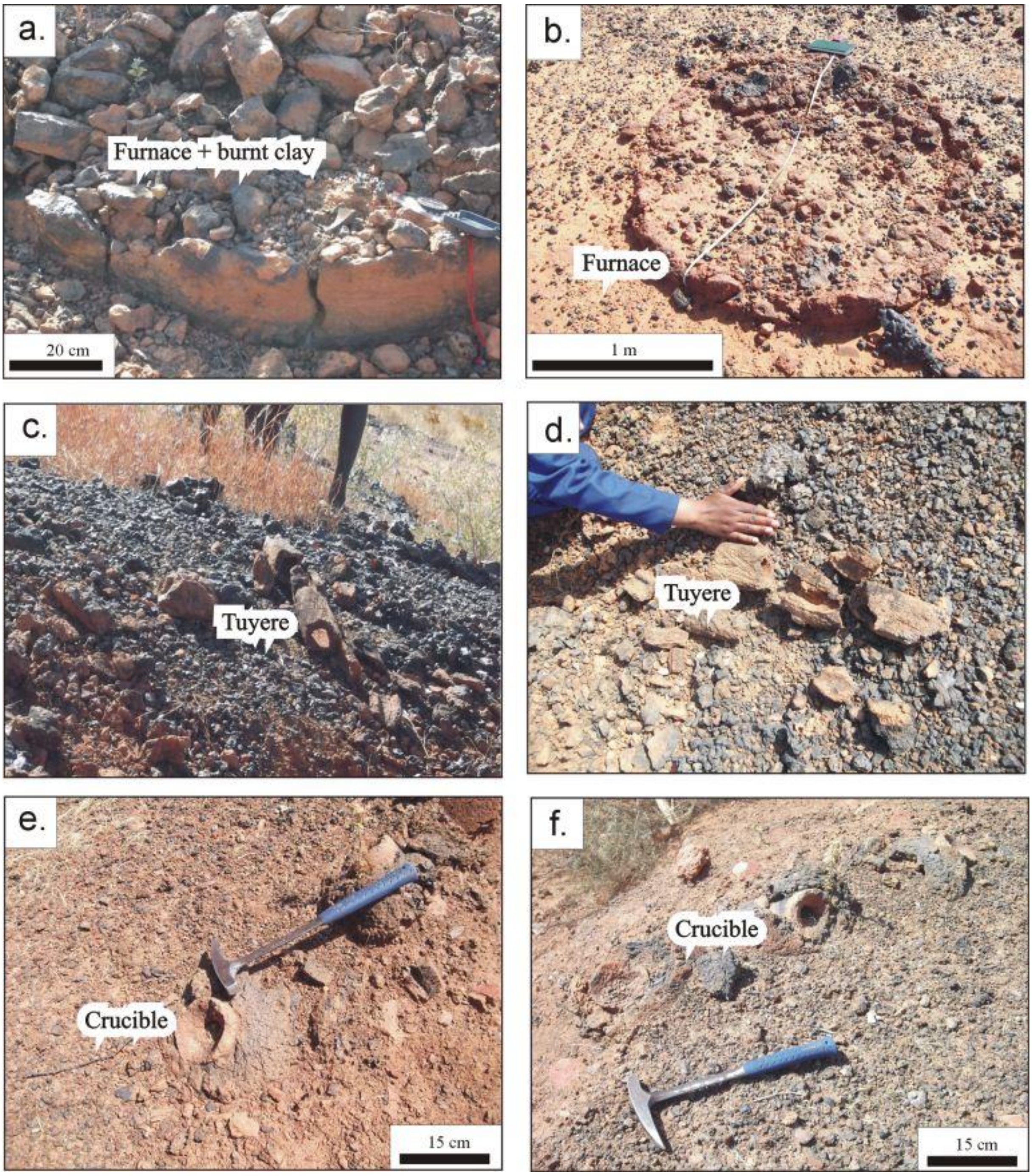

Figure 4.5: *Iron smelting at the Dem site is evidenced from the remains of at least 11 furnace (furnace wall and floor fragments), and hundreds of fragments of tuyeres, crucible, burnt clay and iron slag. A. Burnt clay of the furnace wall. B. Furnace 2 which is representative of all furnace in the Dem mine site. They are typically round with flat or bowl shaped floors. C and D. Tuyeres are scattered around many of the furnaces or welded into the floor of the furnaces with slag. E and F. Crucibles made of clay-sand are also found proximal to the furnace site of welded together with slag.*

The waste rock in the mine sites was dumped near the open casts and underground mines. Open casts tend to produce more waste than underground mines where a minimal quantity of waste was removed to gain access to the ore deposit (Hudson et al., 1999). It is thus that the largest waste piles are located next to the opencast mines.

Waste from the furnaces included slag and furnace fragments which were dumped after smelting and within metres of the furnaces (Figure 4.6). Processing sites were also located proximal to the furnace sites.

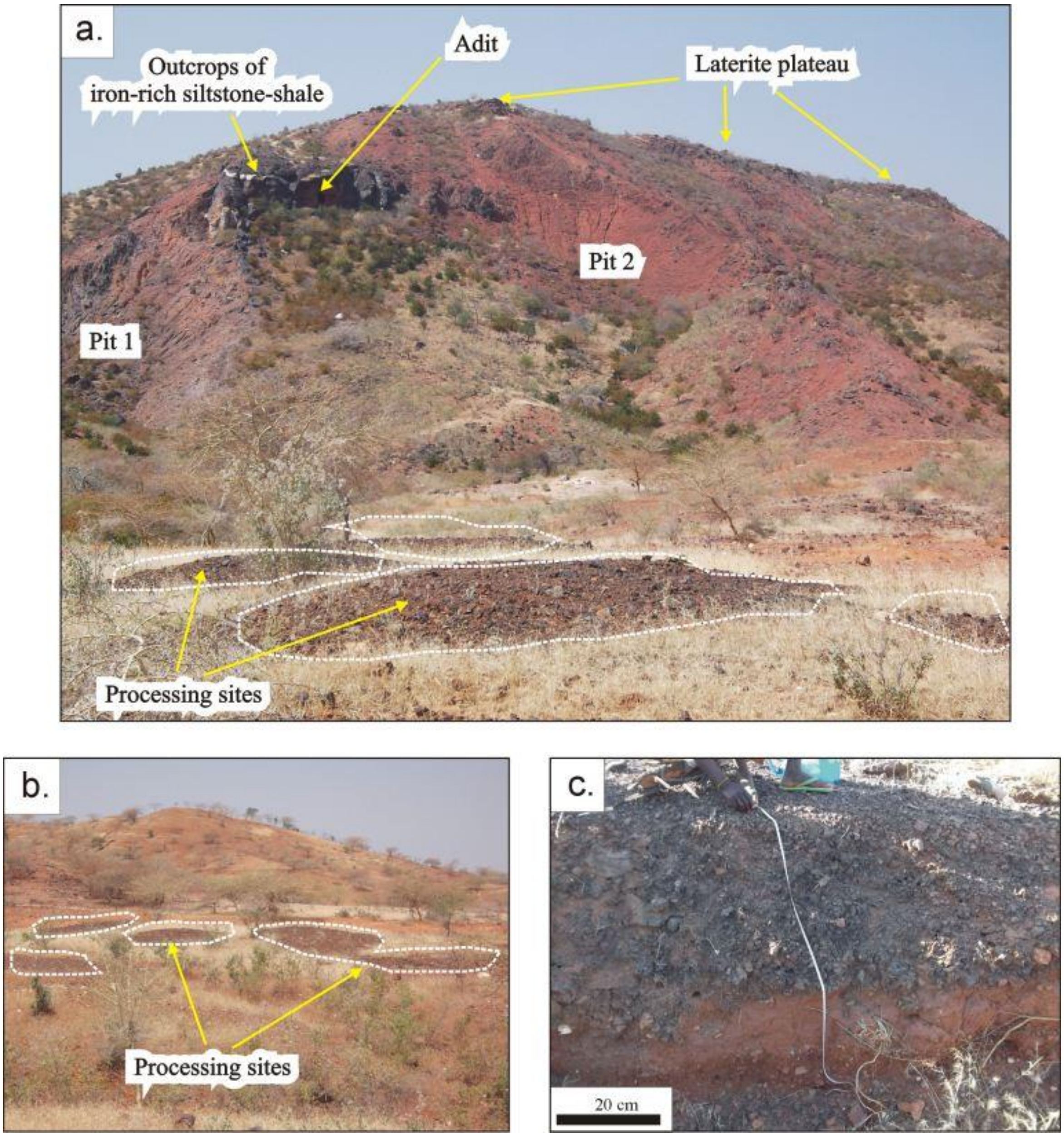

Figure 4.6: *Processing sites at the Dem site. A and B. Numerous processing and slag dump sites are located near the mines and adjacent to furnaces and scattered throughout the area. They indicated that the ore was beneficiated before use in the furnace, or that slag was removed from the ore after smelting. C. Section through a slag dump site next to a furnace 8. It is clear that a significant amount of forging had taken place at Furnace 8.*

Slag is the by-product of iron smelting. It can be defined as a silicate complex formed in the process of Bloomery when iron ore is being reduced in a furnace (Friede et al., 1982). The most important constituent of slag is fayalite (Fe_2SiO_4) and quartz (SiO_2) (Morton and Wingrove 1972).

Slag making has always been a part of steel and iron making. In 1500 BC, the secret to steel and iron making was in the slag formulations (Muszer, 2004). The characteristic behaviour of slag under any operating conditions is a function of its composition and the various constituents in it of which the fluxing constituents are the most important ones. Slag contains gangue minerals from the ore, impurities from the fuel, wüstite, silica and a variety of reaction products formed in the smelting process. There are generally two types of slag including the flow-type and furnace-bottom slag. Flow-type slag is solidified from molten rock, a condition which is lava-like and rippled in appearance. Flow-type slag is black, dense and shiny in appearance. In contrast, furnace-bottom slag contains higher amounts of impurities from the ore, fuel and bloom. It is often spongy, porous and needle-like in texture.

During the process of smelting, slag floats on the surface of the molten product due to the low density of slag. The characteristics of slag such as the volume, density, porosity and grain size is influenced by the cooling rate, temperature and the chemical composition of the iron ore, flux, charcoal and clay. Higher temperatures decrease the viscosity of the melt.

Different types of slag (Figure 4.7) were dumped at different locations in the Dem area and included (1) a dense black-grey flowing type that resulted from a slow cooling rate, (2) a black glassy type resembling an obsidian formed as result of a rapid cooling rate in the presence of water, (3) a spinifex-like texture due to quenching at high temperature, and (4) a clay containing pumice-like slag with vugs that formed due to the release of gas bubbles in the melt.

Due to high silica content of the slag, it is resistant to weathering, thus large amounts of slag fragments were found at the ASM site. Slag waste around Furnace 5 was significant and extended away from the furnaces up to 25-40 metres; it may have produced more slag and was bigger than all the other furnaces.

In summary, the above evidence clearly shows that mining in the study area was important. It must also have been economically viable because a considerable amount of human capital and skill was expended at the site. Ore dressing and processing extended over a considerable area of the study site.

4.5. The greater mining footprint

The Dem ASM site is located 2km west of the Dem village, which is situated at latitude 13°11'17.528" and longitude 1°10'43.199"W. According to Haaland et al. (2004), the successful cycle of historic iron smelting involved; (1) the choice of the smelting site with respect to settlement and

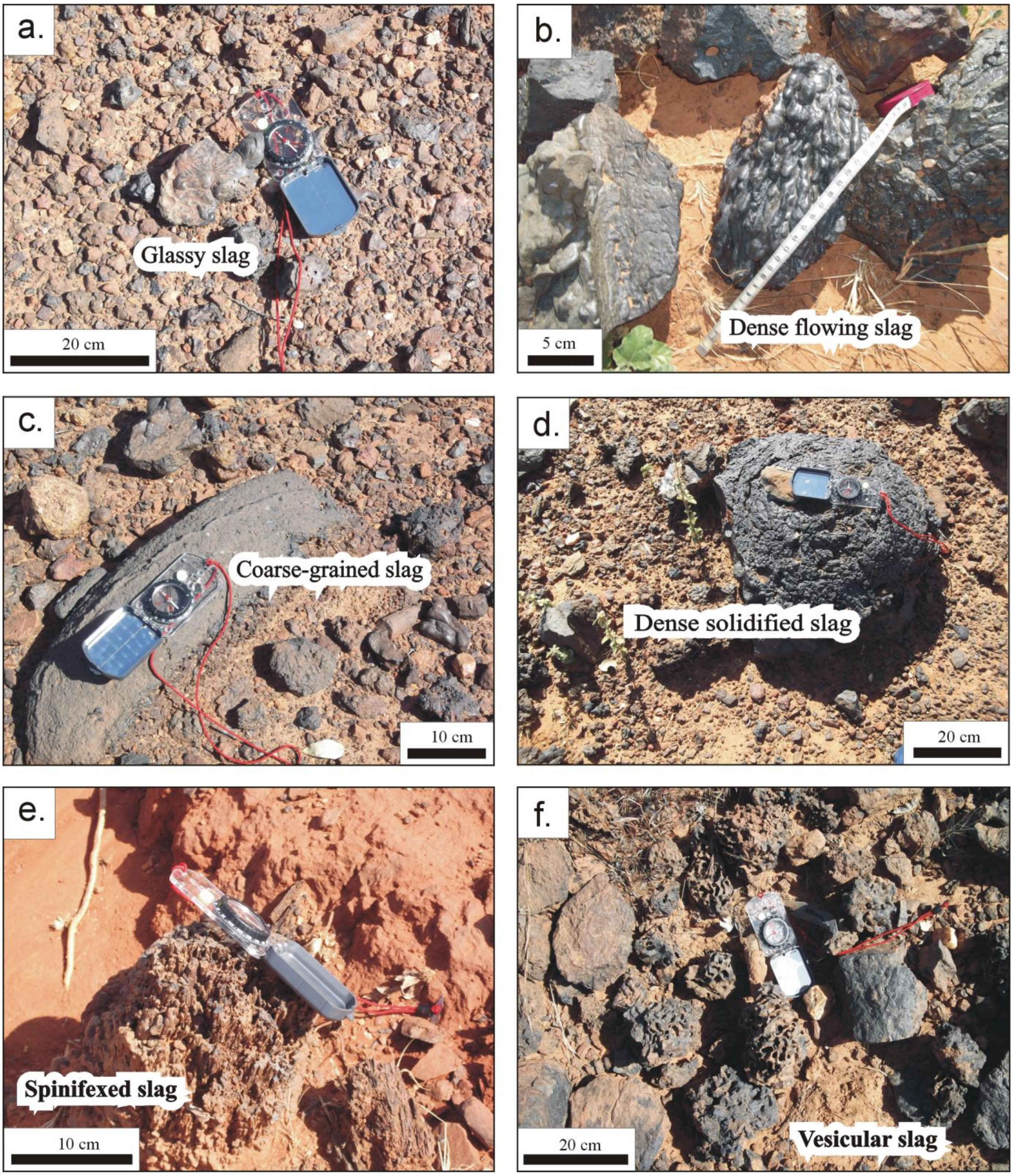

Figure 4.7: *Photographs of the different types of slag in found at the Dem mine site. A. Fragment of glassy slag resembling an obsidian found throughout the Dem site at all furnaces is consequent of rapid cooling. B. Flow type slag from Furnace 5 which is forms during slow cooling from a high temperature melt. C. Coarse grained slag from Furnace 5 formed by slow cooling rate at a relatively constant temperature. D. a dense black-grey flowing type that resulted from a slow cooling rate in cow-pat form, E. Spinifex texture which forms due to quenching at high temperature. F. Vesicular slag with vugs that formed due to the release of gas bubbles in the melt.*

resources (iron ore, charcoal, clay, water and flux), (2) the choice of trees for making charcoal and transporting them to the processing site, (3) clay collection for furnace construction and production of tuyere and crucibles, and (4) distribution of the final product after smelting. Presumably, historic smelters could possibly choose the smelting site near at least one resource. Certainly, the iron-rich resources at Dem gave reason for the other industries to exist; tuyere, crucible and furnace brick production is interpreted to have taken place locally from orange aeolian sand which covers the Dem study area.

Charcoal was the most appropriate fuel for the smelting of iron ore in ancient times but the type of wood used in the Dem study area is a subject of speculation. Charcoal is a by-product of dry distillation of wood and contains high carbon content (Karbowniczek, 2005). It is advantageous because it is easy to produce, has low ash content, contains no sulphur and has a high caloric value meaning, it can maintain very high temperatures in a small volume (Craddock, 1995).

At Dem, an immediate source of charcoal could have been from the valleys to the east of the ASM site which today hosts 2 dams for irrigation and extensive market gardens (Figure 3.1). The vegetation at the valley is presently dominated by large trees and savannah forest. It seems possible that the historic Dem forest could have provided the source of fuel (charcoal) during iron smelting, and perhaps a ready source of water.

A source of flux is also important in iron ore production. Flux is used as a reducing agent that facilitates the chemical reaction and separates the molten metal from the waste (slag) in smelting. Some fluxes used in smelting include carbonate and quartz. In the study area a considerable amount of crushed quartz and outcrops of quartz veins occurs both in the mine sites themselves, but also regionally. A ready source of clean carbonate does not exist although many of the siltstones are carbonaceous in composition and may have acted as a flux during smelting. It is possible that quartz was the main flux, but further study is needed to clarify this aspect of iron ore production at Dem.

An important aspect of the greater mining footprint of the Dem ASM site are the many tracks, which stand proud in the eroding fossil aeolian landscape. Tracks in desert aeolian sands are difficult to eradicate and can remain for decades as trace fossils as evidenced from rehabilitation programs around the world which want to remove tire and track damage in deserts (Burke and Cloete, 2004; Wassenaar et al., 2013). In the Dem study area, tracks are pressed into the fossil alluvial soil (that is currently being eroded) and these lead from mine to furnaces and processing sites, and from the east of the mine site region where the historic Dem forest is speculated to have been situated, to the furnaces. This is interpreted as the representing the routes or paths that the ASM miners used to convey material between, mines, processing sites and/or perhaps from the Dem forest to the furnaces. Significant modern tracks for human movement and/or livestock do not occur in the study (apart from the main road from Kaya through the village of Dem and heading northwest).

In addition, a number of stone tools of unknown use and origin litter the study area (Figure 4.8). These require investigation in any further studies of the ASM site.

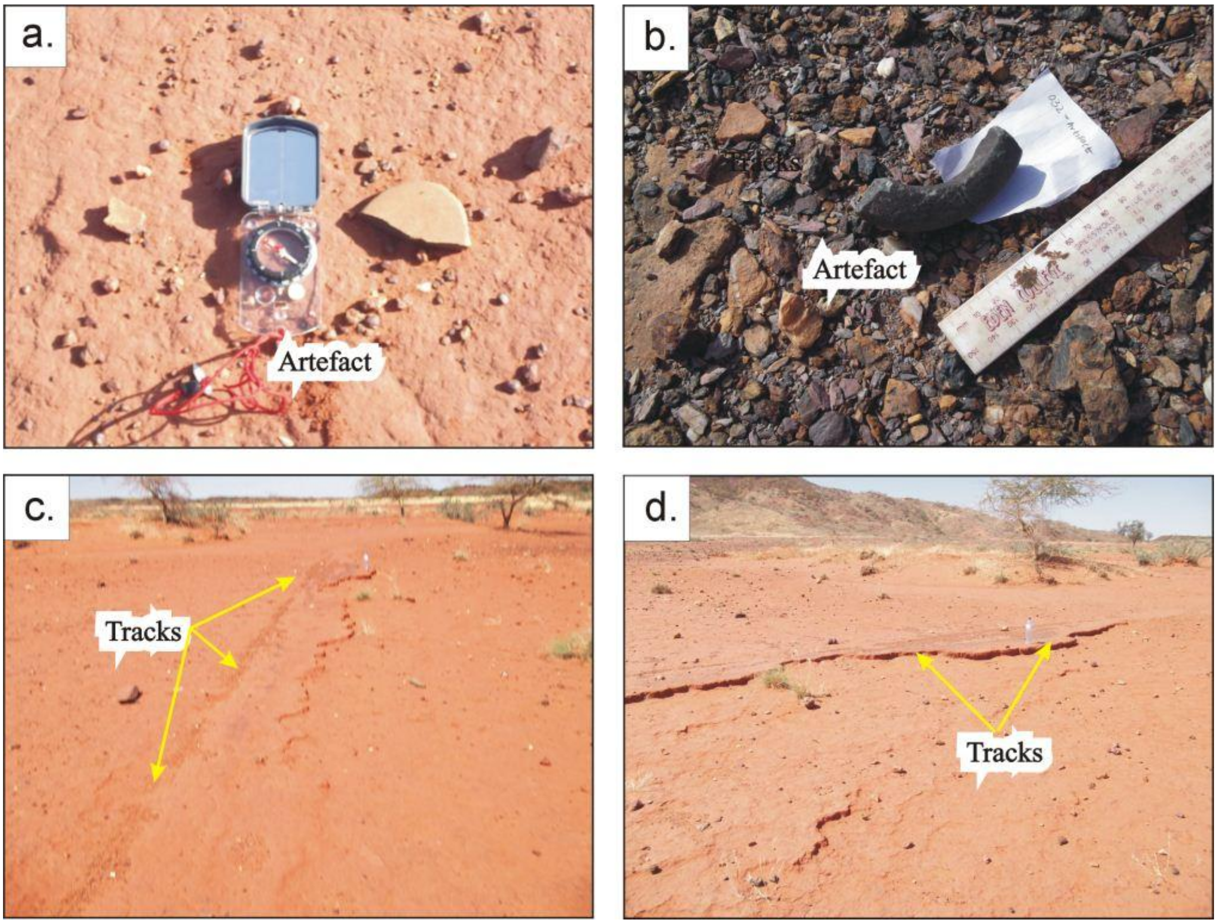

Figure 4.8: *A number of stone tools (A B) litter the Dem site specifically long old tracks (C, D) which link the furnace sites and the mine sites, and around furnaces site. By and large, the purpose or use of these artefacts is not known.*

5. PETROGRAPHY OF ORE BEARING ROCKS AND SLAG

5.1. Introduction

Transmitted light petrography was carried out to attain a more precise identification of the mineralogy and textures of the rock types, ore deposits and slag comprising the Dem area. This section is divided into three parts. The first part describes the petrography of the rock types comprising basalt and metabasalt units, shale units and silcrete units. It focuses on the rock types comprising the different contact relations among the three units.

The second part describes the petrographic features of the ore types comprising the hematite-magnetite, altered quartz vein and lateritic units. The description of the ore in this study was based on numerous field exposures, underground openings such as adits, tunnels and winzes. The sections from mine sites samples were from the deeper parts of the openings of the ore deposit in order to avoid weathering associated with soil forming processes. The third part details the petrography of the iron ore slag. It focuses on the mineralogical composition of the slag. The thin-sections of samples from the mine sites and contact rocks and slag were made.

Ore samples from Dem are dominated by subhedral to euhedral grains of iron ore minerals, many of them are fractured. Sulphide minerals are less abundant than silicates and oxides. Glass and metallic phases are also present in the slag samples. Magnetite and hematite are abundant throughout the ore, ranging from the massive mesobands of interlocking grains to thin microbands and isolated euhedral grains. Other minerals that are also present are goethite ($FeO(OH)$), manganite ($MnO(OH)$ and ulvospinel (Fe_2TiO_4).

The main aim of all the petrological investigation is to assess the mineralogy of host rocks, ore body and slag in order to determine the relationship of iron ore mineralisation before and after smelting and also to establish the texture and structure of the ore minerals in the study.

5.2. Petrography of the host rocks

Six different host and contact rocks types were identified in the study area and included metamorphosed black shale, siltstone, basalt-andesite (partly amydaloidal), and mangacrete, silcrete and ferricrete.

The dominant mineral phases in the shale and siltstone host rocks are unsurprisingly quartz, mica and carbonate, with accessory feldspar, graphite and rarely magnetite. The shale is laminated (Figure 5.1a) with minor patches and veinlets of iron oxides. Some beds are graded. Black shales are graphitic and carbonaceous with a mineralogical assemblage of fine-grained quartz, sericite, carbonate and accessory plagioclase (Figure 5.1b). The siltstone and shale units are graphitic and carbonaceous and sometimes manganiferous.

The basalt-andesite units in the Dem study area are generally massive, and sometimes amygdaloidal. They are strongly to weakly altered and typically chloritized. They are composed of fine to very fine assemblage of plagioclase, clinopyroxene (altered to chlorite), and biotite altered to chlorite (Figure 5.1c). Quartz and rarely carbonate fills vugs as amygdules.

The silicrete units are composed of concretions of goethite and silica surrounding rock fragments, and rarely organic materials and micro-quartz (Figure 5.1d). Vugs are filled with goethite and quartz.

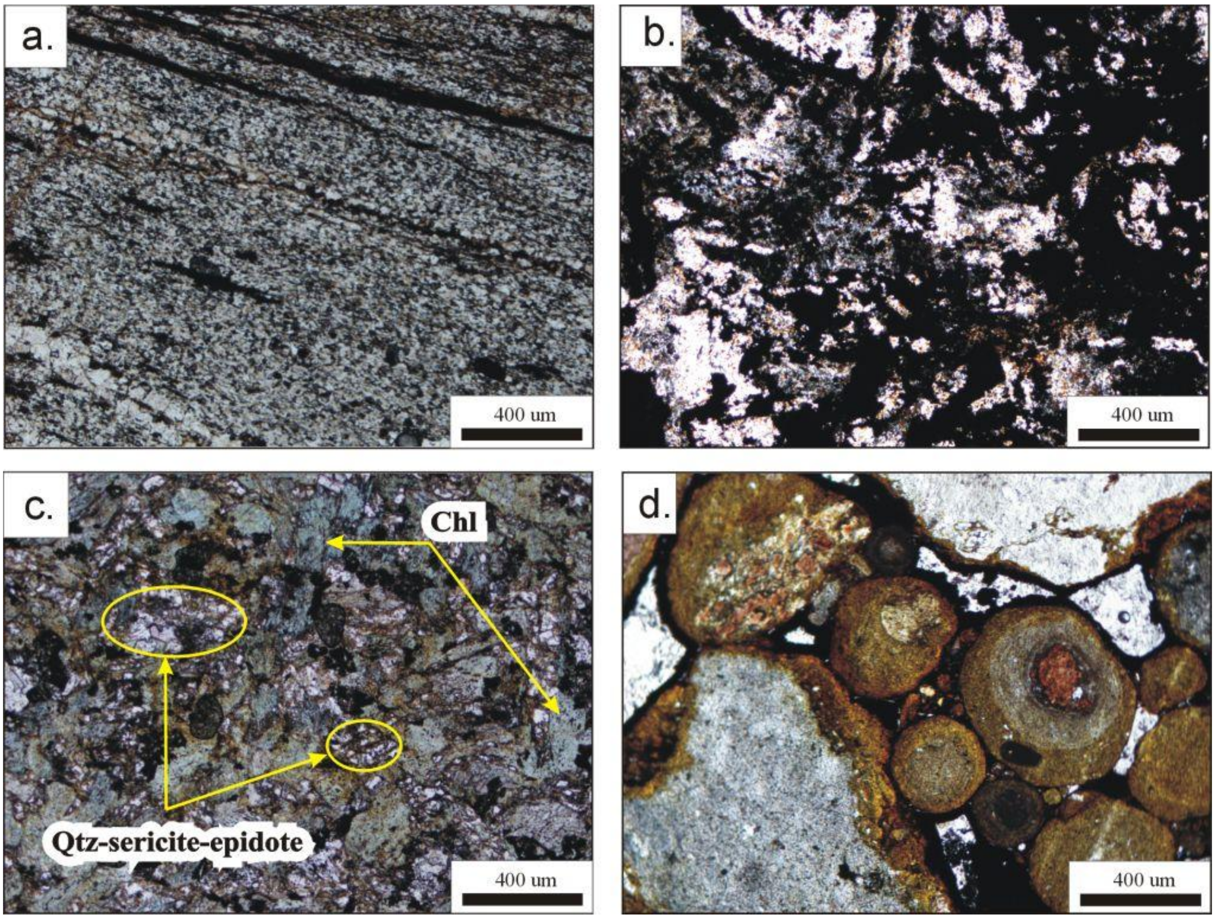

Figure 5.1: *A. Transmitted light photomicrographs of siltstone from sample LD001 SN-114. Siltstone units are composed of quartz (light grey) and goethite (black), with accessory epidote and sericite. B. Transmitted light photomicrographs of iron rich carbonaceous shale from sample LD003 SN-116. Iron oxides are made up of hematite-goethite ± sericite (black). Carbonate-quartz makes up the remainder of the matrix (white). C. Transmitted light photograph of chloritized basalt (Sample LD002 SN115). The basalt is composed of chlorite (after pyroxene), sericite, epidote and quartz, with minor relict plagioclase. Opaque minerals are goethite ± hematite (black). D. Transmitted light photomicrograph of ferruginous silicrete (Sample LD 016, SN121). The silicrete is made up of nodules of goethite and chalcedonic quartz enclosing rock fragments particularly around pisoliths. The rock fragments are also cemented with goethite and chalcedonic quartz.*

5.3. Petrography of the ore bearing rocks

Petrographically the ore bearing rocks consist of goethite-hematite phase as the dominant oxides with silica (Figure 5.2a). Goethite is by far the more abundant iron oxide phase, and is massive. Carbonaceous shale also hosts ore in the study area.

Primary ore is hosted in cataclasite quartz veins (Figure 5.2b). Fractures and micro-faults crosscut the quartz fragments in an extremely irregular array (Figure 5.2b-e). Interstitial areas are filled with oxide minerals that make up the matrix producing an iron rich quartz breccia. The iron oxides are dominated by hematite and/or magnetite that are replaced by spinel. Patches and veins of oxidised iron form part of the thin-section.

5.4. Slag geology and petrology

Slag is found at several furnace sites at Dem. The slag contains primary slag phases including oxides, silicates, sulphides and the metal phase. Common primary minerals include hematite, fayalite glass, and accessory wüstite, ulvospinel, quartz, iron metal, pyrite, and pyrrhotite.

The macroscopic texture and shape of the slag depends on the cooling rate and nature of the furnace where the slag solidified, which cannot be estimated for the furnaces in the study area. However, the slag types include Type 1, which is a dense black glassy slag with flow texture, and Type 2, which is vesicular green-black blocky slag (Figures 5.3a, b). Type 1 slag dominates furnaces 1, 2, 3, 4 and 5 while Type 2 dominates furnaces 8, 9, and 10.

Type 1 slag is interpreted to have resulted from slow cooling from high temperature where gas was mostly released during the cooling process. Type 2 slag is interpreted to have resulted from fast cooling rate from a lower temperature, where gas bubbles were trapped in the cooling slag instead of being released. The entrapment of gas left permanent voids within the solidified slag.

Macroscopically slag samples from furnace 1, 2, and 5 have comparatively high hematite content relative to furnaces 9, 10 and 11. Samples from furnace five had no vesicles; this is interpreted to be the result of a slow cooling rate.

Visible pyrite occurs in samples from furnace five indicating low oxygen fugacity, or resulted from contamination or the feed ore into the furnace. Accessory iron metal is present in samples from furnace ten.

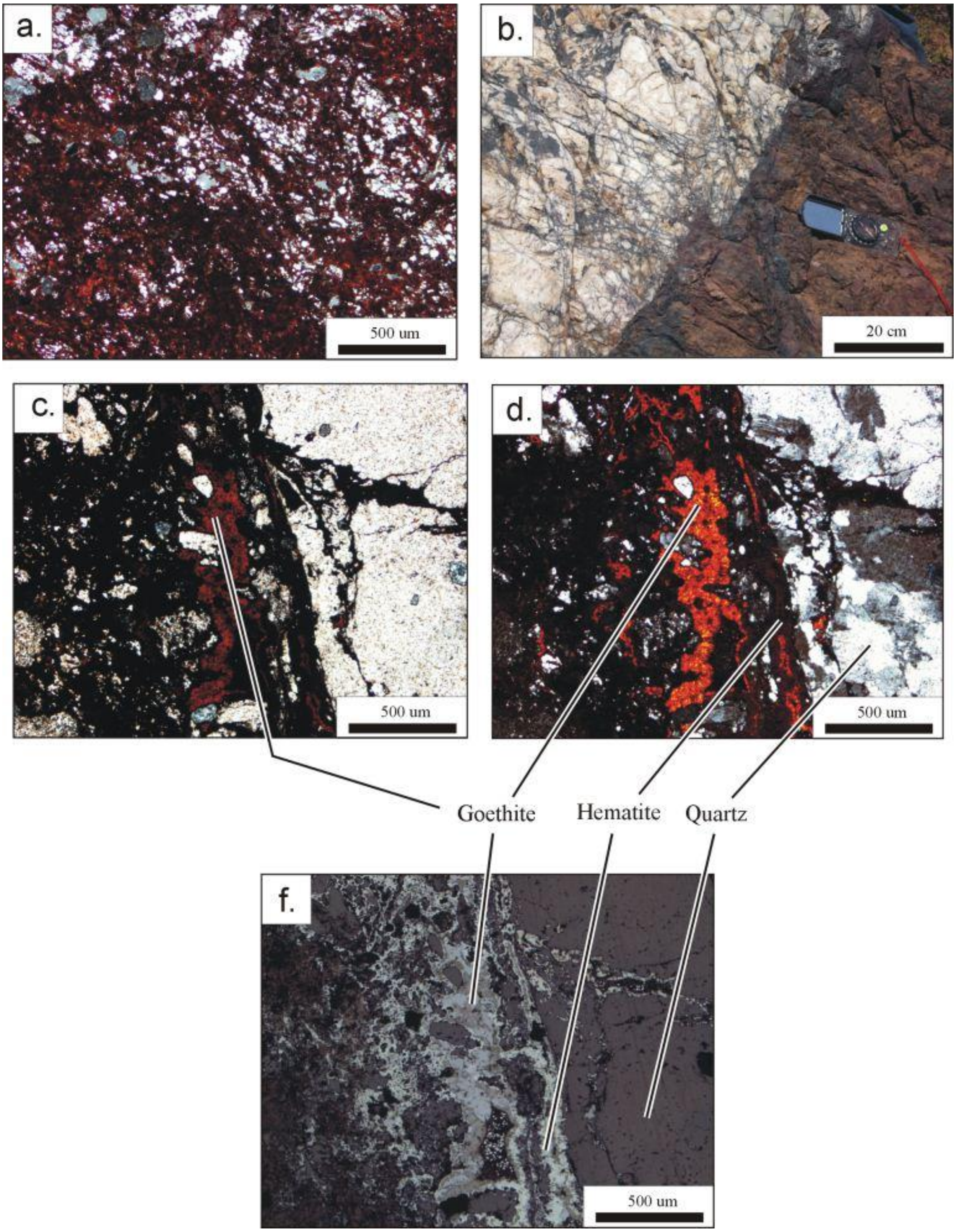

Figure 5.2: *A. Photomicrograph of Fe-rich ore bearing siltstone in transmitted light (cross-polars) which is dominated by goethite-hematite (Sample LD 013, SN-118). B. Quartz cataclasite vein at the base of the valley in open pit 1. Fe-rich fractures and micro-faults crosscut the quartz veins and wall rock indicating they formed after the quartz vein. Photomicrographs from Sample LD 013, SN-118 in transmitted (C.), transmitted crossed polars (D.) and reflected light of quartz cataclasite demonstrating that hematite-goethite dominates veins and fractures which crosscuts quartz in quartz veins (F).*

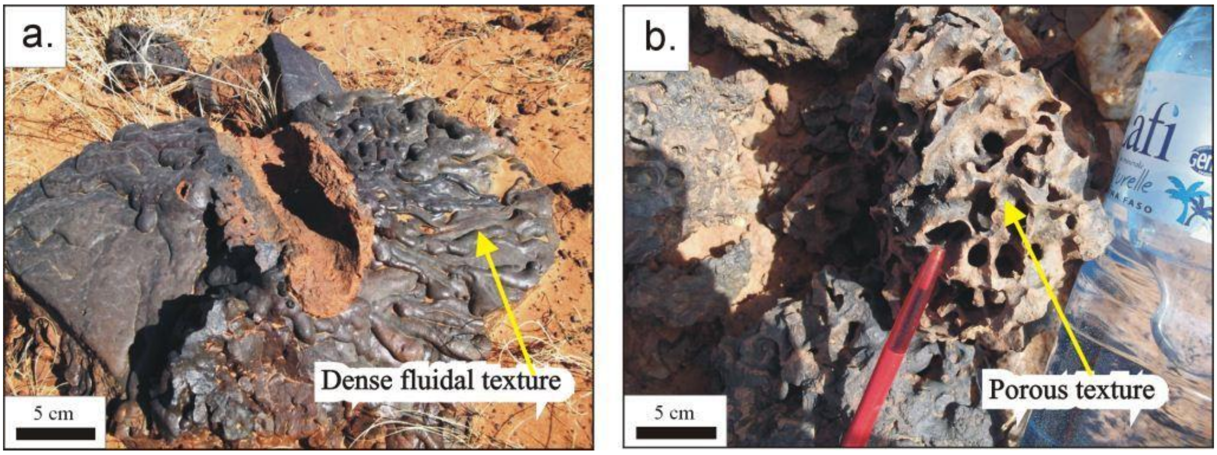

Figure 5.3: *Type 1 dense black glassy slag with flow texture from Furnace 5. B. Type 2 vesicular green-black blocky slag from Furnace 10.*

The common oxide mineral in slag was hematite, with accessory wüstite and magnetite (Figures 5.4a-e). Interlocking crystals of spinifex and herringbone textured hematite are present in samples from all furnaces (Figures 5.4a, b, d, f). The hematite hosts ocelli of quartz and fayalite (Figure 5.4b). Cross-shaped wüstite is present in samples that host massive and semplectic intergrowths of hematite (Figure 5.4c, e), and accessory euhedral magnetite. Fayalite ocelli may dominate in some slag samples (e.g., FOR01-03, FOR09-03, FOR10-10). In some samples of slag, magnetite and hematite have exsolved to form lamellae of light grey hematite and cloth-weave textured ulvospinel (Fe_2TiO_4) in replacement of magnetite. The cloth-weaved texture of accessory ulvospinel is interpreted to be formed as a result of phase unmixing during initial melting (c.f., Spry 1987). It occurs as extremely fine, dark isotropic exsolution in bow-tie and wispy textured crystals.

Ocelli in the slag include fayalite glass (Fe_2SiO_4) and quartz (Figure 5.4b). Fayalite is formed by the reaction of iron oxide (FeO) and silicate gangue minerals in the ore. Fayalite is the common Fe-rich end-member of the olivine solid-solution series that forms at high temperature and reducing conditions. It is present in all samples of slag from the Dem study area. Fayalite occurs as ocelli, fills or lines vesicles (as amygdales) that formed from entrapped gases, and fills fractures which crosscut the hematite matrix of the slag (Figure 5.5a-c). The presence of fayalite glass confirms the rapid cooling or quenching of slag melt.

Partially melted grains of quartz are also present in all samples because some of the iron ore mined at Dem is hosted in quartz cataclasite veins (Figure 5.4b) and it is likely that it was difficult to liberate the iron ore from the quartz. Alternatively, the quartz may have been used as flux.

Pyrite and Fe metal occurs as rare inclusions in the slag samples from the furnaces (Figure 5.5c). It also sometimes fills veins and vesicles. The presence of pyrite is interpreted to mean that the iron ore that entered the furnace was weakly sulphide-bearing, or contaminated with host rocks that were sulphide-bearing (i.e., sulphidic and ferruginous shale and siltstone).

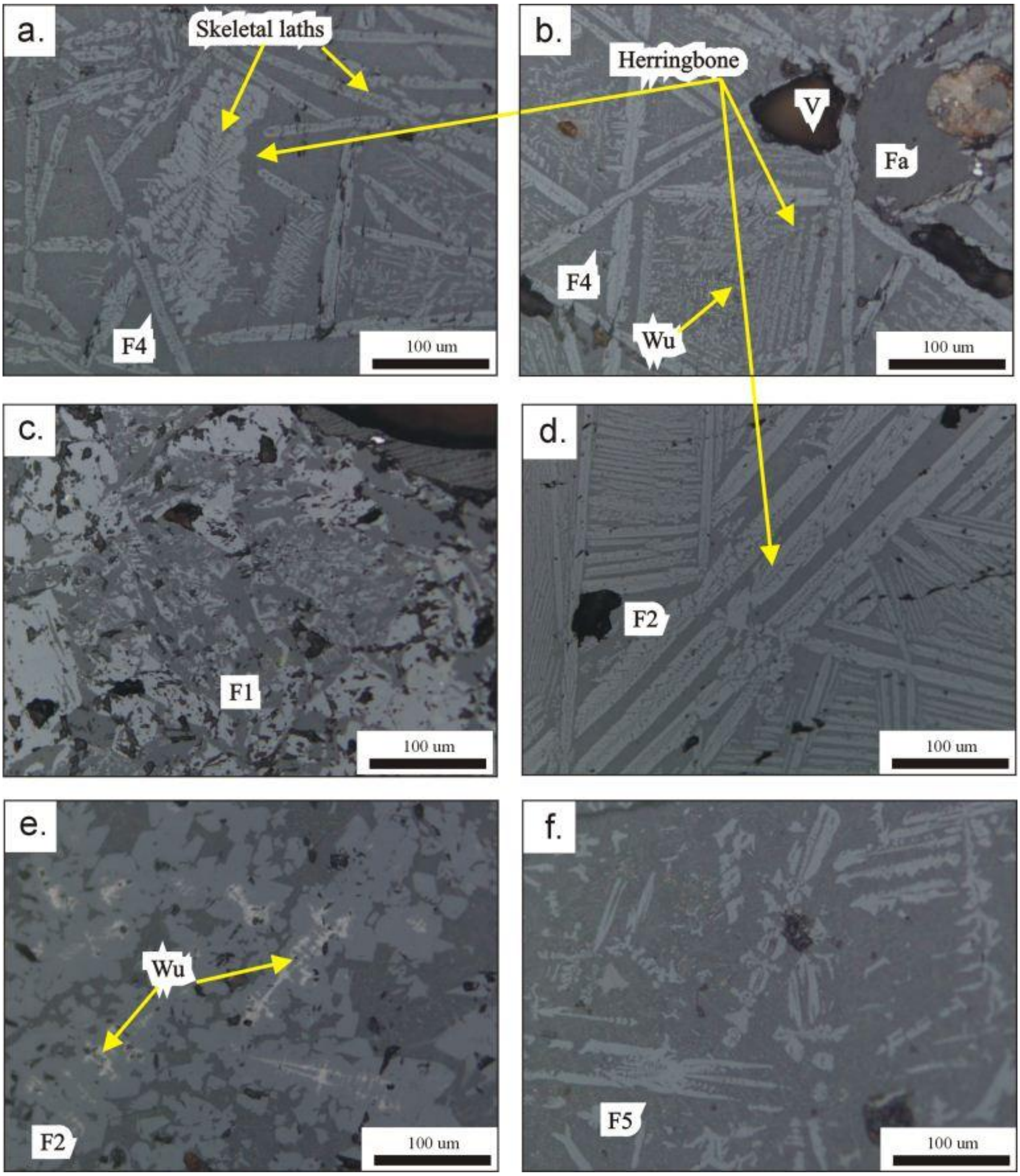

Figure 5.4: *Photomicrographs of slag from the Dem mine site. A. Fine to coarse skeletal hematite with spinifex in a hematite matrix from Furnace 4. B. Herringbone textured hematite-wüstite(Wu) with ocelli of fayalite (Fa) and quartz (Qtz), and vesicles (V) in a hematite matrix. C. Intergrown massive hematite and semplectic hematite. D. Beautiful skeletal structure of hematite spinifex in hematite matrix. E. Cross-formed wüstite (Wu) in subhedral to anhedral hematite in a hematite matrix. F. Skeletal herringbone texture hematite in a hematite matrix. F1, F2, F4, F5 = Furnace 1, 2, 4 or 5.*

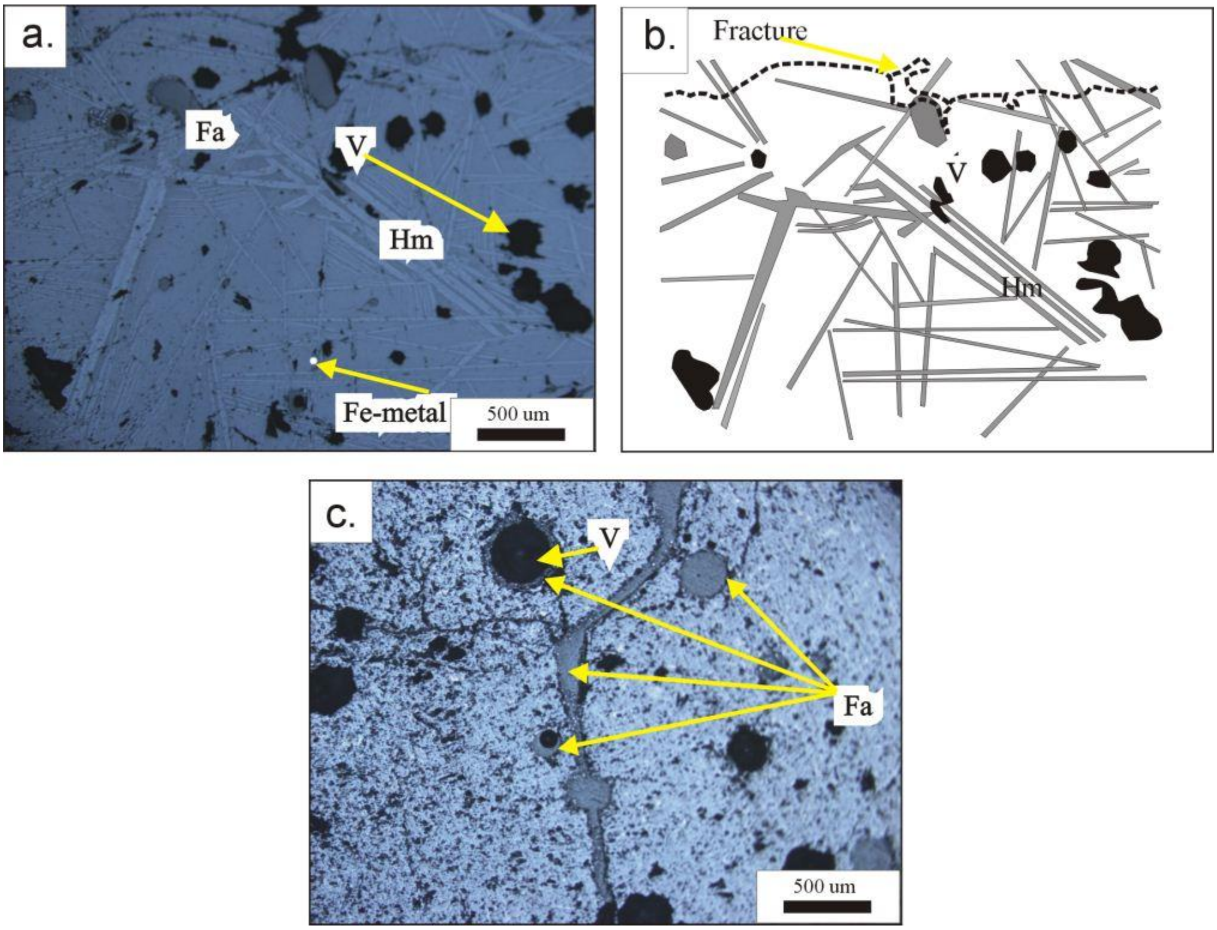

Figure 5.5: *Photomicrographs and sketch from Furnace 9 of fayalite in a hematite spinifex (A, B) and as ocelli, as fill or the lining of vesicles (as amygdules), and fill to fractures that crosscut the hematite matrix of the slag.*

Micro-fault, fractures and hematite veinlets crosscut the spinifex and herringbone textured hematite with micro-displacement of the hematite crystals (Figure 5.6). The veinlets are filled fayalite glass. The infilling of fractures was a crucial late stage of the slag forming process.

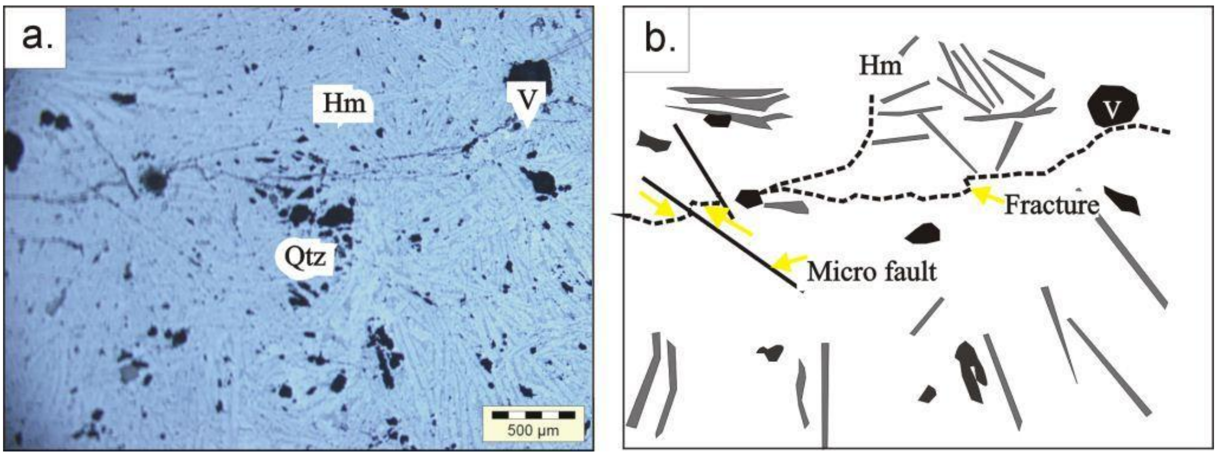

Figure 5.6: *Photomicrograph of micro-fault, fractures and hematite veinlets crosscut the spinifex and herringbone textured hematite.*

5.5. Summary

The major primary phases in both the petrography of the ore and slag are the oxides and silicates and minor carbonates. Iron metal was found in all the samples from the study area. Consequently, it can be speculated that smelters at Dem were effective as they extracted almost all the iron metal. Mineral phases changed in the process of smelting as a result of high temperature and by adding flux, which may have been silica in the form of quartz.

The conditions in the furnace, along with the production processes, lead to the distinctive composition patterns and textural variations of slag. In this study a Bloomery furnace technique was used with tuyeres and crucibles. The yield and volume of iron metal could not be determined.

6. RADIOCARBON DATING PILOT STUDY

6.1. Introduction

As stated in Chapter 3, the main aim of dating charcoal samples from furnaces in the Dem study area, using AMS radiocarbon dating, was to try to constrain the age of forging as a proxy for artisanal mining activity at the Dem mine site, with the assumption that forged charcoal formed at the same time as mining and processing of iron. The sampling of furnaces was undertaken as a pilot study in 2011 with the premise of undertaking further studies if sufficient funding could be found to mount a fuller study and if valuable results could be obtained.

Six surface and near surface charcoal samples were selected and collected from 11 different furnaces (see Figures 3.1 and 3.2). The sampling points of the charcoal samples from furnaces 2, 5, 6, 8 and11 are shown Figures 6.1a-f. Sampling was undertaken in such a way as to have minimal impact on the furnace structures. Samples were prepared at the University of Witwatersrand Johannesburg and radiocarbon dating was performed at Beta Analytical Laboratories in Miami Florida (USA).

The results of the six samples analysed are presented in Table 6.1 which lists the measured and conventional radiocarbon ages. Table 6.2 presents the results of two samples with 1σ (AD/BP) and 2σ (AD/BP) calibrated ages derived after Talma and Vogel (1993).

The method of radiocarbon dating used in this study has been detailed in Section 3.5 and is not repeated here. However, all samples submitted for radiocarbon dating were immediately subjected to substantial quality control measures. They were cross-checked throughout the process to maximise precision. The measurements of each ^{14}C were followed by a statistical error uncertainty known as the 1σ and 2σ. The first statistical error (1σ) indicated that there is a 68% possibility that the true result may fall within 1σ. The second statistical error (2σ) showed that there is a 95% chance that the true result may fall within 2σ (Bowman, 1990).

The conventional ages are reported together with the standard deviation of the laboratory measurement and then doubled to obtain the 95 % probability interval. Conversion of ^{14}C calendar age is dependent on the calibration curve. Figures 6.2 and 6.3 present graphs of the radiocarbon and calibrated ages of the measured samples as reported by Beta Analytical Laboratories. The radiocarbon ages and errors were rounded with respect to the conventions of Stuiver and Polach (1977).

Of significance is sample FOR06-02CAR which gave a conventional radiocarbon age of 430+/-30 BP or a 2σ (95% confidence) age of 1430-1480 AD, which marks a significant period of economic growth in the history of West Africa.

Sample name	Analysis method	Measured radiocarbon age (pMC/ BP)	C^{13}/C^{12} Ratio	Conventional Radiocarbon Age (pMC/ BP)
FOR02-01CAR	AMS-Standard delivery	107.6+/-0.3 pMC	-20.5 ‰	106.7+/-0.3 pMC
FOR05-02CAR	AMS-Standard delivery	105.2+/-0.3 pMC	-16.3 ‰	103.4+/-0.3 pMC
FOR06-02CAR	AMS-Standard delivery	230+/-30 BP	-12.9 ‰	430+/-30 BP
FOR08-01CAR	AMS-Standard delivery	110+/-30 BP	-18.3 ‰	220+/-30 BP
FOR09-01CAR	AMS-Standard delivery	103.8+/-0.4 pMC	-16.0 ‰	101.9+/-0.4 pMC
FOR11-01CAR	AMS-Standard delivery	104.8+/-0.4 pMC	-22.3 ‰	104.3+/-0.4 pMC

Table 6.1: *Results of samples processed and calibrated by Beta Analytic using the Pretoria Calibration Procedure program (Talma and Vogel, 1993).*

Sample name	1 Sigma(AD) 68 %	1 Sigma(BP) 68 %	2 Sigma 95 %	Cal BP
FOR06-02CAR	1440-1460	510-490	1430-1480	520-470
FOR08-01CAR	1650-1670	300-280	1640-1680	310-270
FOR08-01CAR	1780-1800	170-150	1740-1800	210-150

Table 6.2: *Radiocarbon ages from the study area, the dates have been calibrated with the INTCAL04 Radiocarbon Age Calibration after Talma and Vogel (1993).*

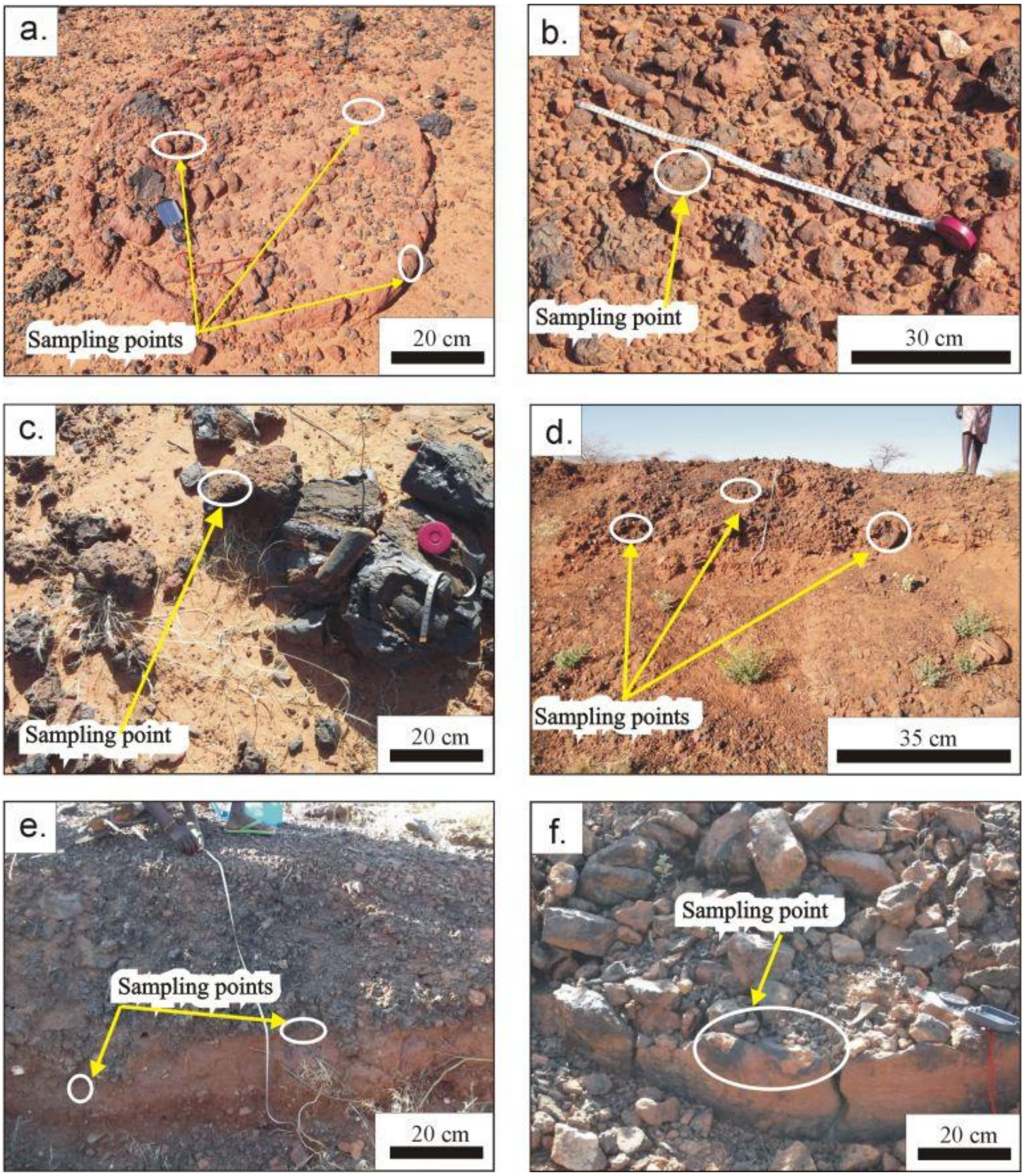

Figure 6.1: *Sampling points from different furnaces. a. Sampling points for furnace 2 from furnace walls. b.-c. sampling points for furnace 5 from furnace and tuyere fragments. d. Sampling points for furnace 6 from the exposed stratigraphy of the furnace. e. Sampling points for furnace 8 from the exposed layers of the furnace. F. Sampling point for furnace 11 from the furnace walls.*

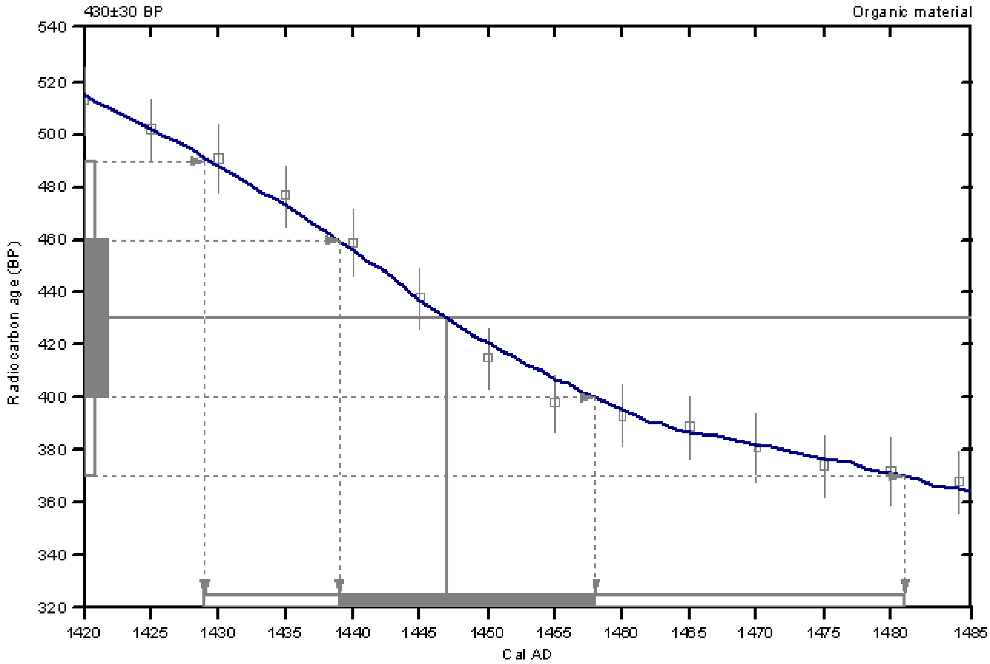

Figure 6.2: *Radiocarbon calibration curve organic material extracted from Furnace 6 (Sample FOR06 02CAR). Radiocarbon age (BP) is plotted against calendar years (AD). White bars correspond to 68% and grey bars correspond to 95% confidence levels, respectively. The 95% confidence level gives an age 1438-1458 AD.*

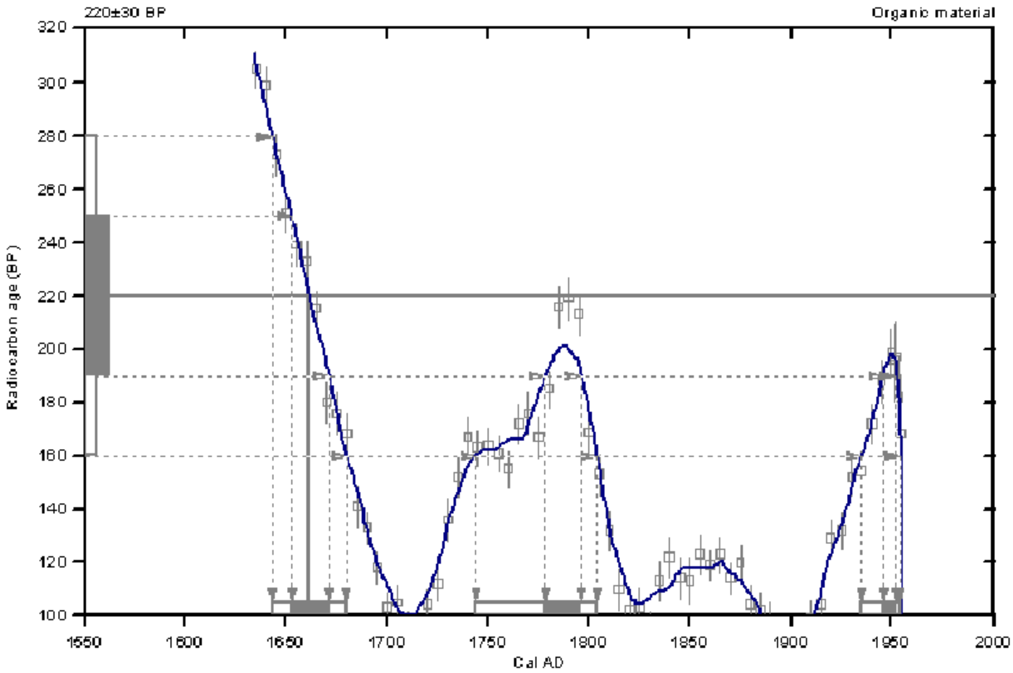

Figure 6.3: *Radiocarbon calibration curve organic material extracted from Furnace 6 (Sample FOR08 02CAR). Radiocarbon age (BP) is plotted against calendar years (AD). White bars correspond to 68% and grey bars correspond to 95% confidence levels, respectively. The 95% confidence level gives ages (1438-1458, 1651-1600, 1756-1759, and 1949-1951) AD.*

6.2. Interpretation of the results of carbon dating

The conventional radiocarbon ages (95% probability) from the Dem iron mine site cover the Roman calendar ages of 1430-1480, 1640-1680, 1740-1800 and 1940-1950 AD Samples FOR02-01CAR, FOR05-02CAR, FOR09-01CAR, and FOR11-01CAR from furnaces 2, 5, 9 and 11, respectively, gave modern dating results, which are 0 BP, thus indicating that modern material had been introduced during the last 60 years or so. Based on the ethnographic evidence presented in Section 3.2, mining, processing or forging of iron did not occur in the Dem region in the last 80 years, and thus these samples can reasonably be assumed to have been contaminated with modern organic material and can be excluded as non-significant.

However, the 2σ calibrated ages (95% probability) for samples FOR06-02CAR and FOR08-01CAR arguably suggest that forging of iron may have been active in the Dem region at Furnace 6 at 1430-1480 AD, and at Furnace 8 at 1640-1680 AD and 1740-1800 AD The samples were collected from deep in the furnace pile, with access being made easy because the sides of the furnaces had been breached and collapsed into a small rivulet. Consequently, the furnace stratigraphy was exposed over approximately 60 centimetres of depth (Figures 6.1d, e). Furnace 6 and 8 are situated immediately east of the open cast and underground mines (Figures 3.1 and 3.2).

Interestingly, although quite limited in number, the ages correspond broadly with the rapid expansion of iron technology from 1400-1600 AD in West Africa (Todd, 1979). They correspond with the rise of the Songhai Empire in the 15th century, and slavery in the 17-18th centuries and/or the first European exploration into West Africa. Thus the radiocarbon ages may represent historical ages of iron working in West Africa; a fuller investigation of the Dem site is thus needed.

Certainly, there is currently little evidence of iron smelting for the period 1430 to 1480 AD for in the northeast Burkina Faso. However, Insol (2000) indicated that iron technology in the period 1400-1600 AD was one of a series of fundamental social assets that assisted the growth of significant centralized kingdoms, particularly the Songhay Empire (under the rule of Sonni Ali) which was seated in Djenne or Timbuktu or Gao. These towns are respectively situated 360 km west, 450 km north-northwest and 370 km northeast of Dem across the international border of present day Burkina Faso and Mali. By 1500 AD the Songhay Empire extended from central Niger in the east to Senegal in the west, and from central Burkina Faso in the south to northern Mali. Olson (1979) argued that the Songhay economy was a clan based system linked to artisanal skill (craft guilds), with the most important being metalwork, mechanics and carpentry; the regional economy was dependant on gold and iron. Trade in gold, iron and salt where central to the Songhai economy and fundamental to its power base (Masonen, 1997; Park, 2011).

Although speculative the limited radiocarbon results for sample FOR06-02CAR may suggest a link between the Dem site and the demand for metal in the region during the 15th century.

In contrast, the period 1640-1680 AD and 1740-1800 AD falls within a period in West Africa of economic and cultural decline (Levtzion, 1980). The decline was followed by slavery with British and French colonials battling for control over coastal ports. Europeans conflicted over land throughout West African countries and brought slave trade into Fulani and Wassoulou Empire (Swartz, 1980). In 1756-1759, from one- to two-thirds of the whole population of the Fulani jihad states comprised enslaved people. This period was followed by the colonial period that took place from 1895-1958 and French colonials took control over West Africa.

7. DISCUSSION

Small scale mining of iron ore was conducted in the Dem study area as evidenced as open cast and underground mines, waste dumps, processing sites, furnaces sites and a relatively large mining footprint. The ASM miners employed both surface and underground methods, which produced two medium bowl-shaped surface mines (OC1 and OC2) and perhaps other smaller working such as OC3, and two underground mines (UG 1 and 2) with small galleries, adits and raises.

Traditional methods of processing were applied and included handpicking, sorting and crushing, which is similar to techniques still used today in Burkina Faso on many artisanal mines.

The host rocks mined at Dem consisted of iron-rich shale, siltstone and laterite. In the iron-rich shales and siltstone, mining focussed on iron-rich alteration zones about quartz veins as the primary ore. The ore was dominantly composed of magnetite (Fe_3O_4) and hematite (Fe_2O_3), with impurities of SiO_2, as occurs in many ancient iron and copper sites that produce an iron silicate slag of low temperature (1200°C) slag (Craddock and Meeks, 1987). The magnetite-hematite rich veins were structurally controlled in the host rocks. Lateritic ore also provided a second source of iron-rich rock for mining at the Dem site.

Processing sites comprised at least 11 furnaces that were dome and circular in shape. The furnaces were filled with crucibles and tuyeres made of clay sand perhaps sourced locally from the alluvial plain on which the furnaces are situated or the Dem Valley which is now occupied by Lac Dem (Figures 3.1; 3.2). Crucibles and tuyeres litter the furnace sites as waste or are welded together with slag in the base of the furnace structure. Waste areas are situated adjacent to most furnaces suggesting a modest level of industrial activity ranging from mining or ore, processing and cleaning, building of furnaces, making of crucibles and tuyeres, and processing the slag after smelting. The presence of at least 11 furnaces with significant mining and processing of ore suggests that the Dem site may have been an important historic iron producing region.

A source of fuel remains speculative but the location of the mine site adjacent to the Lac Dem, which historically was a wooden valley prior to the damming of the lake, may have meant that a source of fuel in the form of timber was readily available. In any case, timber for charcoal may have been transported to the site in the same way that timber for charcoal is transported to the growing urban centres nearby from the forest surrounding the region (Kramer, 2002; Ouedraogo et al., 2010).

A source of flux may have the carbonaceous rocks and quartz that form part of the host rocks of the region, or waste rock to the iron ore. A source of clean limestone which would make an ideal flux does not occur in the region according to regional maps of Hottin and Ouedraogo (1992), Hein et al. (2004) and Castaing et al (2003).

The distinguishing behaviour of slag under any operational environment is based on the slag composition and the range of components in it, where the flux materials and type of ore used are most important (Muszer, 2000). Based on the petrographic descriptions, fayalite, quartz, magnetite and hematite were the dominant minerals in all slag samples with minor sulphides and iron metals. Ulvospinel was identified in a few samples. The presence of fayalite and silica in all slag samples suggests a moderate quality product was produce during smelting or perhaps an iron silicate slag (Craddock and Meeks, 1987). The slag microstructures and macrostructures suggest that the slag cooled at different rates ranging from rapid, fast to slow cooling. Fe-Ti oxide was present in the form of ulvospinel in slag samples.

Iron production at the Dem site was Bloomery furnace smelting, where a fluid state of iron was produced. The quality of ore produced is not known as there is no iron metal artefact discovered but could have ranged from soft iron to steel. This suggests that a good level of smelting knowledge existed at the time.

However, due to the variation of magnetite and hematite content the samples studied, it can be argued that smelting practices were variable from one furnace to another. Furnaces 1, 3, 4 and 5 were more efficient than furnaces 9, 10, due to the amount of Fe-oxide in the slag and the physical appearance of the slag. Iron smelting took place at different cooling rates and encompassed slow cooling rate, fast cooling rate and rapid cooling rate. The slower cooled slag exhibits phaneritic texture with crystals that are large in size (c.f., Craddock and Meeks, 1987; van Oss, 2002). The fast cooling rate exhibits an aphanitic texture wherein the slag will have small crystals with vesicles. The rapid cooling rate produced a granular or glassy texture with very fine crystals that resemble the volcanic rock obsidian (c.f., van Oss, 2002; Stewart, 2007).

Ethnographic research indicated that ASM of iron ore from the Dem site did not take place in the last 80 years or 1932-2012. Additionally, the Museum of Kaya and the National Museum of Burkina Faso does not record iron workings at Dem over the last hundred years. There are also no other historic records of iron making at Dem.

It can thus be reasonably interpreted that the Dem site predates modern iron making in the Kaya region. Radiocarbon dates given for the last 80 years were thus discounted. The age of mining, processing and production is thus tentatively constrained by radiocarbon dating to have been active in 1438-1458 AD, 1600-1651 AD, or 1756-1759 AD.

Iron was initially forged in West Africa as early as the 6th century (Insoll, 1997; Pleiner, 2000) and iron smelting was practiced in the southeast of Burkina Faso by the Bura culture whose culture was focused in the region 250 km southeast of Dem. Iron forging and smelting was thus known to the peoples of West Africa. By the 15th century, forging and smelting of iron (and gold) where central to the region and particularly, the Songhay economy which dominated trade in the region. It is possible that the limited radiocarbon results for sample FOR06-02CAR suggest a link between the Dem site and the demand for metal in the region at that time, but further research is needed to reinforce this interpretation. The multiple ages calculated in sample (FOR08-01CAR) show that reforging occurred and/or that the furnace was the sample was collected might have affected by modern.

.

8. CONCLUSIONS

The mining of iron ore in the Dem study area produced a limited number of underground workings and surface open pits. These mine workings show no modern mechanised mining methodology.

Five ore extraction areas and eleven smelting sites were located. The evidence of iron smelting in the study area includes the remains of at least 11 furnaces (furnace wall and floor fragments), and hundreds of fragments of tuyeres, crucible, burnt clay and iron slag.

The underground mine workings and opencasts were mined by selective mining methods, where mineralised iron-rich fractures and quartz veins were extracted. The mineralisation generally comprised ore of magnetite, hematite and laterite. There are two types of ore deposits in the study area; vein hosted and laterite-ferricrete hosted. The range of ore types mined included high grade magnetite to low grade laterite. The waste rocks included quartz, silicrete and iron-poor laterite.

After the ore was extracted from the open cast and underground mines, it is likely that the ore was transported to the processing sites nearby the mines, with ore being dumped proximal to mining operations, as occurs at ASM sites around the world today. The ore might have been man-hauled to the surface in bags or sacks particularly because there is no evidence at the Dem site of mechanical aids for hoisting and hauling ore. It is possible that the open cast operations were mined by women, children and aged persons, as can be witnessed at ASM sites throughout Burkina Faso and West Africa, with the underground operations being the domain of men.

Different types of slag were dumped proximal to the furnace sites and included (1) a dense black-grey flowing type that resulted from a slow cooling rate, (2) a black glassy type resembling an obsidian formed as result of a rapid cooling rate in the presence of water, (3) a spinifex-like texture due to quenching at high temperature, and (4) a clay containing pumice-like slag with vugs that formed due to the release of gas bubbles in the melt.

A considerable amount of clean crushed quartz and outcrops of quartz veins occurs both in the mine sites themselves, but also regionally, which may have been used as a flux in the smelting process. A ready source of clean carbonate does not exist although many of the siltstones are carbonaceous in composition and may have acted as a flux during smelting.

At Dem, an immediate source of charcoal could have been from the valleys to the east of the ASM site which today hosts dams for irrigation and extensive market gardens.

The dominant mineral phases in the shale and siltstone that are the host rocks to iron ore at Dem are unsurprisingly quartz, mica and carbonate, with accessory feldspar, graphite and rarely magnetite. Petrographically the ore bearing rocks consist of goethite-hematite as the dominant oxides with silica.

The macroscopic texture and shape of the slag depends on the cooling rate and nature of the furnace where the slag solidified. Macroscopically slag samples from furnaces 1, 2, and 5 have comparatively high hematite content. Ocelli in the slag include fayalite glass (Fe_2SiO_4) and quartz. Micro-fault, fractures and hematite veinlets crosscut the spinifex and herringbone textured hematite with micro-displacement of the hematite crystals.

A limited number of radiocarbon dates were obtained from charcoal samples collected from the base of Furnaces 2, 5, 6, 8, 9 and 11. The 2σ calibrated results (95% probability) cover the Roman calendar ages of 1430-1480 AD, 1640-1680 AD and 1740-1800 AD. Ethnographic research argued that mining of iron in the Dem region, or any significant artisanal mining in the Dem region for any metal commodity, had not occurred in the last 80-90 years. Although speculative, the limited radiocarbon results for sample FOR06-02CAR may suggest a link between the Dem site and the demand for metal in the region during the 15th century, European expansion in the 17th to 18th centuries.

RECOMMENDATIONS

The Dem ASM site should be protected and conserved as a historic and cultural monument by the relevant authorities in Burkina Faso at state and provincial levels. The protection will prevent degradation and destruction of the heritage and consequently will preserve the values and history of the area for present and future generations of Africa. The Dem region is important to a fuller understanding of the history and society of the Songhai Empire – it thus adds to the archaeological history of the African peoples. There may be a case to motivate for World Heritage Status but further research in the region is necessary.

REFERENCES

Agricola, G., 1556. De Re Metallica. Translated from Latin Edition of 1556 with Biographical Introduction, Annotations and appendices upon the development of Mining Methods, metallurgical Processes, Geology, Mineralogy and Mining Law from the earliest times to the 16 Century (Translations by Hoover, H.C., Hoover, L.H.) Published for the translators by the Mining Magazine, Salisbury House, London, E.C., 1912, pp 389.

Aitken, M.J., 1990. Science-based Dating in Archaeology. Harlow, England: Longman Archaeology Series, 226 pp.

Anderson, E.C., Libby, F.W 1950. World-wide distribution of natural radiocarbon. Institute of nuclear studies, Department of chemistry, University of Chicago, 81, 6p.

Anonymous, 1999. Social and labour issues in small-scale mines. Report for discussion at the Tripartite Meeting on Social and Labour, Issues in Small-Scale Mines, Geneva, 17-21 May 1999. International Labour Office, Geneva.

Aryee, B.N.A., Ntibery, B.K., Atorkui, E., 2002. Trends in the small-scale mining of precious minerals in Ghana: a perspective on its environmental impact, Journal of Cleaner Production 11, 131-140.

Avery, D.H., Schmidt, P., 1986. The use of preheated air in ancient and recent African iron smelting furnaces. Journal of Field Archaeology 13, 354-357.

Bahn, T., Gerard, P., 1994. Pyrenean History, Archaeology, a very short introduction and the Cambridge illustrated history of Prehistoric Act, 24p.

Bamba, O., Parisot, J-C., Grandin, G., Beauvais, A., 2002. Ferricrete genesis and supergene gold behaviour in Burkina Faso, West Africa. Geological Society, London, Geochemistry: Exploration, Environment, Analysis 2, 3-14.

Baratoux, L., Metelka, V., Naba, S., Jessell, M, W., Gregoire, M., Ganne, J., 2011. Juvenile Paleoproterozoic crust evolution during the Eburnean orogeny (~2.2-2.0 Ga), western Burkina Faso. Precambrian Research 191, 18-45.

Bassot, J.P., 1997. Albitisations dans le Pale protérozoïque de I'Est Sénégal: relations avec les minéralisations ferrifères de la rive gauche de la Faleme. Journal of African Earth Sciences 25 (3), 353-357.

Beauvais, A., D. Chardon, D., 2013. Modes, tempo and spatial variability of Cenozoic denudation: The West African example. Geochemistry, Geophysics, Geosystems, 14, doi: 10.1002/ggge.20093.

Beauvais, A., Ruffet, G., Hénocque, O., Fabrice, C., 2008. Chemical and physical erosion rhythms of the West African Cenozoic morphogenesis: The 39Ar-40Ar dating of supergene K-Mn oxides: Journal of Geophysical Research 113, 15p.

Beukes, N.J., Dorland, H.C., Gutzmer, J., Nedachi, M., Ohmoto, H., 2002. Tropical laterites, life on land, and the history of atmospheric oxygen in the Paleoproterozoic. Geology, 30, 491-494.

Beziat, D., Dubois, M., Debat., P., Nikiema, S., Salvi, S., Tollon, F., 2008. Gold metallogeny in the Birimian craton of Burkina Faso (West Africa). Journal of African Earth Sciences 50, 215-233.

Bierschenk, W.H., 1968. Geohydrological Reconnaissance in Upper Volta. Groundwater 6, 29-40.

Blot, A., 2004. Caracterisation des chapeaux de fer en milieu laterique cuirasse. Comptes Rendus de l'Académie des Sciences, 336, 1473-1480.

Bower, J., 1987. Conflicting goals of mining companies and host governments, Mineral Resource Development: Geopolitics, Economics and Policy, pp. 22-50.

Bowman, S.G.E., 1990. Radiocarbon dating; Interpreting the past. British Museum Publications, 64 p.

Bronner, G., Chauvel, J.J., Triboulet, C., 1990. Geochemistry and knowledge of banded iron formation. The West African shield, an example in Chauvel, J.J., Ancient banded iron formations, regional presentations, Theophrastus, Athens 462 pp.

Brown, E.T., Bourlès, D.L., Colin, F., Safno, Z., Raisbeck, G.M., Yiou, F., 1994. The development of iron crust lateritic systems in Burkina Faso, West Africa examined with in-situ-produced cosmogenic nuclides. Earth and Planetary Science Letters 124, 19-33.

Brunner-Robion, C., Perret, S., Serneels, V., Dembelé, A., Huysecom, E., 2003. A thousand years of iron metallurgy on the Dogon plateau (Mali). Department of Anthropology, University of Geneva, Switzerland; Department of Geosciences, University Fribourg, Switzerland; Mission Culturelle de Bandiagara, Mali 8p.

Burke, A., Cloete, J., 2004. Restoring tire tracks: lessons from the southern Namib Desert. Ecological Restoration 22, 269-274.

Cameroon, Y., 2002. Identifying best practices and building the sustainable livelihoods of communities: Seminar on Artisanal and Small-scale mining in Africa, Wardell Armstrong Consulting Group, UK 13p.

Castaing, C., Billa, M., Milési, J.P., Thiéblemont, 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), 2003. Notice explicative de la Carte géologique et miniére du Burkina Faso à 1/1 000 000.

César, A.C., Bruand, A., Ramanaidou., E.R., Gilkes, R.J., 2002. Microporosity of BIF hosted massive hematite ore. Iron Quadrangle, Brazil, Annals of the Brazilian Academy of Sciences 74, 113–126.

Chaparro, E., 2000. La llamada pequeña minería - un renovado enfoque empresarial. Serie Recursos Naturales e Infraestructura 9, 82 pp.

Childs, S.T., 1989. Style, technology and iron smelting furnaces in Bantu-speaking Africa. Journal of Anthropological Archaeology, 10 332-359.

Childs, S.T., 1991. Style, technology, and iron furnaces in Bantu-speaking Africa. Journal of Anthropological Archaeology 10, 332-359.

Cleere, H.F., 1972. The classification of early iron-smelting furnaces. Antiquaries Journal 52, 8-23.

Cleere, H.F., 1981. The iron Industry of Roman Britain. Some operating Parameters for Roman Ironworks. Archaeological Society Occasional Paper no 1, 125p.

Cole, G., El-Rassi, D., Couture, J.F, 2009. Technical Report on the Bomboré Gold Project in Burkina Faso, West Africa Orezone Gold Corporation 16, 1-132.

Combes, A., 1980. Etude des gisements de fer de la Falémé (Sénégal): rapport sur les travaux de la phase de certification, BGRM 3, 75p.

Coplen, T.B., 1994. Reporting of stable hydrogen, carbon and oxygen isotope abundances. Pure and Applied Chemistry 66, 273-76.

Craddock, P.T., 1995. Early metal mining and production. Smithsonian, Edinburgh, 4, 898-905.

Craddock, P.T., Meeks, N.D. 1987. Iron in ancient copper. Archaeometry 29, 187-204.

Craig, H., 1953. The geochemistry of the stable carbon isotopes. Geochimica et Cosmochimica Acta 3, 53-92.

Craig, J.R., Vaughan, D.J., 1994. Ore Microscopy and Ore Petrography Second Edition. Published by John Wiley and Sons, Inc., New York, 424p.

Cresswell, R.G., 1992. Radiocarbon Dating of Iron Artifacts. Radiocarbon 34, 898-905.

Dasgupta, H.C., Sambasiva Rao, V.V., C. Krishna, C., 1999. Chemical environments of deposition of ancient iron and manganese-rich sediments and cherts. Sedimentary Geology 125, 83-98

Dequincey, O., Chabaux, F., Leprun, J.C., Panquet, H., Clauer, N., Larque, P., 2006. Lanthanide and trace elements mobilization in a lateritic toposequence: inferences from the Kaya laterite in Burkina Faso. European Journal of Soil Science 57, 816-830.

Doherty, R.D., Hutchings, K.M., Smith, J.D., Yörük, S., 1985. The reduction of Hematite to Wustite in a laboratory fluidized bed. Metallurgical Transactions B, 16B, 425-432.

Drever, J.I., 1974. Geochemical model for the origin of Precambrian banded iron formations. Geological Society of America 7, 1099-1106.

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

Friede, H.M., Hejja, A.A., Koursaris A. 1982. Archaeo-metallurgical studies of iron smelting slags from prehistoric sites in Southern Africa. Journal of the South African Institute of Mining and Metallurgy 77, 224-232.

Friede, H.M., Steel, R.H., 1986. Traditional smithing and forging of South African Bloomery iron. South African Archaeological Bulletin 41, 81-86.

Gowlett, J.A.J., 1986. Problems in dating the early human settlement of the Americas' in Archaeological results from accelerator dating. Oxford University Committee for Archaeology Monograph. Oxford 11, 51-59.

Greig, R.C.H., 1937. Iron smelting in Fipa. Tanganyika Notes and Records 4, 77-8l.

Guilbert, J.M., Charles F., 1986. The Geology of Ore Deposits. Freeman, pp. 408-411.

Guo, Z., Liu, K., Lu, X., Ma, H., Li, K., Yuan, S., 2000. The use of AMS radiocarbon dating for Xia Shang Zhou, Chronology, Department of Archaeology, Peking University, Beijing 100871, People's Republic of China, Nuclear Instruments and Methods in Physics Research 172, 724-731.

Haaland, G., Haaland, R., Dea, D., 2004. Furnace and Pot: why the iron smelter is a big pot maker, a case study from South-western Ethiopia, 20pp.

Hein, K.A.A., 2007. Artisanal Mining, Its Place and role in the mining sector. Women in Mining – Taking Stock of the present, shaping the future. Colloquium, 8-9 November 2007, University of the Witwatersrand, Johannesburg 15p.

Hein, K.A.A., Morel, V., Kagoné, O., Kiemde, F., Mayes, K., 2004. Birimian lithological succession and structural evolution in the Goren segment of the Boromo-Goren Greenstone Belt, Burkina Faso. Journal of African Earth Sciences 39, 1-23.

Hentschel, T., Hruschka, F., Priester, M., 2002. Global Report on Artisanal and Small-Scale Mining. Mining, Minerals and Sustainable Development 70, 64p.

Hentschel, T., Hruschka, F., Priester, M., 2003. Artisanal and small-scale mining: challenges and opportunities. International Institute for Environment and Development, London 94p.

Herbet, E., 1993. Iron gender and power, Indiana University. Precious metals of the age of expansion: Papers of the 14th International Congress of the Historical Sciences 123p.

Hilson, G., 2002a. The environmental impact of small-Scale gold mining in Ghana: identifying problems and possible solutions. The Geographical Journal 168, 57-72.

Hilson, G., 2002b. Small-Scale mining and its socio-economic impact in developing countries. Natural Resource Forum 26, 3–13.

Hoadley, M., Limpitlaw, D., 2004. The artisanal and small-Scale mining sector and sustainable livelihoods. In: Mintek Small Scale Mining Conference, Book of Proceedings, 2004, 9 September, NASREC, Johannesburg 9p.

Hogg, A.G., 1992. Assessment of 0.3 ml minivials for radiocarbon dating by liquid scintillation counting of benzene. Radiocarbon 34, 389-393.

Hottin, G., Ouedraogo, O.F., 1992. Carte Géologique du Burkina Faso (2nd Edition). Bureau de Recherches Géologiques et Minières, Burkina Faso.

Hudson, T.L., Fox, F.D., Plumlee, G.S., 1999. Metals, mining and the environment, AGI environmental awareness series, 368p.

ICMM, 2010. Working Together – How large-scale mining can engage with artisanal and small-Scale miners, international finance forum, World Bank, 108p.

Insoll, T., 1997. Iron age Gao: an archaeological contribution. The Journal of African History 38, 1-30.

Ivanyuk, G.Y., Korchak, Y.A., Pakhomovsky, Y.A., Menshikov, Y.P., Yakovenchuk, V,N., 2012. Ulvöspinel from xenoliths of contact altered volcanic and volcanosedimentary rocks in Nepheline Syenites of the Khibiny and Lovozero Plutons. Minerals and parageneses of minerals. Geology of Ore Deposits 54, 575-579.

Journal of African Earth Sciences 41, 407-436.

Karbowniczek, M., 2005. Metallurgical process in ancient shaft furnace, theoretical consideration, Association of Metallurgical Engineers of Serbia 5, 145-155.

Kense, J.F.,1983. Traditional African iron workings, African occasional papers, Department of archaeology, University of Calgary 25p.

Kimberly, M.M., 1989. Exhalative origins of iron formations. Ore Geology Reviews 5, 5-145.

Klemd, R., Hirdes, W., 1997. Origin of an unusual fluid composition in early Proterozoic palaeoplacer and lode-gold deposits in Birimian greenstone terranes of West Africa. South African Journal of Geology 100, 405-414.

Krämer P., 2002. The Fuel Wood Crisis in Burkina Faso, Solar Cooker as an Alternative. Solar cooker archive. Ouagadougou: Burkina Faso.

Kribek, B., Syrokorova, I., Machovic, V., Laufek, F., 2008. Graphitization of organic matter and fluid-deposited graphite in Palaeoproterozoic (Birimian) black shales of the Kaya-Goren greenstone belt (Burkina Faso, West Africa). Journal of Metamorphic Geology 26, 937-958.

Levtzion, N., 1980. Ancient Ghana and Mali. Published by Holmes and Meier Publishing, London, pp 42.

Libby. W.F., 1952. Radiocarbon dating, Chicago (2nd Edition). Chicago press, Chicago III, 124p.

Lovitz, B.A., 2006. Scales responsible for gold mining: Overcoming barriers to cleaner artisanal mining in Southern Ecuador. The Faculty of the Graduate College of the University of Vermont 111p.

Manning, M. P., Reid, R. C., 1977. C-H-0 Systems in the Presence of an Iron Catalyst, Industrial Engineering Chemistry and Process Design Development 16, 23p.

Masonen, P., 1997. Trans-Saharan Trade and the West African Discovery of the Mediterranean. In M'hammad Sabour and Knut S. Vikør (Eds), Ethnic Encounter and Culture Change. Papers from the Third Nordic Conference on Middle Eastern Studies, Bergen 1997, Nordic Research on the Middle East 3, 116-142.

McFarland, D.M., Lawrence, A.R., 1998. Historical Dictionary of Burkina Faso, 2nd Edition. Lanham, Scarecrow Press 360, pp 205-211.

McFarlane, M.J., 1976. Laterite and landscape, London, Academic press, 15p.

Middleton, R., Hein, K.A.A., 1997. An assessment of gold prospectivity in the Pissila region, Burkina Faso, West Africa, Sanmantenga Joint Venture, report no: PROGEN 1, 24p.

Milési, J.P., Feybesse, J.L., Ledru, P., Dommanget, A., Ouedraogo, M.F., Marcoux, E., Prost, A., Vinchon, Ch., Sylvain, J.P., Johan, V., Tegyey, M., Calvez, J.Y., Lagny, P., 1989. West African gold deposits, in their lower Proterozoic lithostructural setting. Chronique de la Recherché Minière 497, 3-98.

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.

Miller, D.E., Van Der Merwe, N.J., 1994. Early Metal Working in Sub Saharan Africa. Journal of African History 35, 1-36.

Morton, G.R., Wingrove, J. 1972. Constitution of Bloomery slags, Part 11. Iron and Steel Institute 21, 478-488.

Mücke, A., 2005. The Nigerian manganese-rich iron-formations and their host rocks—from sedimentation to metamorphism.

Muszer, A., 2000. An outline of ore microscopy. University of Wroclaw, Poland, 233p.

Muszer, A., 2004. Mineralogical characteristics of metallurgical dust in the vicinity of Głogów. Problems of mineral processes 38, 329-340.

Mutemeri N., Petersen, F.W., 2002. Small-scale mining in South Africa: past, present and future. Natural Resources Forum 26, 286-292.

Nahon DB, Tardy Y (1992) The ferruginous laterites. In: Butt CRM, Zeegers H (eds), Regolith exploration geochemistry in tropical and subtropical terrains. Handbook of Exploration Geochemistry 4, Elsevier, Amsterdam, pp 41-55.

Nahon, D., 1991. Introduction to the Petrology of Soils and Chemical Weathering. John Wiley and Sons, New York. 313p.

Neyberg, H., Ladaron, D., Martin, H., Verkaeren, J., 1980. The vanadiferous -magnetite deposits of the Oursi region, Upper Volta. Economic Geology 7, 1042-1052.

Olson, J.S., 1979. The ethnic dimension in American History, 1st Edition. Published by St Marins press, 440p.

Ouedraogo, I., Tigabu, M., Savadogo, P., Compaore, Oden, P.C., Ouadba, J.M., 2010. Land cover change and its relation with population dynamics in Burkina Faso, West Africa. Land degradation and Development 21, 453-462.

Park, D.P., 2011. Climate Change, Human Response and the Origins of Urbanism at Timbuktu. Doctoral Thesis, Yale University, Department of Anthropology, 577p.

Paynter, S. 2006. Regional Variation in Bloomery Smelting Slag of the Iron Age and Romano-British Periods. Archaeometry 48, 271-292.

Peters, L.F.H., Hein, K.A.A., 2013. Volcanic facies and preliminary geochemical observations of the Goren greenstone belt, Burkina Faso. EGU General Assembly 2013, 7-12 April 2013 Vienna, Austria.

Phillipson, D.W., 1975. The chronology of the Iron Age in Bantu Africa; Journal of African history 16, 321-42.

Pleiner, R., 2000. Iron in archaeology: the European Bloomery smelters. Published by Archeologicky Ustav AV CR, Prague, ISBN 80-86124-26-6.

Pryce, T.O., Natapintu, S., 2010. Smelting Iron from Laterite: Technical Possibility or Ethnographic Aberration? University of Hawaii Press. Asian Perspectives 48, 16p.

Read, T. T., 1937. Iron and steel in the Far East. Far Eastern Survey 6, 145-147.

Reimer, P.J., Baillie, M.G.L., Bard, E., Bayliss A, Beck, J.W., Bertrand, C.J.H., Blackwell, P.G., Buck, C.E., Burr, G.S., Cutler, K.B., Damon, P.E., Edwards, R.L., Fairbanks, R.G, Friedrich, M., Guilderson, T.P., Hogg, A.G., Hughen, K.A., Kromer, B., McCormac, G., Manning, S., Bronk Ramsey, C., Reimer, R.W., Remmele, S., Southon, J.R., Stuiver, M.,Talamo, S., Taylor, F.W., van der Plicht, J., Weyhenmeyer, C.E., 2004. IntCal04 atmospheric radiocarbon age calibration, 26–0 cal kyr BP. Radiocarbon, 46, 1059-1086.

Schuhmann R., Powell, R.J., Michal E.J.,1953. Constitution of $FeO-Fe_20_3-SiO_2$ system at slag making temperatures. Metallurgical and Materials Transactions 197, 1097-1l04.

Schwartz, T., 1994. Ferricrete formation and relief inversion. An example from central Sudan, Catena 21, 257-268.

Scott-Garrett, 1956). Romano-British Sites at Chestnuts Hill and Popes Hill, Forest of Dean. Transactions of the Bristol Gloucestershire Archaeological Society 75, 199-202.

Sinding. K., 2005. The dynamics of artisanal and small-scale mining reform. Natural Resources Forum 29, 243-252.

Smith, P., Timothy, G., 1993. Iron and steel industry. Editor, Steel times and Steeltimes Interval, 45p.

Spry, P.G., 1987. The chemistry and origin of zincain spinel associated with the Aggeneys Cu-Pb-Zn-Ag deposits, Namaqualand, South Africa. Mineralium Deposita, 22, 262-268.

Stewart, L.J., 2007. Quench textures, lithification, and modes of crystallization in a cooled slag block from a smelter at Northport, northeastern Washington State. 2007 GSA Denver Annual Meeting (28–31 October 2007), Paper No. 143-48

Stuiver, M., Polach, H.A., 1977. Reporting of 14C data. Radiocarbon 19, 355-363.

Stuiver, M., Reimer, P.J, Braziunas, T.F., 1998. High-precision radiocarbon age calibration for terrestrial and marine samples. Radiocarbon 40, 1127-1151.

Swartz, B.K., 1980. The status of Guinea Coast paleoarchaeological knowledge as seen from Legon 15, 37-40.

Talma, A.S., Vogel, J.C., 1993. A simplified approach to calibrating C14 dates. Radiocarbon 35, 317-322.

Tardy, Y., 1993, Pétrologie des latérites et des sols tropicaux. Paris, Masson, 461p.

Taylor, G., Eggleton, R.A., 2001. Regolith geology and geomorphology. Providing fundamental discussion of regolith properties and chemistry. John Wiley and Sons, 384p.

Taylor, R. 1987, Radiocarbon Dating: An Archaeological Perspective, Academic Press, New York 14p.

Telmer, K., Costa, M., Agelica, R., Araujo, E., Maurice, Y., 2006. The Source and Fate of sediment and mercury in the Tapajos River, Para, Brazilian Amazon: Ground and Space Based Evidence. Journal of Environmental Management 81, pp. 101-13.

Tshibubudze, A., Hein, K.A.A., 2013. Structural setting of gold deposits in the Oudalan-Gorouol volcano-sedimentary belt east of the Markoye Shear Zone, West African craton. Journal of African Earth Sciences 80, 31-47. http://dx.doi.org/10.1016/j.jafrearsci.2012.11.010

Tylecote, R.F., 1965. Iron smelting in pre-industrial communities. Journal of the Iron and Steel Institute 203, 340-348.

Tylecote, R.F., Austin, J.N., and Wraith, A.E., 1971. The mechanism of the Bloomery process in shaft furnaces. Journal of the Iron and Steel Institute 209, 342-63.

United Nations, 2002, Compendium on best practices in Small-Scale Mining in Africa. Economic Commission for Africa.

USGS., 2000. Mineral commodity summaries. United States Geological Survey Reston, 199 p.

Van Oss, H.G., 2002. Slag - Iron and Steel. U.S. Geological Survey Minerals Yearbook 2002, 70.1-70.6.

Verhoogen, J., 1962. Oxidation of iron-titanium oxides in igneous rocks. University of California, Berkeley. The Journal of Geology 70, 168-181.

Vogel, J.C., Fuls. A.,Visser., E, 1993. Pretoria calibration for short lived samples. Radiocarbon 35, 73-85.

Wassenaar, T.D., Henschel, J.R., Pfaffenthaler, M.M., Mutota, E.N., Seely, M.K., Pallett, J. 2012. Ensuring the future of the Namib's biodiversity: Ecological restoration as a key management response to a mining boom. Journal of Arid Environments 93, 126-135.

WAXI, 2013. Confidential final report to the AMIRA sponsors of WAXI phase II, Theme 3 Surface processes, p 594

APPENDIX 1
LITHOLOGICAL DATA

STN PTS	UTM ZONE	E	N	HOST ROCK TYPE	CHARACTER	Features
020	30P	0696192	1459169	hill(scree-claycontact)	Ferricrete-Silicrete-Quartzvein	Contact
020	30P	0696183	1459176	hill(scree-claycontact)	Ferricrete-Silicrete-Quartzvein	Contact
020	30P	0696178	1459181	hill(scree-claycontact)	Ferricrete-Silicrete-Quartzvein	Contact
022	30P	0696168	1459185	hill(scree-claycontact)	basalt,ferricrete,silicrete,quartzvein	Contact
022	30P	0696163	1459186	hill(scree-claycontact)	basalt,ferricrete,silicrete,quartzvein	Contact
022	30P	0696150	1459187	hill(scree-claycontact)	basalt,ferricrete,silicrete,quartzvein	Contact
022	30P	0696136	1459192	hill(scree-claycontact)	basalt,ferricrete,silicrete,quartzvein	Contact
022	30P	0696126	1459195	hill(scree-claycontact)	basalt,ferricrete,silicrete,quartzvein	Contact
022	30P	0696113	1459200	hill(scree-claycontact)	basalt,ferricrete,silicrete,quartzvein	Contact
022	30P	0696104	1459199	hill(scree-claycontact)	basalt,ferricrete,silicrete,quartzvein	Contact
022	30P	0696095	1459199	hill(scree-claycontact)	basalt,ferricrete,silicrete,quartzvein	Contact
022	30P	0696085	1459207	hill(scree-claycontact)	basalt,ferricrete,silicrete,quartzvein	Contact
022	30P	0696076	1459214	hill(scree-claycontact)	basalt,ferricrete,silicrete,quartzvein	Contact
022	30P	0696067	1459220	hill(scree-claycontact)	basalt,ferricrete,silicrete,quartzvein	Contact
022	30P	0696053	1459220	hill(scree-claycontact)	basalt,ferricrete,silicrete,quartzvein	Contact
022	30P	0696043	1459218	hill(scree-claycontact)	basalt,ferricrete,silicrete,quartzvein	Contact
022	30P	0696031	1459218	hill(scree-claycontact)	basalt,ferricrete,silicrete,quartzvein	Contact
022	30P	0696020	1459217	hill(scree-claycontact)	basalt,ferricrete,silicrete,quartzvein	Contact
023	30P	0696004	1459212	hill(scree-claycontact)	basalt,ferricrete,silicrete,quartzvein	Contact
023	30P	0696088	1459206	hill(scree-claycontact)	basalt,ferricrete,silicrete,quartzvein	Contact
023	30P	0696968	1459202	hill(scree-claycontact)	basalt,ferricrete,silicrete,quartzvein	Contact
023	30P	0696958	1459194	hill(scree-claycontact)	basalt,ferricrete,silicrete,quartzvein	Contact
024	30P	0695947	1459186	hill(scree-claycontact)	basalt,ferricrete,silicrete,quartzvein	Contact
024	30P	0695938	1459179	hill(scree-claycontact)	basalt,ferricrete,silicrete,quartzvein	Contact
024	30P	0695929	1459168	hill(scree-claycontact)	basalt,ferricrete,silicrete,quartzvein	Contact
024	30P	0695926	1459163	hill(scree-claycontact)	basalt,ferricrete,silicrete,quartzvein	Contact
024	30P	0695913	1459156	hill(scree-claycontact)	basalt,ferricrete,silicrete,quartzvein	Contact
024	30P	0695898	1459151	hill(scree-claycontact)	basalt,ferricrete,silicrete,quartzvein	Contact
024	30P	0695889	1459150	hill(scree-claycontact)	basalt,ferricrete,silicrete,quartzvein	Contact
024	30P	0695880	1459150	hill(scree-claycontact)	basalt,ferricrete,silicrete,quartzvein	Contact
038	30P	0696276	1458524	hill(basalt-quartzveincontact)	Basalt-quartzvein	contact
038	30P	0696268	1458524	hill(basalt-quartzveincontact)	Basalt-quartzvein	contact
038	30P	0696263	1458515	hill(basalt-quartzveincontact)	Basalt-quartzvein	contact
038	30P	0696268	1458513	hill(basalt-quartzveincontact)	Basalt-quartzvein	contact
038	30P	0696276	1458508	hill(basalt-quartzveincontact)	Basalt-quartzvein	contact
038	30P	0696280	1458503	hill(basalt-quartzveincontact)	Basalt-quartzvein	contact
038	30P	0696286	1458503	hill(basalt-quartzveincontact)	Basalt-quartzvein	contact
038	30P	0696294	1458504	hill(basalt-quartzveincontact)	Basalt-quartzvein	contact
038	30P	0696295	1458515	hill(basalt-quartzveincontact)	Basalt-quartzvein	contact
038	30P	0696288	1458522	hill(basalt-quartzveincontact)	Basalt-quartzvein	contact
038	30P	0696280	1458528	hill(basalt-quartzveincontact)	Basalt-quartzvein	contact
040	30P	0695832	1458223	meta-sediments-	Meta-sediments-ironformation	Contact

				Ironformation		
040	30P	0695844	1458222	meta-sediments-Ironformation	Meta-sediments-ironformation	Contact
040	30P	0695852	1458222	meta-sediments-Ironformation	Meta-sediments-ironformation	Contact
040	30P	0695865	1458222	meta-sediments-Ironformation	Meta-sediments-ironformation	Contact
040	30P	0695880	1458221	meta-sediments-Ironformation	Meta-sediments-ironformation	Contact
040	30P	0695891	1458217	meta-sediments-Ironformation	Meta-sediments-ironformation	Contact
040	30P	0695902	1458209	meta-sediments-Ironformation	Meta-sediments-ironformation	Contact
041	30P	0695914	1458205	Shale	Ironformation-shalecontact	Contact
041	30P	0695925	1458206	Shale	Ironformation-shalecontact	Contact
041	30P	0695937	1458212	Shale	Ironformation-shalecontact	Contact
041	30P	0695952	1458215	Shale	Ironformation-shalecontact	Contact
041	30P	0695963	1458222	Shale	Ironformation-shalecontact	Contact
042	30P	0695958	1458233	Shale	Ironformation-shalecontact	Contact
042	30P	0695946	1458233	Shale	Ironformation-shalecontact	Contact
042	30P	0695935	1458234	Shale	Ironformation-shalecontact	Contact
042	30P	0695928	1458237	Shale	Ironformation-shalecontact	Contact
043	30P	0695924	1458241	Ironformation	Ironformation-shalecontact	Contact
043	30P	0695938	1458240	Ironformation	Ironformation-shalecontact	Contact
043	30P	0695945	1458245	Ironformation	Ironformation-shalecontact	Contact
043	30P	0695953	1458251	Ironformation	Ironformation-shalecontact	Contact
043	30P	0695963	1458254	Ironformation	Ironformation-shalecontact	Contact
043	30P	0695971	1458258	Ironformation	Ironformation-shalecontact	Contact
043	30P	0695982	1458264	Ironformation	Ironformation-shalecontact	Contact
043	30P	0695989	1458271	Ironformation	Ironformation-shalecontact	Contact
044	30P	0695989	1458255	Manganeserichshale	Ironformation-shalecontact	Contact
044	30P	0695996	1458260	Manganeserichshale	Ironformation-shalecontact	Contact
044	30P	0695002	1458266	Manganeserichshale	Ironformation-shalecontact	Contact
045	30P	0695012	1458276	Manganeserichshale	Ironformation-shalecontact	Contact
045	30P	0695019	1458285	Manganeserichshale	Ironformation-shalecontact	Contact
045	30P	0695016	1458299	Manganeserichshale	Ironformation-shalecontact	Contact
045	30P	0695019	1458299	Manganeserichshale	Ironformation-shalecontact	Contact
045	30P	0695014	1458303	Manganeserichshale	Ironformation-shalecontact	Contact
045	30P	0695014	1458309	Manganeserichshale	Ironformation-shalecontact	Contact
046	30P	0695019	1458315	Manganeserichshale	Ironformation-shalecontact	Contact
046	30P	0695016	1458321	Manganeserichshale	Ironformation-shalecontact	Contact
046	30P	0696020	1458325	Manganeserichshale	Ironformation-shalecontact	Contact
047	30P	0696030	1458335	hill(scree-claycontact)	scree(gabbro,ferricrete,quartzvein)	Contact
047	30P	0696031	1458349	hill(scree-claycontact)	scree(gabbro,ferricrete,quartzvein)	Contact
047	30P	0696035	1458357	hill(scree-claycontact)	scree(gabbro,ferricrete,quartzvein)	Contact
047	30P	0696039	1458368	hill(scree-claycontact)	scree(gabbro,ferricrete,quartzvein)	Contact
047	30P	0696040	1458392	hill(scree-claycontact)	scree(gabbro,ferricrete,quartzvein)	Contact
048	30P	0696036	1458401	Shale	shale-screecontact	Contact

048	30P	0696030	1458411	Shale	shale-screecontact	Contact
049	30P	0696030	1458422	clay	shale-claycontact	Contact
049	30P	0696038	1458432	clay	shale-claycontact	Contact
049	30P	0696041	1458439	clay	shale-claycontact	Contact
049	30P	0696046	1458444	clay	shale-claycontact	Contact
049	30P	0696050	1458452	clay	shale-claycontact	Contact
050	30P	0696062	1458446	hill(scree-claycontact)	scree(ferricrete,silicrete,quartzvein)	Contact
050	30P	0696070	1458439	hill(scree-claycontact)	scree(ferricrete,silicrete,quartzvein)	Contact
050	30P	0696078	1458444	hill(scree-claycontact)	scree(ferricrete,silicrete,quartzvein)	Contact
050	30P	0696089	1458433	hill(scree-claycontact)	scree(ferricrete,silicrete,quartzvein)	Contact
050	30P	0696091	1458428	hill(scree-claycontact)	scree(ferricrete,silicrete,quartzvein)	Contact
050	30P	0696108	1458430	hill(scree-claycontact)	scree(ferricrete,silicrete,quartzvein)	Contact
051	30P	0696114	1458431	hill(scree-claycontact)	scree(ferricrete)	Contact
051	30P	0696129	1458442	hill(scree-claycontact)	scree(ferricrete)	Contact
051	30P	0696122	1458453	hill(scree-claycontact)	scree(ferricrete)	Contact
051	30P	0696124	1458459	hill(scree-claycontact)	scree(ferricrete)	Contact
051	30P	0696121	1458471	hill(scree-claycontact)	scree(ferricrete)	Contact
051	30P	0696116	1458484	hill(scree-claycontact)	scree(ferricrete)	Contact
051	30P	0696106	1458492	hill(scree-claycontact)	scree(ferricrete)	Contact
051	30P	0696093	1458502	hill(scree-claycontact)	scree(ferricrete)	Contact
051	30P	0696089	1458511	hill(scree-claycontact)	scree(ferricrete)	Contact
051	30P	0069679	1458519	hill(scree-claycontact)	scree(ferricrete)	Contact
051	30P	0696069	1458528	hill(scree-claycontact)	scree(ferricrete)	Contact
051	30P	0696059	1458531	hill(scree-claycontact)	scree(ferricrete)	Contact
051	30P	0696046	1458532	hill(scree-claycontact)	scree(ferricrete)	Contact
051	30P	0696028	1458538	hill(scree-claycontact)	scree(ferricrete)	Contact
051	30P	0696007	1458545	hill(scree-claycontact)	scree(ferricrete)	Contact
051	30P	0696995	1458544	hill(scree-claycontact)	scree(ferricrete)	Contact
051	30P	0696985	1458539	hill(scree-claycontact)	scree(ferricrete)	Contact
051	30P	0696977	1458539	ferricrete+quartzveincontact	ferricrete-quartzvein	Contact
052	30P	0695958	1458527	ferricrete+quartzveincontact	ferricrete-quartzvein	Contact
052	30P	0695962	1458537	ferricrete+quartzveincontact	ferricrete-quartzvein	Contact
052	30P	0695963	1458544	ferricrete+quartzveincontact	ferricrete-quartzvein	Contact
052	30P	0695964	1458557	ferricrete+quartzveincontact	ferricrete-quartzvein	Contact
052	30P	0695975	1458561	ferricrete+quartzveincontact	ferricrete-quartzvein	Contact
052	30P	0695986	1458564	ferricrete+quartzveincontact	ferricrete-quartzvein	Contact
052	30P	0695995	1458565	ferricrete+quartzveincontact	ferricrete-quartzvein	Contact
052	30P	0695004	1458575	ferricrete+quartzveincontact	ferricrete-quartzvein	Contact
052	30P	0695003	1458583	ferricrete+quartzveincontact	ferricrete-quartzvein	Contact
052	30P	0695007	1458593	ferricrete+quartzveincontact	ferricrete-quartzvein	Contact
053	30P	0695017	1458605	hill(basalt-shalecontact)	basalt-shale	Contact
053	30P	0695003	1458615	hill(basalt-shalecontact)	basalt-shale	Contact
053	30P	0695991	1458622	hill(basalt-shalecontact)	basalt-shale	Contact
053	30P	0695983	1458628	hill(basalt-shalecontact)	basalt-shale	Contact
053	30P	0695968	1458629	hill(basalt-shalecontact)	basalt-shale	Contact
053	30P	0695011	1458620	hill(basalt-shalecontact)	basalt-shale	Contact
053	30P	0695027	1458627	hill(basalt-shalecontact)	basalt-shale	Contact
053	30P	0695040	1458635	hill(basalt-shalecontact)	basalt-shale	Contact

054	30P	0695053	1458639	hill(quartz-vein)	quartz-vein	Contact
055	30P	0696066	1458648	hill(quartz-vein)	quartz-vein	Contact
055	30P	0696055	1458653	hill(quartz-vein)	quartz-vein	Contact
055	30P	0696046	1458658	hill(quartz-vein)	quartz-vein	Contact
055	30P	0696035	1458668	hill(quartz-vein)	quartz-vein	Contact
055	30P	0696034	1458678	hill(quartz-vein)	quartz-vein	Contact
055	30P	0696044	1458681	hill(quartz-vein)	quartz-vein	Contact
056	30P	0696049	1458675	hill(quartz-vein-basalt)	quartzvein-basalt	Contact
056	30P	0696059	1458671	hill(quartz-vein-basalt)	quartzvein-basalt	Contact
056	30P	0696072	1458664	hill(quartz-vein-basalt)	quartzvein-basalt	Contact
056	30P	0696084	1458656	hill(quartz-vein-basalt)	quartzvein-basalt	Contact
056	30P	0696088	1458649	hill(quartz-vein-basalt)	quartzvein-basalt	Contact
056	30P	0696094	1458662	hill(quartz-vein-basalt)	quartzvein-basalt	Contact
056	30P	0696103	1458669	hill(quartz-vein-basalt)	quartzvein-basalt	Contact
056	30P	0696107	1458675	hill(quartz-vein-basalt)	quartzvein-basalt	Contact
056	30P	0696119	1458675	hill(quartz-vein-basalt)	quartzvein-basalt	Contact
056	30P	0696121	1458664	hill(quartz-vein-basalt)	quartzvein-basalt	Contact
056	30P	0696125	1458652	hill(quartz-vein-basalt)	quartzvein-basalt	Contact
056	30P	0696136	1458646	hill(quartz-vein-basalt)	quartzvein-basalt	Contact
056	30P	0696152	1458625	hill(quartz-vein-basalt)	quartzvein-basalt	Contact
057	30P	0696166	1458621	hill(ferricrete)	ferricrete	Contact
057	30P	0696177	1458615	hill(ferricrete)	ferricrete	Contact
059	30P	0696224	1458658	hill(meta-basalt)	meta-basalt-ferricretecontact	Contact
059	30P	0696216	1458666	hill(meta-basalt)	meta-basalt-ferricretecontact	Contact
059	30P	0696204	1458670	hill(meta-basalt)	meta-basalt-ferricretecontact	Contact
059	30P	0696194	1458671	hill(meta-basalt)	meta-basalt-ferricretecontact	Contact
059	30P	0696180	1458674	hill(meta-basalt)	meta-basalt-ferricretecontact	Contact
059	30P	0696168	1458680	hill(meta-basalt)	meta-basalt-ferricretecontact	Contact
059	30P	0696147	1458684	hill(meta-basalt)	meta-basalt-ferricretecontact	Contact
059	30P	0696134	1458691	hill(meta-basalt)	meta-basalt-ferricretecontact	Contact
059	30P	0696124	1458696	hill(meta-basalt)	meta-basalt-ferricretecontact	Contact
059	30P	0696109	1458703	hill(meta-basalt)	meta-basalt-ferricretecontact	Contact
060	30P	0696099	1458704	ferricrete	meta-basalt-ferricretecontact	Contact
060	30P	0696096	1458697	ferricrete	meta-basalt-ferricretecontact	Contact
060	30P	0696090	1458699	ferricrete	meta-basalt-ferricretecontact	Contact
060	30P	0696079	1458701	ferricrete	meta-basalt-ferricretecontact	Contact
060	30P	0696066	1458699	ferricrete	meta-basalt-ferricretecontact	Contact
060	30P	0696054	1458702	ferricrete	meta-basalt-ferricretecontact	Contact
060	30P	0696047	1458709	ferricrete	meta-basalt-ferricretecontact	Contact
060	30P	0696033	1458716	ferricrete	meta-basalt-ferricretecontact	Contact
060	30P	0696023	1458721	ferricrete	meta-basalt-ferricretecontact	Contact
060	30P	0696021	1458731	ferricrete	meta-basalt-ferricretecontact	Contact
061	30P	0696999	1458745	qtz-vein,ferricrete,meta-basalt	meta-basalt-ferricretecontact	Contact
061	30P	0696004	1458749	qtz-vein,ferricrete,meta-basalt	meta-basalt-ferricretecontact	Contact
061	30P	0696010	1458766	qtz-vein,ferricrete,meta-basalt	meta-basalt-ferricretecontact	Contact

062	30P	0696027	1458755	hill(basalt)	meta-basalt-ferricrete-basaltcontact	Contact
062	30P	0696037	1458757	hill(basalt)	meta-basalt-ferricrete-basaltcontact	Contact
062	30P	0696053	1458747	hill(basalt)	meta-basalt-ferricrete-basaltcontact	Contact
062	30P	0696063	1458749	hill(basalt)	meta-basalt-ferricrete-basaltcontact	Contact
062	30P	0696072	1458754	hill(basalt)	meta-basalt-ferricrete-basaltcontact	Contact
062	30P	0696084	1458747	hill(basalt)	meta-basalt-ferricrete-basaltcontact	Contact
062	30P	0696098	1458740	hill(basalt)	meta-basalt-ferricrete-basaltcontact	Contact
062	30P	0696111	1458739	hill(basalt)	meta-basalt-ferricrete-basaltcontact	Contact
062	30P	0696131	1458724	hill(basalt)	meta-basalt-ferricrete-basaltcontact	Contact
062	30P	0696153	1458729	hill(basalt)	meta-basalt-ferricrete-basaltcontact	Contact
063	30P	0696167	1458734	hill(basalt)	meta-basalt-ferricrete-basaltcontact	Contact
063	30P	0696181	1458735	hill(basalt)	meta-basalt-ferricrete-basaltcontact	Contact
063	30P	0696179	1458746	hill(basalt)	meta-basalt-ferricrete-basaltcontact	Contact
063	30P	0696169	1458753	hill(basalt)	meta-basalt-ferricrete-basaltcontact	Contact
063	30P	0696157	1458759	hill(basalt)	meta-basalt-ferricrete-basaltcontact	Contact
063	30P	0696139	1458769	hill(basalt)	meta-basalt-ferricrete-basaltcontact	Contact
063	30P	0696127	1458775	hill(basalt)	meta-basalt-ferricrete-basaltcontact	Contact
063	30P	0696118	1458784	hill(basalt)	meta-basalt-ferricrete-basaltcontact	Contact
063	30P	0696107	1458794	hill(basalt)	meta-basalt-ferricrete-basaltcontact	Contact
063	30P	0696094	1458799	hill(basalt)	meta-basalt-ferricrete-basaltcontact	Contact
063	30P	0696082	1458804	hill(basalt)	meta-basalt-ferricrete-basaltcontact	Contact
063	30P	0696192	1458740	hill(basalt)	meta-basalt-ferricrete-basaltcontact	Contact
063	30P	0696212	1458740	hill(basalt)	meta-basalt-ferricrete-basaltcontact	Contact
063	30P	0696220	1458747	hill(basalt)	meta-basalt-ferricrete-basaltcontact	Contact
063	30P	0696222	1458761	hill(basalt)	meta-basalt-ferricrete-basaltcontact	Contact
063	30P	0696219	1458775	hill(basalt)	meta-basalt-ferricrete-basaltcontact	Contact
063	30P	0696212	1458786	hill(basalt)	meta-basalt-ferricrete-basaltcontact	Contact
063	30P	0696207	1458792	hill(basalt)	meta-basalt-ferricrete-basaltcontact	Contact
063	30P	0696200	1458804	hill(basalt)	meta-basalt-ferricrete-basaltcontact	Contact
063	30P	0696213	1458802	hill(basalt)	meta-basalt-ferricrete-basaltcontact	Contact
063	30P	0696227	1458800	hill(basalt)	meta-basalt-ferricrete-basaltcontact	Contact
063	30P	0696240	1458804	hill(basalt)	meta-basalt-ferricrete-basaltcontact	Contact
063	30P	0696251	1458799	hill(basalt)	meta-basalt-ferricrete-basaltcontact	Contact
063	30P	0696254	1458787	hill(basalt)	meta-basalt-ferricrete-basaltcontact	Contact
063	30P	0696261	1458772	hill(basalt)	meta-basalt-ferricrete-basaltcontact	Contact
063	30P	0696274	1458763	hill(basalt)	meta-basalt-ferricrete-basaltcontact	Contact
063	30P	0696288	1458754	hill(basalt)	meta-basalt-ferricrete-basaltcontact	Contact
063	30P	0696301	1458754	hill(basalt)	meta-basalt-ferricrete-basaltcontact	Contact
063	30P	0696308	1458764	hill(basalt)	meta-basalt-ferricrete-basaltcontact	Contact
063	30P	0696316	1458778	hill(basalt)	meta-basalt-ferricrete-basaltcontact	Contact
063	30P	0696317	1458781	hill(basalt)	meta-basalt-ferricrete-basaltcontact	Contact
063	30P	0696305	1458789	hill(basalt)	meta-basalt-ferricrete-basaltcontact	Contact
063	30P	0696303	1458802	hill(basalt)	meta-basalt-ferricrete-basaltcontact	Contact
063	30P	0696298	1458812	hill(basalt)	meta-basalt-ferricrete-basaltcontact	Contact
063	30P	0696292	1458819	hill(basalt)	meta-basalt-ferricrete-basaltcontact	Contact
063	30P	0696273	1458823	hill(basalt)	meta-basalt-ferricrete-basaltcontact	Contact
063	30P	0696257	1458830	hill(basalt)	meta-basalt-ferricrete-basaltcontact	Contact
063	30P	0696241	1458828	hill(basalt)	meta-basalt-ferricrete-basaltcontact	Contact

063	30P	0696228	1458834	hill(basalt)	meta-basalt-ferricrete-basaltcontact	Contact
063	30P	0696234	1458845	hill(basalt)	meta-basalt-ferricrete-basaltcontact	Contact
063	30P	0696241	1458859	hill(basalt)	meta-basalt-ferricrete-basaltcontact	Contact
063	30P	0696245	1458865	hill(basalt)	meta-basalt-ferricrete-basaltcontact	Contact
063	30P	0696259	1458867	hill(basalt)	meta-basalt-ferricrete-basaltcontact	Contact
063	30P	0696270	1458864	hill(basalt)	meta-basalt-ferricrete-basaltcontact	Contact
063	30P	0696274	1458870	hill(basalt)	meta-basalt-ferricrete-basaltcontact	Contact
063	30P	0696283	1458884	hill(basalt)	meta-basalt-ferricrete-basaltcontact	Contact
063	30P	0696280	1458893	hill(basalt)	meta-basalt-ferricrete-basaltcontact	Contact
063	30P	0696277	1458904	hill(basalt)	meta-basalt-ferricrete-basaltcontact	Contact
063	30P	0696268	1458921	hill(basalt)	meta-basalt-ferricrete-basaltcontact	Contact
063	30P	0696264	1458932	hill(basalt)	meta-basalt-ferricrete-basaltcontact	Contact
063	30P	0696253	1458937	hill(basalt)	meta-basalt-ferricrete-basaltcontact	Contact
063	30P	0696241	1458944	hill(basalt)	meta-basalt-ferricrete-basaltcontact	Contact
063	30P	0696226	1458956	hill(basalt)	meta-basalt-ferricrete-basaltcontact	Contact
063	30P	0696215	1458962	hill(basalt)	meta-basalt-ferricrete-basaltcontact	Contact
063	30P	0696196	1458969	hill(basalt)	meta-basalt-ferricrete-basaltcontact	Contact
063	30P	0696181	1458974	hill(basalt)	meta-basalt-ferricrete-basaltcontact	Contact
063	30P	0696165	1458982	hill(basalt)	meta-basalt-ferricrete-basaltcontact	Contact
063	30P	0696152	1458989	hill(basalt)	meta-basalt-ferricrete-basaltcontact	Contact
063	30P	0696141	1458999	hill(basalt)	meta-basalt-ferricrete-basaltcontact	Contact
063	30P	0696128	1458001	hill(basalt)	meta-basalt-ferricrete-basaltcontact	Contact
063	30P	0696111	1458997	hill(basalt)	meta-basalt-ferricrete-basaltcontact	Contact
063	30P	0696101	1458996	hill(basalt)	meta-basalt-ferricrete-basaltcontact	Contact
063	30P	0696090	1458992	hill(basalt)	meta-basalt-ferricrete-basaltcontact	Contact
063	30P	0696091	1458007	hill(basalt)	meta-basalt-ferricrete-basaltcontact	Contact
063	30P	0696099	1458020	hill(basalt)	meta-basalt-ferricrete-basaltcontact	Contact
063	30P	0696104	1458031	hill(basalt)	meta-basalt-ferricrete-basaltcontact	Contact
063	30P	0696116	1458041	hill(basalt)	meta-basalt-ferricrete-basaltcontact	Contact
063	30P	0696131	1458050	hill(basalt)	meta-basalt-ferricrete-basaltcontact	Contact
063	30P	0696145	1458057	hill(basalt)	meta-basalt-ferricrete-basaltcontact	Contact
063	30P	0696160	1458067	hill(basalt)	meta-basalt-ferricrete-basaltcontact	Contact
063	30P	0696151	1458074	hill(basalt)	meta-basalt-ferricrete-basaltcontact	Contact
063	30P	0696125	1458073	hill(basalt)	meta-basalt-ferricrete-basaltcontact	Contact
063	30P	0696100	1458074	hill(basalt)	meta-basalt-ferricrete-basaltcontact	Contact
063	30P	0695919	1459176	hill(basalt)	meta-basalt-ferricrete-basaltcontact	Contact
063	30P	0695906	1459174	hill(basalt)	meta-basalt-ferricrete-basaltcontact	Contact
063	30P	0695892	1459171	hill(basalt)	meta-basalt-ferricrete-basaltcontact	Contact
063	30P	0695884	1459179	hill(basalt)	meta-basalt-ferricrete-basaltcontact	Contact
063	30P	0695882	1459194	hill(basalt)	meta-basalt-ferricrete-basaltcontact	Contact
063	30P	0695874	1459203	hill(basalt)	meta-basalt-ferricrete-basaltcontact	Contact
063	30P	0695860	1459207	hill(basalt)	meta-basalt-ferricrete-basaltcontact	Contact
063	30P	0695846	1459204	hill(basalt)	meta-basalt-ferricrete-basaltcontact	Contact
063	30P	0695844	1459213	hill(basalt)	meta-basalt-ferricrete-basaltcontact	Contact
063	30P	0695849	1459221	hill(basalt)	meta-basalt-ferricrete-basaltcontact	Contact
063	30P	0695853	1459230	hill(basalt)	meta-basalt-ferricrete-basaltcontact	Contact
063	30P	0695855	1459242	hill(basalt)	meta-basalt-ferricrete-basaltcontact	Contact
063	30P	0695858	1459255	hill(basalt)	meta-basalt-ferricrete-basaltcontact	Contact

063	30P	0695858	1459268	hill(basalt)	meta-basalt-ferricrete-basaltcontact	Contact
063	30P	0695847	1459282	hill(basalt)	meta-basalt-ferricrete-basaltcontact	Contact
063	30P	0695834	1459299	hill(basalt)	meta-basalt-ferricrete-basaltcontact	Contact
063	30P	0695827	1459308	hill(basalt)	meta-basalt-ferricrete-basaltcontact	Contact
065	30P	0695813	1459319	hill(silicrete)	basalt-sillicretecontact	Contact
065	30P	0695801	1459321	hill(silicrete)	basalt-sillicretecontact	Contact
065	30P	0695785	1459317	hill(silicrete)	basalt-sillicretecontact	Contact
065	30P	0695774	1459316	hill(silicrete)	basalt-sillicretecontact	Contact
065	30P	0695763	1459309	hill(silicrete)	basalt-sillicretecontact	Contact
065	30P	0695752	1459304	hill(silicrete)	basalt-sillicretecontact	Contact
065	30P	0695745	1459295	hill(silicrete)	basalt-sillicretecontact	Contact
065	30P	0695734	1459289	hill(silicrete)	basalt-sillicretecontact	Contact
065	30P	0695728	1459291	hill(silicrete)	basalt-sillicretecontact	Contact
066	30P	0695720	1459301	hill(silicrete)	basalt-sillicretecontact	Contact
066	30P	0695709	1459313	hill(silicrete)	basalt-sillicretecontact	Contact
066	30P	0695700	1459326	hill(silicrete)	basalt-sillicretecontact	Contact
066	30P	0695690	1459333	hill(silicrete)	basalt-sillicretecontact	Contact
066	30P	0695684	1459340	hill(silicrete)	basalt-sillicretecontact	Contact
066	30P	0695683	1459352	hill(silicrete)	basalt-sillicretecontact	Contact
067	30P	0695682	1459362	hill(basalt)	basalt-sillicretecontact	Contact
067	30P	0695683	1459374	hill(basalt)	basalt-sillicretecontact	Contact
067	30P	0695670	1459373	hill(basalt)	basalt-sillicretecontact	Contact
067	30P	0695660	1459376	hill(basalt)	basalt-sillicretecontact	Contact
067	30P	0695630	1459382	hill(basalt)	basalt-sillicretecontact	Contact
067	30P	0695636	1459391	hill(basalt)	basalt-sillicretecontact	Contact
067	30P	0695629	1459402	hill(basalt)	basalt-sillicretecontact	Contact
067	30P	0696625	1459414	hill(basalt)	basalt-sillicretecontact	Contact
067	30P	0696622	1459420	hill(basalt)	basalt-sillicretecontact	Contact
067	30P	0696610	1459430	hill(basalt)	basalt-sillicretecontact	Contact
067	30P	0696602	1459429	hill(basalt)	basalt-sillicretecontact	Contact
067	30P	0696592	1459438	hill(basalt)	basalt-sillicretecontact	Contact
067	30P	0696587	1459449	hill(basalt)	basalt-sillicretecontact	Contact
067	30P	0696588	1459474	hill(basalt)	basalt-sillicretecontact	Contact
067	30P	0696589	1459435	hill(basalt)	basalt-sillicretecontact	Contact
067	30P	0696586	1459498	hill(basalt)	basalt-sillicretecontact	Contact
067	30P	0696584	1459511	hill(basalt)	basalt-sillicretecontact	Contact
067	30P	0696583	1459529	hill(basalt)	basalt-sillicretecontact	Contact
067	30P	0696578	1459548	hill(basalt)	basalt-sillicretecontact	Contact
067	30P	0696578	1459565	hill(basalt)	basalt-sillicretecontact	Contact
067	30P	0696571	1459582	hill(basalt)	basalt-sillicretecontact	Contact
067	30P	0696563	1459593	hill(basalt)	basalt-sillicretecontact	Contact
067	30P	0696547	1459610	hill(basalt)	basalt-sillicretecontact	Contact
068	30P	0696385	1459760	hill(basalt)	basalt-sillicretecontact	Contact
068	30P	0696400	1459747	hill(basalt)	basalt-sillicretecontact	Contact
068	30P	0696409	1459734	hill(basalt)	basalt-sillicretecontact	Contact
068	30P	0696421	1459724	hill(basalt)	basalt-sillicretecontact	Contact
068	30P	0696431	1459714	hill(basalt)	basalt-sillicretecontact	Contact
068	30P	0696445	1459711	hill(basalt)	basalt-sillicretecontact	Contact

068	30P	0696452	1459712	hill(basalt)	basalt-sillicretecontact	Contact
068	30P	0696466	1459717	hill(basalt)	basalt-sillicretecontact	Contact
068	30P	0696485	1459720	hill(basalt)	basalt-sillicretecontact	Contact
068	30P	0696503	1459716	hill(basalt)	basalt-sillicretecontact	Contact
068	30P	0696518	1459718	hill(basalt)	basalt-sillicretecontact	Contact
068	30P	0696536	1459722	hill(basalt)	basalt-sillicretecontact	Contact
068	30P	0696559	1459724	hill(basalt)	basalt-sillicretecontact	Contact
068	30P	0696583	1459712	hill(basalt)	basalt-sillicretecontact	Contact
068	30P	0696583	1459688	hill(basalt)	basalt-sillicretecontact	Contact
068	30P	0696587	1459680	hill(basalt)	basalt-sillicretecontact	Contact
068	30P	0696598	1459674	hill(basalt)	basalt-sillicretecontact	Contact
068	30P	0696610	1459669	hill(basalt)	basalt-sillicretecontact	Contact
068	30P	0696623	1459660	hill(basalt)	basalt-sillicretecontact	Contact
068	30P	0696644	1459644	hill(basalt)	basalt-sillicretecontact	Contact
068	30P	0696663	1458634	hill(basalt)	basalt-sillicretecontact	Contact
068	30P	0696667	1458616	hill(basalt)	basalt-sillicretecontact	Contact
068	30P	0696669	1458601	hill(basalt)	basalt-sillicretecontact	Contact
068	30P	0696666	1458592	hill(basalt)	basalt-sillicretecontact	Contact
068	30P	0696652	1458577	hill(basalt)	basalt-sillicretecontact	Contact
068	30P	0696631	1458587	hill(basalt)	basalt-sillicretecontact	Contact
068	30P	0696617	1458591	hill(basalt)	basalt-sillicretecontact	Contact
068	30P	0696604	1458601	hill(basalt)	basalt-sillicretecontact	Contact
068	30P	0696590	1458616	hill(basalt)	basalt-sillicretecontact	Contact
068	30P	0696584	1458629	hill(basalt)	basalt-sillicretecontact	Contact
068	30P	0696572	1458633	hill(basalt)	basalt-sillicretecontact	Contact
068	30P	6966550	1458632	hill(basalt)	basalt-sillicretecontact	Contact
068	30P	0696538	1458626	hill(basalt)	basalt-sillicretecontact	Contact
068	30P	0696524	1458616	hill(basalt)	basalt-sillicretecontact	Contact
068	30P	0696509	1458611	hill(basalt)	basalt-sillicretecontact	Contact
068	30P	0696497	1458595	hill(basalt)	basalt-sillicretecontact	Contact
068	30P	0696489	1458582	hill(basalt)	basalt-sillicretecontact	Contact
068	30P	0696489	1458563	hill(basalt)	basalt-sillicretecontact	Contact
068	30P	0696499	1458553	hill(basalt)	basalt-sillicretecontact	Contact
068	30P	0696507	1458543	hill(basalt)	basalt-sillicretecontact	Contact
068	30P	0696519	1458538	hill(basalt)	basalt-sillicretecontact	Contact
068	30P	0696536	1458530	hill(basalt)	basalt-sillicretecontact	Contact
068	30P	0696553	1458533	hill(basalt)	basalt-sillicretecontact	Contact
068	30P	0696564	1458537	hill(basalt)	basalt-sillicretecontact	Contact
068	30P	0696571	1458541	hill(basalt)	basalt-sillicretecontact	Contact
068	30P	0696575	1458559	hill(basalt)	basalt-sillicretecontact	Contact
068	30P	0696587	1458573	hill(basalt)	basalt-sillicretecontact	Contact
068	30P	0696589	1458586	hill(basalt)	basalt-sillicretecontact	Contact
070	30P	0696304	1458815	hill(siltstone)	silicrete-siltstonecontact	Contact
070	30P	0696047	1458625	hill(siltstone)	silicrete-siltstonecontact	Contact
070	30P	0696040	1458632	hill(siltstone)	silicrete-siltstonecontact	Contact
070	30P	0696039	1458645	hill(siltstone)	silicrete-siltstonecontact	Contact
070	30P	0696030	1458650	hill(siltstone)	silicrete-siltstonecontact	Contact
070	30P	0696025	1458654	hill(siltstone)	silicrete-siltstonecontact	Contact

070	30P	0696015	1458666	hill(siltstone)	silicrete-siltstonecontact	Contact
070	30P	0696996	1458665	hill(siltstone)	silicrete-siltstonecontact	Contact
070	30P	0696995	1458667	hill(siltstone)	silicrete-siltstonecontact	Contact
070	30P	0696985	1458674	hill(siltstone)	silicrete-siltstonecontact	Contact
070	30P	0696977	1458675	hill(siltstone)	silicrete-siltstonecontact	Contact
070	30P	0696963	1458675	hill(siltstone)	silicrete-siltstonecontact	Contact
070	30P	0696945	1458673	hill(siltstone)	silicrete-siltstonecontact	Contact
070	30P	0696935	1458673	hill(siltstone)	silicrete-siltstonecontact	Contact
070	30P	0696929	1458674	hill(siltstone)	silicrete-siltstonecontact	Contact
070	30P	0696928	1458675	hill(siltstone)	silicrete-siltstonecontact	Contact
070	30P	0696923	1458679	hill(siltstone)	silicrete-siltstonecontact	Contact
070	30P	0696927	1458676	hill(siltstone)	silicrete-siltstonecontact	Contact
070	30P	0696950	1458672	hill(siltstone)	silicrete-siltstonecontact	Contact
070	30P	0696964	1458669	hill(siltstone)	silicrete-siltstonecontact	Contact
070	30P	0696975	1458660	hill(siltstone)	silicrete-siltstonecontact	Contact
070	30P	0695980	1458654	hill(siltstone)	silicrete-siltstonecontact	Contact
070	30P	0695989	1458643	hill(siltstone)	silicrete-siltstonecontact	Contact
070	30P	0695996	1458644	hill(siltstone)	silicrete-siltstonecontact	Contact
070	30P	0695997	1458643	hill(siltstone)	silicrete-siltstonecontact	Contact
070	30P	0695001	1458638	hill(siltstone)	silicrete-siltstonecontact	Contact
070	30P	0695996	1458635	hill(siltstone)	silicrete-siltstonecontact	Contact
070	30P	0695993	1458635	hill(siltstone)	silicrete-siltstonecontact	Contact
070	30P	0695985	1458638	hill(siltstone)	silicrete-siltstonecontact	Contact
070	30P	0695978	1458643	hill(siltstone)	silicrete-siltstonecontact	Contact
070	30P	0696001	1458631	hill(siltstone)	silicrete-siltstonecontact	Contact
070	30P	0696015	1458631	hill(siltstone)	silicrete-siltstonecontact	Contact
070	30P	0696005	1458616	hill(siltstone)	silicrete-siltstonecontact	Contact
070	30P	0696014	1458610	hill(siltstone)	silicrete-siltstonecontact	Contact
070	30P	0695719	1458578	hill(silicrete-ferricrete)	ferricrete-silicretecontact	Contact
070	30P	0695695	1458572	hill(silicrete-ferricrete)	ferricrete-silicretecontact	Contact
070	30P	0695688	1458569	hill(silicrete-ferricrete)	ferricrete-silicretecontact	Contact
070	30P	0695684	1458563	hill(silicrete-ferricrete)	ferricrete-silicretecontact	Contact
070	30P	0695692	1458550	hill(silicrete-ferricrete)	ferricrete-silicretecontact	Contact
070	30P	0695705	1458546	hill(silicrete-ferricrete)	ferricrete-silicretecontact	Contact
070	30P	0695713	1458537	hill(silicrete-ferricrete)	ferricrete-silicretecontact	Contact
070	30P	0695720	1458528	hill(silicrete-ferricrete)	ferricrete-silicretecontact	Contact
070	30P	0695723	1458517	hill(silicrete-ferricrete)	ferricrete-silicretecontact	Contact
070	30P	0695732	1458509	hill(silicrete-ferricrete)	ferricrete-silicretecontact	Contact
070	30P	0695736	1458506	hill(silicrete-ferricrete)	ferricrete-silicretecontact	Contact
070	30P	0695748	1458486	hill(silicrete-ferricrete)	ferricrete-silicretecontact	Contact
070	30P	0695757	1458473	hill(slate)	ferricrete-silicrete-slatecontact	Contact
070	30P	0695769	1458459	hill(slate)	ferricrete-silicrete-slatecontact	Contact
070	30P	0695783	1458460	hill(slate)	ferricrete-silicrete-slatecontact	Contact
070	30P	0695794	1458467	hill(slate)	ferricrete-silicrete-slatecontact	Contact
070	30P	0695783	1458460	hill(slate)	ferricrete-silicrete-slatecontact	Contact
070	30P	0695768	1458467	hill(slate)	ferricrete-silicrete-slatecontact	Contact
070	30P	0695786	1458460	hill(slate)	ferricrete-silicrete-slatecontact	Contact
070	30P	0695806	1458442	hill(slate)	ferricrete-silicrete-slatecontact	Contact

070	30P	0695811	1458441	hill(graphiticshale)	slate-graphiticshalecontact	Contact
070	30P	0695823	1458434	hill(graphiticshale)	slate-graphiticshalecontact	Contact
070	30P	0695837	1458439	hill(graphiticshale)	slate-graphiticshalecontact	Contact
070	30P	0695840	1458439	hill(graphiticshale)	slate-graphiticshalecontact	Contact
070	30P	0695848	1458434	hill(graphiticshale)	slate-graphiticshalecontact	Contact
070	30P	0695853	1458427	hill(graphiticshale)	slate-graphiticshalecontact	Contact
070	30P	0695857	1458426	hill(graphiticshale)	slate-graphiticshalecontact	Contact
079	30P	0695861	1458425	hill(graphiticshale-qtzvein)	qtzvein-graphiticshalecontact	Contact
079	30P	0695868	1458419	hill(graphiticshale-qtzvein)	qtzvein-graphiticshalecontact	Contact
079	30P	0695882	1458411	hill(graphiticshale-qtzvein)	qtzvein-graphiticshalecontact	Contact
079	30P	0695888	1458409	hill(graphiticshale-qtzvein)	qtzvein-graphiticshalecontact	Contact
079	30P	0695903	1458398	hill(graphiticshale-qtzvein)	qtzvein-graphiticshalecontact	Contact
079	30P	0695900	1458391	hill(graphiticshale-qtzvein)	qtzvein-graphiticshalecontact	Contact
079	30P	0695904	1458372	hill(graphiticshale-qtzvein)	qtzvein-graphiticshalecontact	Contact
079	30P	0695887	1458375	hill(graphiticshale-qtzvein)	qtzvein-graphiticshalecontact	Contact
079	30P	0695882	1458377	hill(graphiticshale-qtzvein)	qtzvein-graphiticshalecontact	Contact
079	30P	0695873	1458375	hill(graphiticshale-qtzvein)	qtzvein-graphiticshalecontact	Contact
079	30P	0695871	1458363	hill(graphiticshale-qtzvein)	qtzvein-graphiticshalecontact	Contact
079	30P	0695856	1458358	hill(graphiticshale-qtzvein)	qtzvein-graphiticshalecontact	Contact
079	30P	0695849	1458354	hill(graphiticshale-qtzvein)	qtzvein-graphiticshalecontact	Contact
080	30P	0695851	1458350	hill(qtzvein-greywacke)	qtzvein-greywackecontact	Contact
080	30P	0695847	1458344	hill(qtzvein-greywacke)	qtzvein-greywackecontact	Contact
080	30P	0695838	1458337	hill(qtzvein-greywacke)	qtzvein-greywackecontact	Contact
080	30P	0695839	1458324	hill(qtzvein-greywacke)	qtzvein-greywackecontact	Contact
080	30P	0695844	1458313	hill(qtzvein-greywacke)	qtzvein-greywackecontact	Contact
080	30P	0695840	1458302	hill(qtzvein-greywacke)	qtzvein-greywackecontact	Contact
080	30P	0695857	1458270	hill(qtzvein-greywacke)	qtzvein-greywackecontact	Contact
080	30P	0695875	1458244	hill(qtzvein-greywacke)	ferricrete-greywackecontact	Contact
081	30P	0696016	1457966	hill(ferricrete)	ferricrete-greywackecontact	Contact
081	30P	0696010	1457968	hill(ferricrete)	ferricrete-greywackecontact	Contact
081	30P	0696006	1457967	hill(ferricrete)	ferricrete-greywackecontact	Contact
081	30P	0696004	1457965	hill(ferricrete)	ferricrete-greywackecontact	Contact
081	30P	0696002	1457964	hill(ferricrete)	ferricrete-greywackecontact	Contact
081	30P	0696998	1457962	hill(ferricrete)	ferricrete-greywackecontact	Contact
081	30P	0696998	1457958	hill(ferricrete)	ferricrete-greywackecontact	Contact
081	30P	0696001	1457955	hill(ferricrete)	ferricrete-greywackecontact	Contact
081	30P	0696003	1457954	hill(ferricrete)	ferricrete-greywackecontact	Contact
081	30P	0696009	1457955	hill(ferricrete)	ferricrete-greywackecontact	Contact
081	30P	0696013	1457957	hill(ferricrete)	ferricrete-greywackecontact	Contact
081	30P	0696016	1457961	hill(ferricrete)	ferricrete-greywackecontact	Contact
081	30P	0696018	1457966	hill(ferricrete)	ferricrete-greywackecontact	Contact
081	30P	0696014	1457968	hill(ferricrete)	ferricrete-greywackecontact	Contact
082	30P	0696022	1457969	hill(ferricrete)	ferricrete-greywackecontact	Contact
082	30P	0696029	1457971	hill(ferricrete)	ferricrete-greywackecontact	Contact
082	30P	0696037	1457976	hill(ferricrete)	ferricrete-greywackecontact	Contact
082	30P	0696045	1457983	hill(ferricrete)	ferricrete-greywackecontact	Contact
082	30P	0696056	1457986	hill(ferricrete)	ferricrete-greywackecontact	Contact
082	30P	0696059	1457984	hill(ferricrete)	ferricrete-greywackecontact	Contact

082	30P	0696063	1457981	hill(ferricrete)	ferricrete-greywackecontact	Contact
082	30P	0696066	1457972	hill(ferricrete)	ferricrete-greywackecontact	Contact
082	30P	0696067	1457970	hill(ferricrete)	ferricrete-greywackecontact	Contact
082	30P	0696046	1457984	hill(ferricrete)	ferricrete-greywackecontact	Contact
082	30P	0696030	1457970	hill(ferricrete)	ferricrete-greywackecontact	Contact
082	30P	0696012	1457971	hill(ferricrete)	ferricrete-greywackecontact	Contact
082	30P	0696998	1457971	hill(ferricrete)	ferricrete-greywackecontact	Contact
082	30P	0696983	1457971	hill(ferricrete)	ferricrete-greywackecontact	Contact
082	30P	0696052	1457971	hill(ferricrete)	ferricrete-greywackecontact	Contact
082	30P	0696070	1457973	hill(ferricrete)	ferricrete-greywackecontact	Contact
082	30P	0696075	1457963	hill(ferricrete)	ferricrete-greywackecontact	Contact
082	30P	0696086	1457950	hill(ferricrete)	ferricrete-greywackecontact	Contact
082	30P	0696091	1457961	hill(ferricrete)	ferricrete-greywackecontact	Contact
082	30P	0696096	1457966	hill(ferricrete)	ferricrete-greywackecontact	Contact
082	30P	0696099	1457980	hill(ferricrete)	ferricrete-greywackecontact	Contact
082	30P	0696099	1457992	hill(ferricrete)	ferricrete-greywackecontact	Contact
083	30P	0696102	1457072	hill(scree-claycontact)	scree(ferricrete-silicrete)	Contact
083	30P	0696097	1457010	hill(scree-claycontact)	scree(ferricrete-silicrete)	Contact
083	30P	0696094	1457018	hill(scree-claycontact)	scree(ferricrete-silicrete)	Contact
083	30P	0696096	1457026	hill(scree-claycontact)	scree(ferricrete-silicrete)	Contact
083	30P	0696091	1457030	hill(scree-claycontact)	scree(ferricrete-silicrete)	Contact
083	30P	0696084	1457036	hill(scree-claycontact)	scree(ferricrete-silicrete)	Contact
083	30P	0696076	1457037	hill(scree-claycontact)	scree(ferricrete-silicrete)	Contact
083	30P	0696068	1457043	hill(scree-claycontact)	scree(ferricrete-silicrete)	Contact
083	30P	0696062	1457048	hill(scree-claycontact)	scree(ferricrete-silicrete)	Contact
083	30P	0696048	1457039	hill(scree-claycontact)	scree(ferricrete-silicrete)	Contact
083	30P	0696036	1457036	hill(scree-claycontact)	scree(ferricrete-silicrete)	Contact
083	30P	0696029	1457033	hill(scree-claycontact)	scree(ferricrete-silicrete)	Contact
083	30P	0696019	1457040	hill(scree-claycontact)	scree(ferricrete-silicrete)	Contact
083	30P	0696017	1457042	hill(scree-claycontact)	scree(ferricrete-silicrete)	Contact
083	30P	0696010	1457043	hill(scree-claycontact)	scree(ferricrete-silicrete)	Contact
083	30P	0696010	1457055	hill(scree-claycontact)	scree(ferricrete-silicrete)	Contact
083	30P	0696999	1457062	hill(scree-claycontact)	scree(ferricrete-silicrete)	Contact
125	30P	0695581	1459453	hill(basalt)	basalt-sillicretecontact	Contact
125	30P	0695607	1459422	hill(basalt)	basalt-sillicretecontact	Contact
125	30P	0695658	1459425	hill(basalt)	basalt-sillicretecontact	Contact
126	30P	0695664	1459418	hill(silicrete)	basalt-sillicretecontact	Contact
127	30P	0695670	1459390	hill(barkqtz-vein)	silicrete-qtzveincontact	Contact
128	30P	0695702	1459370	hill(silicrete)	silicrete-qtzveincontact	Contact
128	30P	0695764	1459331	hill(basalt)	basalt-sillicretecontact	Contact
128	30P	0695799	1459334	hill(basalt)	basalt-sillicretecontact	Contact
128	30P	0695821	1459331	hill(basalt)	basalt-sillicretecontact	Contact
128	30P	0695849	1459316	hill(basalt)	basalt-sillicretecontact	Contact
128	30P	0695883	1459273	hill(basalt)	basalt-sillicretecontact	Contact
125	30P	0695581	1459453	hill(basalt)	basalt-sillicretecontact	Contact
125	30P	0695607	1459422	hill(basalt)	basalt-sillicretecontact	Contact
125	30P	0695658	1459425	hill(basalt)	basalt-sillicretecontact	Contact
126	30P	0695664	1459418	hill(silicrete)	basalt-sillicretecontact	Contact

127	30P	0695670	1459390	hill(barkqtz-vein)	silicrete-qtzveincontact	Contact
128	30P	0695702	1459370	hill(silicrete)	silicrete-qtzveincontact	Contact
128	30P	0695764	1459331	hill(basalt)	basalt-sillicretecontact	Contact
128	30P	0695799	1459334	hill(basalt)	basalt-sillicretecontact	Contact
128	30P	0695821	1459331	hill(basalt)	basalt-sillicretecontact	Contact
128	30P	0695849	1459316	hill(basalt)	basalt-sillicretecontact	Contact
128	30P	0695883	1459273	hill(basalt)	basalt-sillicretecontact	Contact

APPENDIX-2
SAMPLING

STNPTS	UTM ZONE	EASTINGS	NORTHINGS	HOST ROCK TYPE	CHARACTER	STRUCTURE	SAMPLENOS
090	30P	0696151	1459198	furnace3	carbonsample	furnacesampling	FOR03-01CAR
090	30P	0696152	1459197	furnace3	metallurgicalsample	furnacesampling	FOR03-01MET
090	30P	0696146	1459190	furnace3	chimneysample	furnacesampling	FOR03-01TUB
090	30P	0696152	1459188	furnace3	metallurgicalsample	furnacesampling	FOR03-02MET
091	30P	0696185	1459251	furnace4	carbonsample	furnacesampling	FOR04-01CAR
091	30P	0696170	1459243	furnace4	metallurgicalsample	furnacesampling	FOR04-01MET
091	30P	0696157	1459252	furnace4	metallurgicalsample	furnacesampling	FOR04-02MET
092	30P	0696114	1459322	Metal head artefact	artefact	artefact	092-ARTIFACT
093	30P	0695772	1459587	furnace5	carbonsample	furnacesampling	FOR05-01CAR
093	30P	0695771	1459585	furnace5	carbonsample	furnacesampling	FOR05-02CAR
093	30P	0695769	1459604	furnace5	metallurgicalsample	furnacesampling	FOR05-01MET
093	30P	0695762	1459634	furnace5	metallurgicalsample	furnacesampling	FOR05-02MET
093	30P	0695738	1459618	furnace5	metallurgicalsample	furnacesampling	FOR05-03MET
093	30P	0695761	1459713	furnace5	chimneysample	furnacesampling	FOR05-01TUB
093	30P	0695773	1459568	furnace5	metallurgicalsample	furnacesampling	FOR05-04MET
094	30P	0696082	1459618	furnace1	carbonsample	furnacesampling	FOR01-01CAR
094	30P	0696082	1459618	furnace1	metallurgicalsample	furnacesampling	FOR01-01MET
094	30P	0696091	1459215	furnace1	metallurgicalsample	furnacesampling	FOR01-02MET
094	30P	0696086	1459209	furnace1	metallurgicalsample	furnacesampling	FOR01-03MET
094	30P	0696082	1459214	furnace1	chimneysample	furnacesampling	FOR01-01TUB
095	30P	0696150	1459196	furnace2	carbonsample	furnacesampling	FOR02-01CAR
095	30P	0696154	1459193	furnace2	metallurgicalsample	furnacesampling	FOR02-01MET
095	30P	0696154	1459194	furnace2	chimneysample	furnacesampling	FOR02-01TUB
095	30P	0696154	1459194	furnace2	metallurgicalsample	furnacesampling	FOR02-02MET

095	30P	0696148	1459187	furnace2	carbonsample	furnacesampling	FOR02-02CAR
095	30P	0696148	1459187	furnace2	carbonsample	furnacesampling	FOR02-03CAR
096	30P	0696306	1458628	furnace8	carbonsample	furnacesampling	FOR08-01CAR
096	30P	0696310	1458626	furnace8	metallurgicalsample	furnacesampling	FOR08-01MET
096	30P	0696310	1458626	furnace8	metallurgicalsample	furnacesampling	FOR08-02MET
096	30P	0696314	1458625	furnace8	carbonsample	furnacesampling	FOR08-02CAR
096	30P	0696298	1458616	furnace8	carbonsample	furnacesampling	FOR08-03CAR
096	30P	0696294	1458632	furnace8	chimneysample	furnacesampling	FOR08-01TUB
097	30P	0696316	1458540	furnace9	carbonsample	furnacesampling	FOR09-01CAR
097	30P	0696316	1458540	furnace9	metallurgicalsample	furnacesampling	FOR09-01MET
097	30P	0696313	1458542	furnace9	carbonsample	furnacesampling	FOR09-02MET
097	30P	0696310	1458542	furnace9	metallurgicalsample	furnacesampling	FOR09-02CAR
097	30P	0696316	1458540	furnace9	carbonsample	furnacesampling	FOR09-01CAR
097	30P	0696316	1458540	furnace9	metallurgicalsample	furnacesampling	FOR09-01MET
097	30P	0696313	1458542	furnace9	carbonsample	furnacesampling	FOR09-02MET
097	30P	0696310	1458542	furnace9	metallurgicalsample	furnacesampling	FOR09-02CAR
097	30P	0696303	1458547	furnace9	carbonsample	furnacesampling	FOR09-03MET
097	30P	0696311	1458542	furnace9	metallurgicalsample	furnacesampling	FOR09-01TUB
098	30P	0696377	1458816	furnace6	carbonsample	furnacesampling	FOR06-01CAR
098	30P	0696376	1458817	furnace6	carbonsample	furnacesampling	FOR06-02CAR
098	30P	0696376	1458817	furnace6	metallurgicalsample	furnacesampling	FOR06-01MET
098	30P	0696377	1458818	furnace6	metallurgicalsample	furnacesampling	FOR06-02MET
098	30P	0696377	1458818	furnace6	chimneysample	furnacesampling	FOR06-01TUB
098	30P	0696379	1458818	furnace6	metallurgicalsample	furnacesampling	FOR06-03MET
112	30P	0696166	1458017	furnace10	carbonsample	furnacesampling	FOR10-01CAR
113	30P	0696168	1458010	furnace8	carbonsample	furnacesampling	FOR10-02CAR
113	30P	0696167	1458010	furnace10	metallurgicalsample	furnacesampling	FOR10-01MET
113	30P	0696168	1458012	furnace10	metallurgicalsample	furnacesampling	FOR10-02MET
113	30P	0696171	1458013	furnace10	metallurgicalsample	furnacesampling	FOR10-03MET
113	30P	0696166	1458011	furnace10	chimneysample	furnacesampling	FOR10-01TUB

114	30P	0696025	1458639	hill(shale)	shale-basalt contact	Contactsampling	LD-001
115	30P	0695937	1458604	hill(basalt)	shale-basaltcontact	Contactsampling	LD-002
116	30P	0695826	1458563	hill(graphiticshale)	shale-basaltcontact	Contactsampling	LD-003
117	30P	0695798	1458580	Minesite (shale)	minesitesampling	Minesitesampling	LD-004
117	30P	0695796	1458577	Minesite (alteredquartz-vein)	minesitesampling	Minesitesampling	LD-005
117	30P	0695794	1458581	Minesite(shale-hematite)	minesitesampling	Minesitesampling	LD-006
117	30P	0695799	1458588	Minesite(fibrousFeveins)	minesitesampling	Minesitesampling	LD-007
113	30P	0696167	1458010	furnace10	metallurgicalsample	furnacesampling	FOR10-01MET
113	30P	0696168	1458012	furnace10	metallurgicalsample	furnacesampling	FOR10-02MET
113	30P	0696171	1458013	furnace10	metallurgicalsample	furnacesampling	FOR10-03MET
113	30P	0696166	1458011	furnace10	chimneysample	furnacesampling	FOR10-01TUB
114	30P	0696025	1458639	hill(shale)	shale-basaltcontact	Contactsampling	LD-001
115	30P	0695937	1458604	hill(basalt)	shale-basaltcontact	Contactsampling	LD-002
116	30P	0695826	1458563	hill(graphiticshale)	shale-basaltcontact	Contactsampling	LD-003
117	30P	0695798	1458580	Minesite(shale)	minesitesampling	Minesitesampling	LD-004
118	30P	0695796	1458577	Minesite(alteredquartz-vein)	minesitesampling	Minesitesampling	LD-005
118	30P	0695794	1458581	Minesite(shale-hematite)	minesitesampling	Minesitesampling	LD-006
118	30P	0695799	1458588	Minesite(fibrousFeveins)	minesitesampling	Minesitesampling	LD-007
113	30P	0696167	1458010	furnace10	metallurgicalsample	furnacesampling	FOR10-01MET
113	30P	0696168	1458012	furnace10	metallurgicalsample	furnacesampling	FOR10-02MET
113	30P	0695799	1458588	Minesite(hematiteveins)	minesitesampling	Minesitesampling	LD-008
113	30P	0695799	1458588	Minesite(hematiteveins)	minesitesampling	Minesitesampling	LD-009
113	30P	0695794	1458578	Minesite(Ferichshale)	minesitesampling	Minesitesampling	LD-010
117	30P	0695794	1458578	Minesite(hematite)	minesitesampling	Minesitesampling	LD-011
117	30P	0695799	1458588	Minesite(hematiteveins)	minesitesampling	Minesitesampling	LD-008
117	30P	0695799	1458588	Minesite(hematiteveins)	minesitesampling	Minesitesampling	LD-009
117	30P	0695794	1458578	Minesite(Ferichshale)	minesitesampling	Minesitesampling	LD-010
117	30P	0695794	1458578	Minesite(hematite)	minesitesampling	Minesitesampling	LD-011
117	30P	0695794	1458578	Minesite(shale)	minesitesampling	Minesitesampling	LD-012
118	30P	0695785	1458593	Minesite(Fe-veinsinshale)	minesitesampling	Minesitesampling	LD-013

119	30P	0695769	1458588	hill(ferricrete)	shale-ferricretecontact	Contactsampling	LD-014
120	30P	0695704	1458572	hill(ferricrete)	shale-ferricretecontact	Contactsampling	LD-015
121	30P	0695702	1458547	hill(silicrete)	silicrete-ferricretecontact	Contactsampling	LD-016
122	30P	0695747	1458490	hill(shale)	silicrete-shalecontact	Contactsampling	LD-017
123	30P	0695747	1458490	hill(meta-shale)	graphiticmeta-shale	Contactsampling	LD-018
117	30P	0695794	1458578	Minesite(shale)	minesitesampling	Minesitesampling	LD-012
118	30P	0695785	1458593	Minesite(Fe-veinsinshale)	minesitesampling	Minesitesampling	LD-013
119	30P	0695769	1458588	hill(ferricrete)	shale-ferricretecontact	Contactsampling	LD-014
120	30P	0695704	1458572	hill(ferricrete)	shale-ferricretecontact	Contactsampling	LD-015
121	30P	0695702	1458547	hill(silicrete)	silicrete-ferricretecontact	Contactsampling	LD-016
122	30P	0695747	1458490	hill(shale)	silicrete-shalecontact	Contactsampling	LD-017

APPENDIX-3

SELECTED SAMPLES FOR PETROGRAPHIC STUDIES

STN	UTM ZONE	E	N	HOST ROCK TYPE	CHARACTER	STRUCTURE	SAMPLENOS	Thin Section	pb
117	30P	0695798	1458580	shale	minesite	Minesite	LD-004	yes	
117	30P	0695796	1458577	alteredqtz-vein	minesite	Minesite	LD-005	yes	
117	30P	0695794	1458581	shale-hematite	minesite	Minesite	LD-006	yes	
117	30P	0695799	1458588	fibrousFeveins	minesite	Minesite	LD-007	yes	
117	30P	0695799	1458588	hematiteveins	minesite	Minesite	LD-008	yes	
117	30P	0695799	1458588	hematiteveins	minesite	Minesite	LD-009	yes	
117	30P	0695794	1458578	Ferichshale	minesite	Minesite	LD-010	yes	
117	30P	0695794	1458578	hematite	minesite	Minesite	LD-011	yes	
117	30P	0695794	1458578	shale	minesite	Minesite	LD-012	yes	
118	30P	0695785	1458593	Fe-veinsinshale	minesite	Minesite	LD-013	yes	
124	30P	0696021	1457966	Febearingshale	minesite	Minesite	LD-019		yes
124	30P	0696021	1457966	shale	minesite	Minesite	LD-020		yes
124	30P	0696021	1457966	hematiteveins	minesite	Minesite	LD-021	yes	
124	30P	0696021	1457966	graphiticshale	minesite	Minesite	LD-022		yes
124	30P	0696018	1457962	Mnrichshale	minesite	Minesite	LD-024		yes
114	30P	0696025	1458639	shale	shale-basalt	Contact	LD-001	yes	
115	30P	0695937	1458604	basalt	shale-basalt	Contact	LD-002	yes	
116	30P	0695826	1458563	Graphitic shale	shale-basalt	Contact	LD-003	yes	
119	30P	0695769	1458588	ferricrete	shale-ferricrete	Contact	LD-014	yes	
120	30P	0695704	1458572	ferricrete	shale-ferricrete	Contact	LD-015	yes	
121	30P	0695702	1458547	silicrete	silicrete-ferricrete	Contact	LD-016	yes	yes
091	30P	0696170	1459243	forge4	forge	furnace	FOR04-01MET	yes	yes
091	30P	0695762	1459634	forge5	forge	furnace	FOR05-02MET	yes	yes
091	30P	0695773	1459568	forge5	forge	furnace	FOR05-04MET	yes	yes
094	30P	0696082	1459618	forge1	forge	furnace	FOR01-01MET	yes	yes
094	30P	0696086	1459209	forge1	forge	furnace	FOR01-03MET	yes	yes
096	30P	0696154	1459194	forge2	forge	furnace	FOR02-02MET	yes	yes
096	30P	0696316	1458540	forge9	forge	furnace	FOR09-03MET	yes	yes
112	30P	0696168	1458012	forge10	forge	furnace	FOR10-02MET	yes	yes
112	30P	0696171	1458013	forge11	forge	furnace	FOR11-04MET		yes

APPENDIX-4

CARBON SAMPLES

STN PTS	UTM ZONE	EASTINGS	NORTHINGS	HOST ROCK TYPE	CHARACTER	STRUCTURE	SAMPLE NOS
090	30P	0696151	1459198	forge 3	carbon sample	forge sampling	FOR03-01 CAR
090	30P	0696146	1459190	forge 3	chimney sample	forge sampling	FOR03-01 TUB
091	30P	0696185	1459251	forge 4	carbon sample	forge sampling	FOR04-01 CAR
093	30P	0695772	1459587	forge 5	carbon sample	forge sampling	FOR05-01 CAR
093	30P	0695771	1459585	forge 5	carbon sample	forge sampling	FOR05-02 CAR
093	30P	0695761	1459713	forge 5	chimney sample	forge sampling	FOR05-01 TUB
094	30P	0696082	1459618	forge 1	carbon sample	forge sampling	FOR01-01 CAR
094	30P	0696082	1459214	forge 1	chimney sample	forge sampling	FOR01-01 TUB
095	30P	0696150	1459196	forge 2	carbon sample	forge sampling	FOR02-01 CAR
095	30P	0696154	1459194	forge 2	chimney sample	forge sampling	FOR02-01 TUB
095	30P	0696148	1459187	forge 2	carbon sample	forge sampling	FOR02-02 CAR
095	30P	0696148	1459187	forge 2	carbon sample	forge sampling	FOR02-03 CAR
096	30P	0696306	1458628	forge 8	carbon sample	forge sampling	FOR08-01 CAR
096	30P	0696314	1458625	forge 8	carbon sample	forge sampling	FOR08-02 CAR
096	30P	0696298	1458616	forge 8	carbon sample	forge sampling	FOR08-03 CAR
096	30P	0696294	1458632	forge 8	chimney sample	forge sampling	FOR08-01 TUB
097	30P	0696316	1458540	forge 9	carbon sample	forge sampling	FOR09-01 CAR
097	30P	0696310	1458542	forge 9	carbon sample	forge sampling	FOR09-02CAR
097	30P	0696311	1458542	forge 9	metallurgical sample	forge sampling	FOR09-01 TUB
098	30P	0696377	1458816	forge 6	carbon sample	forge sampling	FOR06-01 CAR
098	30P	0696376	1458817	forge 6	carbon sample	forge sampling	FOR06-02CAR
098	30P	0696377	1458818	forge 6	chimney sample	forge sampling	FOR06-01 TUB
112	30P	0696166	1458017	forge 10	carbon sample	forge sampling	FOR10-01 CAR
112	30P	0696168	1458010	forge 10	carbon sample	forge sampling	FOR10-02 CAR
112	30P	0696166	1458011	forge 10	chimney sample	forge sampling	FOR10-01 TUB