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Second Projet de Renforcement Institutionnel du Secteur Minier de la République Islamique de Mauritanie (PRISM-II)

Algoma-, Superior-, and Oolitic-Type Iron Deposits of the Islamic Republic of Mauritania:

Phase V, Deliverable 83

By Cliff D.Taylor, Carol A. Finn, Eric D. Anderson, Mohamed Yeslem Ould El Joud, Ahmed Ould Taleb Mohamed, and John D. Horton

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Multiple spellings are used in various literatures, and may be reflected in the text.

This report is preliminary and has not been reviewed for conformity with U.S. Geological Survey editorial standards or for stratigraphic nomenclature.

The report is being released in both English and French. In both versions, we use the French-language names for formal stratigraphic units.

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Algoma-, Superior-, and Oolitic-Type Iron Deposits of the Islamic Republic of Mauritania

2 Summary

High-grade hematitic iron ores (or HIF, containing 60–65 percent Fe) have been mined in Mauritania from Superior-type iron deposits since 1952. Depletion of the high grade ores in recent years has resulted in a number of new projects focused on lower grade magnetite ores in Algoma-type banded iron formation (or BIF, containing approximately 35 percent Fe). Large deposits of oolitic-type iron ores are also present in Phanerozoic sedimentary rocks in Mauritania. According to recent U.S. Geological Survey figures, Mauritania is the fifteenth largest iron producer in the World and currently has about 1.1 billion tonnes of crude iron ore reserves (USGS, 2012).

The main hosts for Algoma-type iron ore are BIF in: (1) the Mesoarchean rocks of the Tiris Complex and (2) Amsaga Complex, (3) the Mesoarchean Lebzenia Group in the greenstone belts of the Tasiast-Tijirit terrane, and (4) the Saouda Group of the Inchiri district. Neoarchean Algoma-type BIF is present in the (5) Eizzene and Oumachouema Groups of the Inchiri district, (6) the Ijibbitene Group of the Ijibbitene massif, and (7) the Guenieba and Gadel Groups of the Gorgol Noir Complex in the southern Mauritanides. Superior-type iron ores are restricted to the allochthonous Paleoproterozoic sequences of the Kediat Ijil and Guelb El Mhaoudat, which overlie the Tiris Complex. Paleoproterozoic BIF are present in the Sfariat belt, which hosts at least three known occurrences, and at Guelb Zednes, all of which are interpreted as fragments of Superior-type iron formation that have been either imbricated with or allochthonously deposited on the Mesoarchean-Paleoproterozoic suture zone during the Birimian orogeny.

Phanerozoic oolitic ironstones are hosted in the upper Silurian and lower Devonian rocks of the Gara Bouya Ali Group and the Zemmour Group in the Tindouf Basin in northern Mauritania and in the end Ordovician Tichit Group, the Silurian Oued Chig Group, and the lower Devonian Tenemouj Group in the Taoudeni Basin near Tidjikja. These rock groups define 11 permissive tracts for Algoma-, Superior-, and oolitic-type iron deposits in Mauritania.

1 Contents

Figures

Conversion Factors

SI to Inch/Pound

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
decimeter (dm)	0.32808	foot (ft)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Area	
hectare (ha)	2.471	acre
square meter (m^2)	0.0002471	acre
square kilometer (km^2)	0.3861	square mile (mi^2)
	Volume	
cubic kilometer (km^3)	0.2399	cubic mile (mi^3)
	Mass	
gram (g)	0.03527	ounce, avoirdupois (oz)
kilogram (kg)	2.205	pound avoirdupois (lb)
megagram (Mg)	1.102	ton, short (2,000 lb)
megagram (Mg)	0.9842	ton, long (2,240 lb)
metric ton per day	1.102	ton per day (ton/d)
megagram per day (Mg/d)	1.102	ton per day (ton/d)
metric ton per year	1.102	ton per year (ton/yr)
	Pressure	
kilopascal (kPa)	0.009869	atmosphere, standard (atm)
kilopascal (kPa)	0.01	bar
	Energy	
joule (J)	0.0000002	kilowatthour (kWh)

ppm, parts per million; ppb, parts per billion; Ma, millions of years before present; m.y., millions of years; Ga, billions of years before present; 1 micron or micrometer (μor μm) = 1×10^{-6} meters; Tesla (T) = the field intensity generating 1 Newton of force per ampere (A) of current per meter of conductor

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

°F=(1.8×°C)+32

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

°C=(°F-32)/1.8

Coordinate information is referenced to the World Geodetic System (WGS 84)

Acronyms

AMT	Audio-magnetotelluric
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
AVIRIS	Airborne Visible/Infrared Imaging Spectrometer
BIF	Banded iron formation
BLEG	Bulk leach extractable gold
BGS	British Geological Survey
BRGM	Bureau de Recherches Géologiques et Minières (Mauritania)
BUMIFOM	The Bureau Minier de la France d'Outre-Mer
CAMP	Central Atlantic Magmatic Province
CGIAR-CSI	Consultative Group on International Agricultural Research-Consortium for Spatial Information
DEM	Digital Elevation Model
DMG	Direction des Mines et de la Géologie
EMPA	Electron Microprobe Analysis
EM	Electromagnetic (geophysical survey)
EOS	Earth Observing System
eU	Equivalent uranium
GGISA	General Gold International
GIF	Granular iron formation
GIFOV	Ground instantaneous field of view
GIS	Geographic Information System
HIF	High grade hematitic iron ores
IHS	Intensity/Hue/Saturation
IAEA	International Atomic Energy Agency
IOCG	Iron oxide copper-gold deposit
IP	Induced polarization (geophysical survey)
IRM	Islamic Republic of Mauritania
JICA	Japan International Cooperation Agency
JORC	Joint Ore Reserves Committee (Australasian)
LIP	Large Igneous Province
LOR	Lower limit of reporting
LREE	Light rare-earth element
METI	Ministry of Economy, Trade and Industry (Japan)
MICUMA	Société des Mines de Cuivre de Mauritanie
MORB	Mid-ocean ridge basalt
E-MORB	Enriched mid-ocean ridge basalt
N-MORB	Slightly enriched mid-ocean ridge basalt
T-MORB	Transitional mid-ocean ridge basalt
Moz	Million ounces
MVT	Mississippi Valley-type deposits
NASA	United States National Aeronautics and Space Administration
NLAPS	National Landsat Archive Processing System
OMRG	Mauritanian Office for Geological Research

ONUDI	(UNIDO) United Nations Industrial Development Organization
PRISM	Projet de Renforcement Institutionnel du Secteur Minier
PGE	Platinum-group elements
RC	Reverse circulation drilling
REE	Rare earth element
RGB	Red-green-blue color schema
RTP	Reduced-to-pole
SARL	Société à responsabilité limitée
SEDEX	Sedimentary exhalative deposits
SIMS	Secondary Ionization Mass Spectrometry
SNIM	Société National Industrielle et Minière (Mauritania)
SP	Self potential (geophysical survey)
SRTM	Shuttle Radar Topography Mission
SWIR	Shortwave infrared
TIMS	Thermal Ionization Mass Spectrometry
TISZ	Tacarat-Inemmaudene Shear Zone
TM	Landsat Thematic Mapper
UN	United Nations
UNDP	United Nations Development Program
US	United States
USA	United States of America
USGS	United States Geological Survey
UTM	Universal Transverse Mercator projection
VHMS	Volcanic-hosted massive sulfide
VisNIR	Visible near-infrared spectroscopy
VLF	Very low frequency (geophysical survey)
VMS	Volcanogenic massive sulfide deposit
WDS	Wavelength-dispersive spectroscopy
WGS	World Geodetic System

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Algoma-, Superior-, and oolitic-type iron deposits of the Islamic Republic of Mauritania:

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By Cliff D.Taylor,[1] Carol A. Finn,[1] Eric D. Anderson,[1] Mohamed Yeslem Ould El Joud,[2] Ahmed Ould Taleb Mohamed,[3] and John D. Horton[1]

3 Introduction

High grade hematitic iron ores, containing 60–65 percent Fe, have been mined in Mauritania from Superior-type iron deposits since 1952. Depletion of the high grade ores in recent years has resulted in a number of new projects focused upon lower grade magnetite ores in Algoma-type banded iron formation (BIF) containing approximately 35 percent Fe. Mauritania is the 15th largest iron producer in the world and currently has about 1.1 billion tonnes (Gt = $1x10^9$ tonnes) of crude iron ore reserves (U.S. Geological Survey, 2012; see document for USGS discussion and definitions of reserve/resource categories. In this paper, an attempt is made to identify whether quoted reserve/resource figures from sources other than the USGS have been calculated based on internationally accepted methods such as the Australasian Code for Reporting of Exploration Results, Mineral Resources and Ore Reserves [the Joint Ore Reserves Committee (JORC) Code] or other JORC-compliant methods. In cases where reserve/resource figures are non-compliant with JORC or other internationally accepted reporting codes or the source(s) of figures cannot be identified, the terms "reserve" or "resource" are used). Production is mainly controlled by Société National Industrielle et Minière (SNIM), a parastatal company that is 78 percent owned by the Mauritanian government. Iron ores account for about 50 percent of the export earnings of the country. About 11 million tonnes (Mt) per year are shipped from three mines hosted in Mesoarchean (Guelb el Rhein) to Paleoproterozoic (Guelb El Mhaoudat and TO14) rocks near Zouérate in the western Rgueibat Shield. These ores are sent to loading facilities on the Atlantic coast at Nouadhibou via a 700-kilometer (km) railway constructed exclusively for this purpose. In 2001, SNIM formed a joint venture with Australia's Sphere Investments to study options for open-pit mining and beneficiation of the magnetite deposit at Guelb El Aouj.The deposit has JORC-compliant measured, indicated, and inferred resources of 701 million tons (Mt) of magnetite ore with a grade of 36.3 percent Fe. Planned production is 7 Mt/yr of direct reduction grade pellets (Mining Journal, 2006; Sphere Minerals Ltd., 2012). Sphere was granted a 30-year exploitation license on Guelb El Aouj in March 2008, and was then acquired by Xstrata in 2010 along with projects at nearby Askaf and Lebtheinia in the Tasiast-Tijirit terrane. ArcelorMittal is reportedly drilling for magnetite ores at Guelb Agareb. Additional

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interest in Algoma-type BIF has resulted in exploration projects at Guelb Tamagot in the Oumachoueima Group and the Kaouat El Khadra project in the Saouda Group of the Inchiri district.

Highly speculative iron resources also exist at the El Khader geothitic gossan in the Inchiri district and in Phanerozoic oolitic ironstones of the west-central Taoudeni and Tindouf Basin margins.These deposits are well known and are of low interest due to unfavorable economics of mining and beneficiation.

4 Brief Descriptions of the Major Types of Sediment-Hosted Iron Deposits

4.1 Origin and Types of Iron Formation

Banded iron formation (BIF, also known as banded ironstone) is a distinctive type of iron-rich sedimentary rock. A typical BIF consists of alternating layers of iron-poor quartzite, shale, or chert and nearly monomineralic Fe-oxide (magnetite (Fe_3O_4) or hematite (Fe_2O_3), -carbonate, -silicate, or -sulfide minerals. BIF may have clastic (granular texture, referred to as granular iron formation or GIF) or chemical sedimentary textures, and banding on a micro (mm), meso (cm), and macro scale (James, 1954, Clout and Simonson, 2005). BIF occurs in rocks as old as 3.7 Ga, and became abundant around the time of the great oxygenation event at approximately 2.4 Ga, and are less common after about 1.8 Ga (Cloud, 1973, fig. 1). BIF is globally the most important commercial source of iron ore, with some of the largest known deposits occurring in the Lake Superior Region of the northern USA and Canada, the Transvaal Basin of South Africa, the Carajas province in Brazil, and the Hamersley Basin of Western Australia (Clout and Simonson, 2005; fig. 2).There are three major types of iron deposits described below that are distinctly different in regard to their age, size, textures, mineralogy, and style of origin.

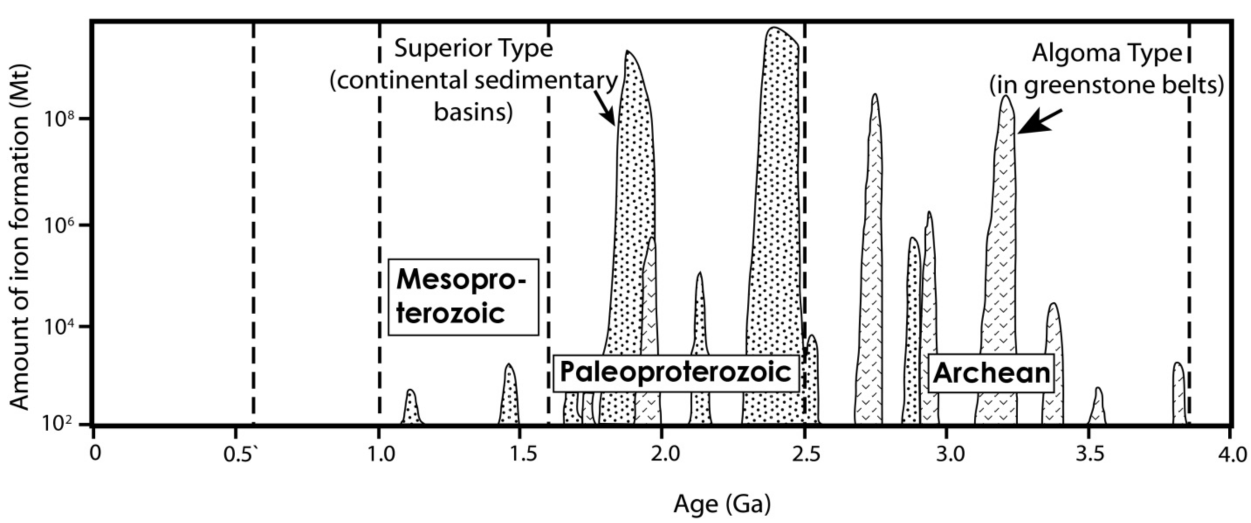

Figure 1. Age distribution of global iron formation (modified from Beukes and Gutzmer, 2008).

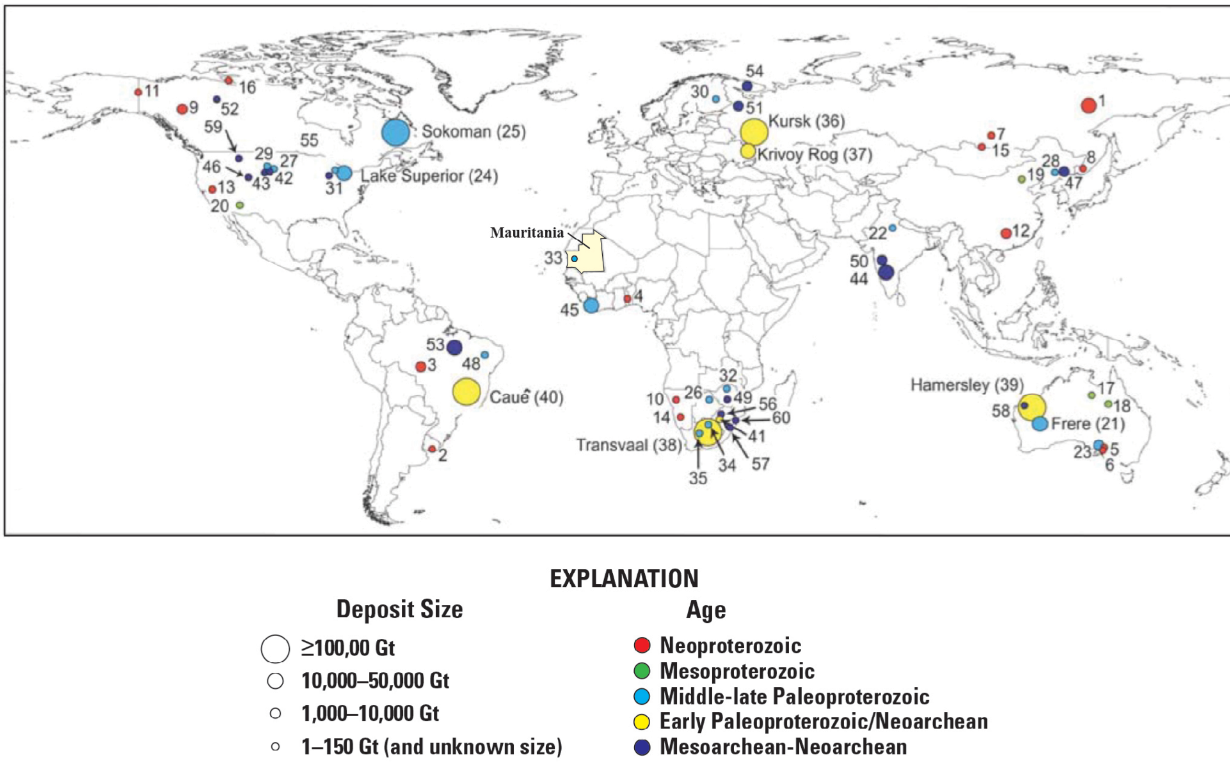

Figure 2. Global distribution of iron formation (modified from Bekker and others, 2010).

Algoma-Type Iron Formation

Algoma-type deposits are the oldest BIF.They are generally of small size and occur in Archean greenstone belts around the world.They occur in submarine volcanic or volcanosedimentary sequences poor in oolites, clastic grains and other normal sedimentary features.The occurrence of GIF in Algoma-type deposits is extremely rare. They are thought to form as hydrothermal exhalative deposits on the sea floor.The association with volcanic rocks and deep-water turbidites generally is interpreted as indicating formation in environments similar to volcanic-hosted massive sulfide deposits. They are products of extensional tectonics at spreading centers (Cannon, 1986a).

Superior-Type Iron Formation

Superior-type deposits are laterally extensive and well defined sequences of BIF thought to have formed as chemical sediments from Fe-saturated oceans during the global oxygenation of the atmosphere-ocean systems in the Late Archean-Early Proterozoic. Although the exact mechanisms for the formation of Superior-type BIF are highly controversial (see Clout and Simonson, 2005 and references therein), a conventional concept is that the banded iron layers were formed in sea water as the result of oxygen released by photosynthetic cyanobacteria (bluegreen algae), combining with dissolved iron in Earth's oceans to form insoluble iron oxides. These chemical precipitates settle from the water column to form a thin layer on the substrate, alternating with anoxic mud or silica gel (resulting in bands of shale or chert). Each band is similar to a varve, to the extent that the banding is assumed to result from cyclic variations in available oxygen. It is unclear whether the banding is seasonal, as a result of a feedback oscillation in ocean chemistry or if it represents some other cycle. It is assumed that initially the Earth started out with vast amounts of reduced iron dissolved in the world's acidic seas.

Eventually, as photosynthetic organisms generated oxygen, the available iron in the Earth's oceans was precipitated out as iron oxides. At the tipping point where the oceans became permanently oxygenated, small variations in oxygen production produced pulses of free oxygen in the surface waters, alternating with pulses of iron oxide deposition.

The sedimentary textures of Superior-type BIF show a significant change with time. Younger deposits tend to have a higher prevalence of GIF and are in conformable contact with tidally cross-bedded quartz arenites and stromatolitic dolomites indicative of shallow water depositional environments. Older Superior-type BIF have less GIF and are thought to have been deposited in deep shelf to upper continental slope environments, whereas the younger deposits are generally regarded as part of passive margin sequences on broad, sediment-starved continental shelves (Cannon, 1986b; Clout and Simonson, 2005)

Regardless of the details of their origin and subsequent modification during diagenesis and metamorphism, most BIF consists predominantly of magnetite-rich layers and have bulk iron content in the 30–35 percent range. Such rock, referred to as taconite ores in North America, can be profitably mined but require beneficiation to produce a product containing approximately 65 percent iron. A more desirable iron ore, referred to as martite-goethite, or high grade hematite (HIF) ores, contains approximately 56–68 percent iron and have been modified by a natural process of upgrading from BIF protore to HIF by silica destruction and oxidation of magnetite. This process is thought to occur through a variety of processes involving leaching by fluids including hypogene hydrothermal fluids, supergene weathering, and variants or combinations of these basic models. Details of the processes by which BIF protores are upgraded to HIF ores are as contentious as the process of formation of the original BIF. As a result, much of the recent work on BIF has focused on this process (Morey, 1999; Powell and others, 1999; Taylor and others, 2001; Dalstra and Guedes, 2004; Clout and Simonson, 2005; Lobato and others, 2008).

In the early 1900s, there was debate about the role of descending waters related to weathering versus heated ascending water. The importance of hot water was established by the work of Gruner (1930). He placed crushed silica and distilled water in a bomb for 20 to 28 hours at 200° C and recorded the solution of silica as follows: from quartz, 37 ppm; from silica gel 800 ppm; from chalcedony, 151 ppm. When heated to 300° C, solubilities were 958, 1,410, and 899 ppm respectively. These experiments showed that water at 300° C can leach large amounts of silica from BIF at the same time as oxidation of magnetite to hematite takes place. Gruner attributed the high temperature required for heating of groundwater to diabase sills and flows related to a younger group of basalt flows, which overlie the Lake Superior iron deposits.

Tyler (1949) studied the iron silicates (stilpnomelane, minnasotaite, grunerite) that formed from the metamorphism of the BIF by basaltic intrusions. He concluded that the low silica content of the hematitic ores was due to solution and removal of these silicates rather than to the direct solution of quartz.

More recent views (see Powell and others, 1999; Morey, 1999) call upon advancing foldbelts adjacent to belts of BIF to provide the heated solutions capable of producing hematitic ores. Fluid inclusion evidence indicates that such fluids can have temperatures between 200 and 400° C and the highland area produced by the tectonism could provide the hydraulic head to move the fluids into the iron deposits.

Phanerozoic Oolitic Ironstones

Ironstone is a sedimentary rock, either deposited as a ferruginous sediment or formed later by replacement, that contains enough iron to be mined as an iron ore. The term is generally restricted to hard, coarsely banded, non-banded, and non-cherty sedimentary rocks of Phanerozoic age, although there are examples of Proterozoic age. They are composed of iron oxides, carbonates, and silicates including goethite, hematite, magnetite, siderite, and chamosite (Wikipedia, 2012). Worldwide, there are over 500 known occurrences with past production coming from a handful of now-inactive districts. In the economic geology literature, ironstone deposits are referred to as the Clinton-type (Simpson and Gray, 1968) or Minette-type (Teyssen, 1984; 1989; Siehl and Thein, 1989) after the type localities in Silurian ironstones of the eastern United States and Jurassic ironstones of Lorraine, France, respectively (Maynard and Van Houten, 2004; Mucke and Farshad, 2005).

Phanerozoic ironstones are commonly composed of iron-rich ooids derived from two readily available weathering products, iron oxide and clay. Oolitic ironstones are chemically distinguished from Precambrian BIF by their silica content. In general, BIF has SiO_2 contents higher than 50 weight percent, whereas the SiO_2 content of ironstones is below about 35 weight percent (James, 1992; Mucke and Farshad, 2005). Oolitic ironstones can be further distinguished based upon mineralogical and geochemical aspects into two subtypes based upon the type of clay they are composed of: (1) chamosite ironstones, and (2) kaolinite ironstones. Chamosite is a member of the chlorite mineral group (Mucke and Farshad, 2005). Due to the large body of data suggesting that ooids are the products of shallow marine settings (Davies and others, 1978), oolitic ironstones are generally regarded as a type of marine strata (Van Houten and Bhattacharyya, 1982; Young, 1989). Oolitic ironstones, by definition containing >5 volume percent ooids and >15 weight percent iron (Young, 1989; Mucke and Farshad, 2005), accumulate in three types of cratonic basins flooded by shallow seas. They form in: (1) foredeeps along the interior portions of mobile belts during periods of tectonic quiescence and diminished detrital influx, (2) intracratonic basins characterized by prolonged stability, and (3) cratonic margins at times of divergence or initial convergence of lithospheric plates (Van Houten and Bhattacharyya, 1982; Van Houton and Arthur, 1989).

The distribution of Phanerozoic oolitic ironstones through time is marked by two major periods of deposition (Van Houten and Arthur, 1989). They began to accumulate locally in the Late Cambrian following the break-up and dispersal of Laurasian cratonic fragments and then became widespread from earliest Ordovician to latest Devonian time. The second major period was initiated by the break-up of Pangaea resulting in dispersal of cratonic blocks and gradual sea level rise. Local development of ironstones began in early Triassic time and persisted from the early Jurassic to middle Cenozoic (Van Houten and Bhattacharyya, 1982). Van Houten and Bhattacharyya (1982) have noted that these two periods of ironstone deposition correspond to greenhouse stages of the Phanerozoic climatic record. These were periods marked by mild climate, the generation of abundant organic matter, and high rates of marine detrital sedimentation on the continents.

The formation of oolitic ironstones is favored by open ocean circulation around dispersed cratonic fragments at times of sea level high stands, extensive marine transgression, a mild maritime climate and subdued tectonic activity. These conditions also favor deep continental weathering, which provides the iron and clay for the formation of iron-rich ooids (Van Houten and Bhattacharyya, 1982). Accumulation of oolitic ironstones occurs in relatively low-energy paralic to shallow marine settings, commonly along broadly embayed coastlines. Lagoonal settings protected by breaker bars and sediment-starved settings distant from deltaic sources of detrital input are ideal for the formation of ferric oxide-chamosite ooids (Van Houten and Bhattacharyya, 1982).

In detail, Phanerozoic iron-bearing beds are composed of three distinct facies: (1) nodular, commonly pyritic, sideritic shale in nonmarine to paralic “coal measures,” and locally in muddy offshore deposits, (2) sandy and shelly shallow marine sediment with abundant glauconite pellets, and (3) ferric oxide-chamosite oolite deposits.The standard vertical succession consists of the black shale facies at the base of a sequence, overlain by gray shale and siltstone, then by sandstone with graded bedding and hummocky cross-stratification suggesting tempestites, and finally by sandstone or oolitic ironstone with bipolar cross-stratification suggesting intertidal deposition (Van Houten and Bhattacharyya, 1982; Maynard and Van Houten, 2004; fig. 3).

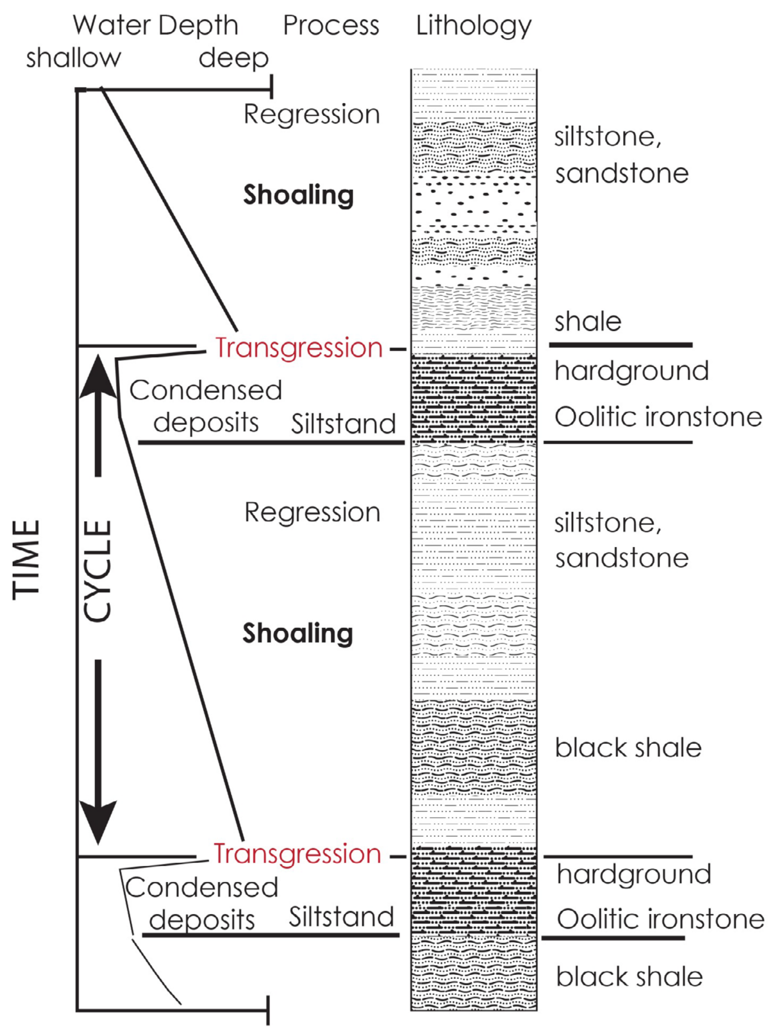

Figure 3. General stratigraphy and facies distribution of Phanerozoic oolitic ironstone (modified from Maynard and Van Houten, 2004).

Oolitic ironstones are condensed deposits that form during a transitional stage either at the end of a regional regression or the beginning of a renewed transgression.An iron formation may consist of a few to tens of shoaling upwards sequences produced by small-scale regressions, one or several of which may have led to the accumulation of an oolitic ironstone deposit (Van Houten and Bhattacharyya, 1982). A single sequence may range from a few meters to as many as 300 meters in thickness.Dimensions of an ironstone deposit may be 2 to 5 meters thick and 2 to 10 kilometers long (Maynard and Van Houten, 2004).

5. Mineral Deposits and Occurrences in Mauritania

Proven and possible reserves in the Zouérate area are 300 million tonnes of direct shipping ore (65 percent Fe) and 3,000 million tonnes of magnetite ore, requiring beneficiation

(35 percent Fe). About 12 million tonnes per year are shipped from three areas (fig. 4) of Archean and Paleoproterozoic rocks in the western Rgueibat Shield (Mining-technology.com, 2012). The permissive terrane is clearly defined on the geologic map by the distribution of Algoma-type ferruginous quartzite units in the Archean rocks and by the distribution of Superior-type BIF in allochthonous klippes of Paleoproterozoic rocks. Production is mainly controlled by Société National Industrielle et Minière (SNIM). SNIM currently produces direct shipping HIF ores from Superior-type BIF in the Kediat Ijil and Guelb El Mhaoudat and magnetite ores from Algoma-type BIF at Guelb el Rhein. In March, 2008, Sphere Investments was granted a 30-year exploitation license on Guelb el Aouj. This deposit has JORC-compliant measured, indicated and inferred resources of 701 million tonnes of magnetite ore with a grade of 36.3 percent iron. Planned production is seven million tonnes per year of direct reduction grade pellets (Mining Journal, 2006; Sphere Minerals Ltd., 2012).

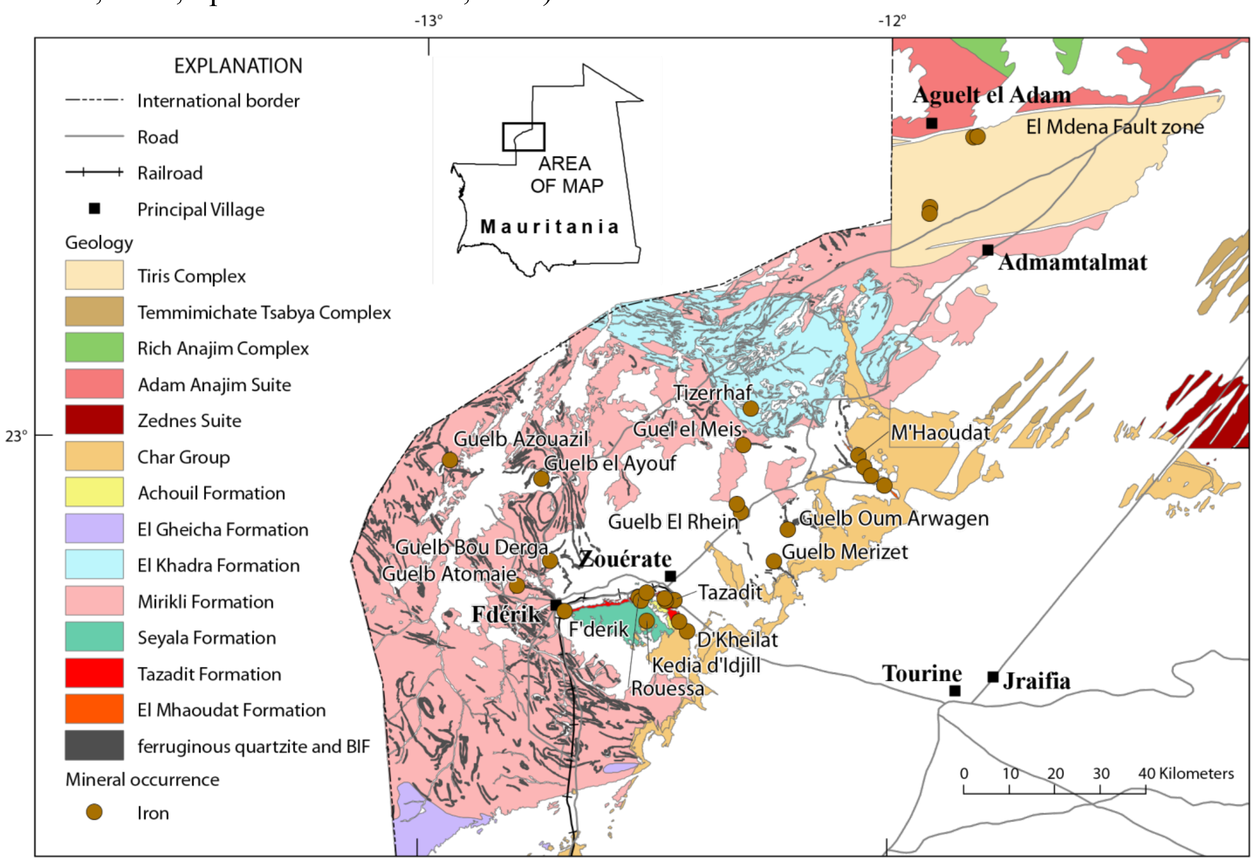

Figure 4. Simplified geology of the Mesoarchean Tiris Complex showing Paleoproterozoic inselbergs of the Kediat Ijil, Guelb El Mhaoudat, and the location of producing iron mines, deposits, and occurrences.

5.1 Superior-Type Iron Deposits in Mauritania

High grade hematitic iron ores, containing 60–65 percent Fe, have been mined in Mauritania from Superior-type BIF deposits since 1952. Mauritania is the 15th largest iron producer in the World and currently has about 1.1 billion tonnes (Gt) of crude iron ore reserves (U.S. Geological Survey, 2012). Production is mainly controlled by Société National Industrielle et Minière (SNIM), a parastatal company that is 78 percent owned by the Mauritanian government. Iron ores account for about 50 percent of the export earnings of the country. About 11 million tonnes (Mt) per year are shipped from three mines (fig. 4), hosted in Mesoarchean to Paleoproterozoicrocks near Zouérate in the western Rgueibat Shield to loading facilities on the Atlantic coast at Nouadhibou via a 700 km railway constructed exclusively for this purpose. In

2004 and 2005, 60 percent of the production was from Superior-type HIF and 40 percent from Algoma-type BIF (http://www.mining-technology.com, 2012). Two of the producing mines are developed in Paleoproterozoic Superior-type BIF of the allochthonous Ijil Complex of the Kediat Ijil (the Tazadit #14 pit, sectors 1 and 2) and Guelb El Mhaoudat (El Mhaoudat pits #1through 4), which are described in this section. Depletion of the high grade ores in recent years has resulted in a number of new projects focused upon lower grade magnetite ores in Algoma-type BIF containing 35 percent Fe. These iron ores are discussed in section 5.2. Other occurrences of BIF of probable Paleoproterozoic age, tentatively correlated with the Ijil Complex, are present in the Sfariat Belt and at Guelb Zednes. They are also discussed below.

History of Iron Mining in the F'Derik-Zouérate Area

The history of iron mining in the F'Derik-Zouérate area has been summarized by several sources including (Oksengorn, 1973; Marot and others, 2003; O'Connor and others, 2005; and (mining-technology.com, 2012). The earliest reference to iron in the region is by Abou-Obeid-El Bekhri in 1068 who records a mountain called "Idrar en Ouzzal" in Berber, which translates as the mountain of iron. However, the iron deposits in the F'Derik area were probably known and worked in antiquity and several have Berber names such as "El Hadid" meaning iron and "El Meiss" meaning magnet (Oksengorn, 1973; O'Connor and others, 2005). Marot and others (2003) comment that since antiquity the economic history of northern Mauritania has been dominated by Berber nomads and the Trans-Saharan trade. Since at least the 10th century, the Trans-Saharan road of the West, from Morocco to the black kingdoms of sub-Saharan Africa, passed by the water wells of Tiris and Zemmour. These caravans transported copper (from Akjoujt), salt from the saltworks of Ijil, and especially gold from the Senegal River. By the 14th century, accounts of travellers mention the "Iron Mountain" of the Zouérate area (Marot and others, 2003).

In 1900, the free Spanish convention on the sovereignty of Rio de Oro granted the saltworks of Ijil (and consequently the huge iron resources) to France, which was followed by the first geological expeditions in the region (Marot and others, 2003). The first modern reference to the iron deposits is a brief record in the Imperial Mineral Resources Bureau for 1922 which records under Mauritania the remark "Iron ore is said to occur in the Tagant and Ijil districts where traces of native workings are reported to have been found. The ore is not now being worked". A further brief reference in 1933 records the use of iron ore in the construction of Fort Gouraud (F'Derik)and the first geological studies in 1937 and 1939 identified iron ore in Kediat Ijil (O'Connor and others, 2005).

Miferma (Mines de Fer de Mauritanie) was created in 1952 to exploit iron ore deposits in the Kediat Ijil (Kediat is the Arabic word for "range"), a prominent range composed almost entirely of BIF sticking well above the flat geology of the underlying Tiris Complex. A mining center was constructed at Zouérate off the northeastern flank of the Kediat, together with port facilities at Nouadhibou on the Atlantic coast. Both facilities have their own power plants and are linked by a 700-km railway (Mining-technology.com, 2012).

Nationalization of the Miferma consortium in 1974–1975 created SNIM (Société Nationale Industrielle et Minière). The Mauritanian government now owns 78 percent of SNIM and Arab financial and mining organizations own the balance. Production rapidly grew to 11–12 Mt/y, a level that has generally been maintained by serial upgrading of the facilities (Mining-technology.com, 2012).

Open-pit mining of direct-shipping hematite ore, using rotary drills, small shovels and trucks, commenced in 1963 at the F'Derik, Rouessa and Tazadit pits. The TO14 deposit, discovered in 1991, is a deep orebody of direct-shipping grade located at the southeastern limit of the Kediat Ijil. Primary and secondary crushing is done at Tazadit and the ore is railed to

Nouadhibou in trains of up to 220 cars, each carrying 84 tonnes. The ore is stockpiled then reclaimed, crushed and screened for loading into vessels of up to 150,000 dwt. SNIM scheduled the start of work on a second loading facility for 180,000 dwt ships during 2005 (Mining-technology.com, 2012).

As the high-grade direct-shipping ore was being depleted, a crushing plant for lower grades was installed at Rouessa in 1973. Thereafter, the Algoma-type Guelb el Rhein magnetite resource just to the north-northeast of Zouérate was developed. Economics required that the lower grade magnetite ores should be upgraded for rail haulage and a 6 Mt/y plant was built at Guelb el Rhein. Primary crushing and autogenous grinding is followed by magnetic and gravity separation (Mining-technology.com, 2012).

Exploitation of a new, direct-shipping-grade ore discovery at Guelb El Mhaoudat, 50 km further east, began in 1991. The road and rail infrastructure was again extended and new equipment was purchased. The new equipment was used to mine the harder Guelb el Rhein magnetite and the equipment there was moved to Guelb El Mhaoudat. When TO14 was discovered close to Tazadit in 1991 it was developed immediately using equipment from Guelb el Rhein and other Kediat Ijil mines (Mining-technology.com, 2012).

In the late 1990s, SNIM upgraded the terminal handling facilities at Nouadhibou, commissioning new tertiary and quaternary crushing and screening at the Point Central plant to maintain production at 12 Mt/y. A 960 t/h regrinding circuit at the Guelb el Rhein plant opened in November 2000 (Mining-technology.com, 2012).

Recent investment has further upgraded Guelb el Rhein and modernized the railway. In April 2006, the SNIM board announced plans to increase output to permit the export of 14 Mt/y ore by 2010, primarily by adding new equipment at the Guelb el Rhein and TO14 mines (Mining-technology.com, 2012). Furthermore, this project would be the first stage of a progressive capacity hike to 25 Mt/y. In March 2007, SNIM and Sphere signed a Memorandum of Understanding with Saudi Basic Industries Corporation and Qatar Steel Company covering joint development of the Guelb El Aouj project, subject to a satisfactory bankable feasibility study (Mining-technology.com, 2012).

5.1.1 The Kediat Ijil

As described above, the Kediat Ijil is a prominent range of hills trending east-west in a roughly triangular shaped block between the towns of Zouérate and F'Derik (fig. 5). The range is approximately 25 km long and 15 km wide at the widest point. As currently mapped (O'Connor and others, 2005), outcrop of the Kediat Ijil covers approximately 170 square kilometers (km^2) based on Geographic Information System (GIS) measurements. The entire inselberg is thought to consist of an allochthonous (or para-autochthonous) series of thrust nappes composed almost entirely of iron formation and associated sedimentary rocks of the Ijil Complex and overlying Seyala Formation (O'Connor and others, 2005). The Kediat Ijil as well as the Guelb El Mhaoudat were transported southwestward during the Birimian orogeny from 2,100 to 2,000 Ma and now lie approximately 130 km to the southwest of the Archean-Proterozoic suture zone marked by the El Mdena Fault (figs. 6-8; Schofield and Gillespie, 2007). Although all attempts to directly date the Ijil Complex have failed, the shallow marine platformal nature of the associated sedimentary rocks, the contrasting nature of the jasper-rich BIF of the Ijil Complex with the ferruginous quartzites of the Tiris Complex, and geologic relationships with other directly dated rock units suggest that the Ijil Complex is Paleoproterozoic in age and represents Superior-type BIF that was deposited on the northeastern passive margin of the Archean Rgueibat Shield.

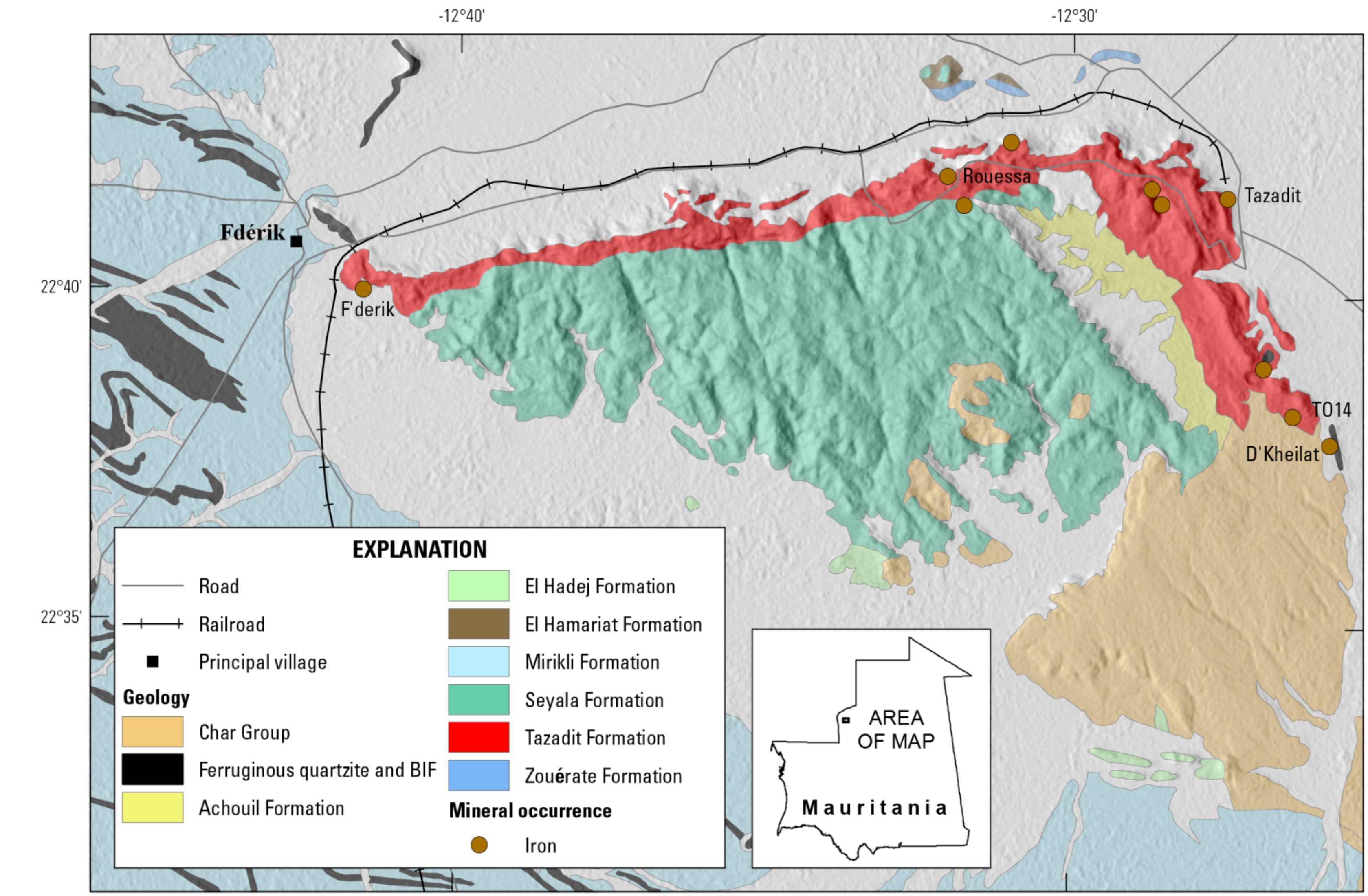

Figure 5. Geology of the Kediat Ijil and locations of major iron deposits.

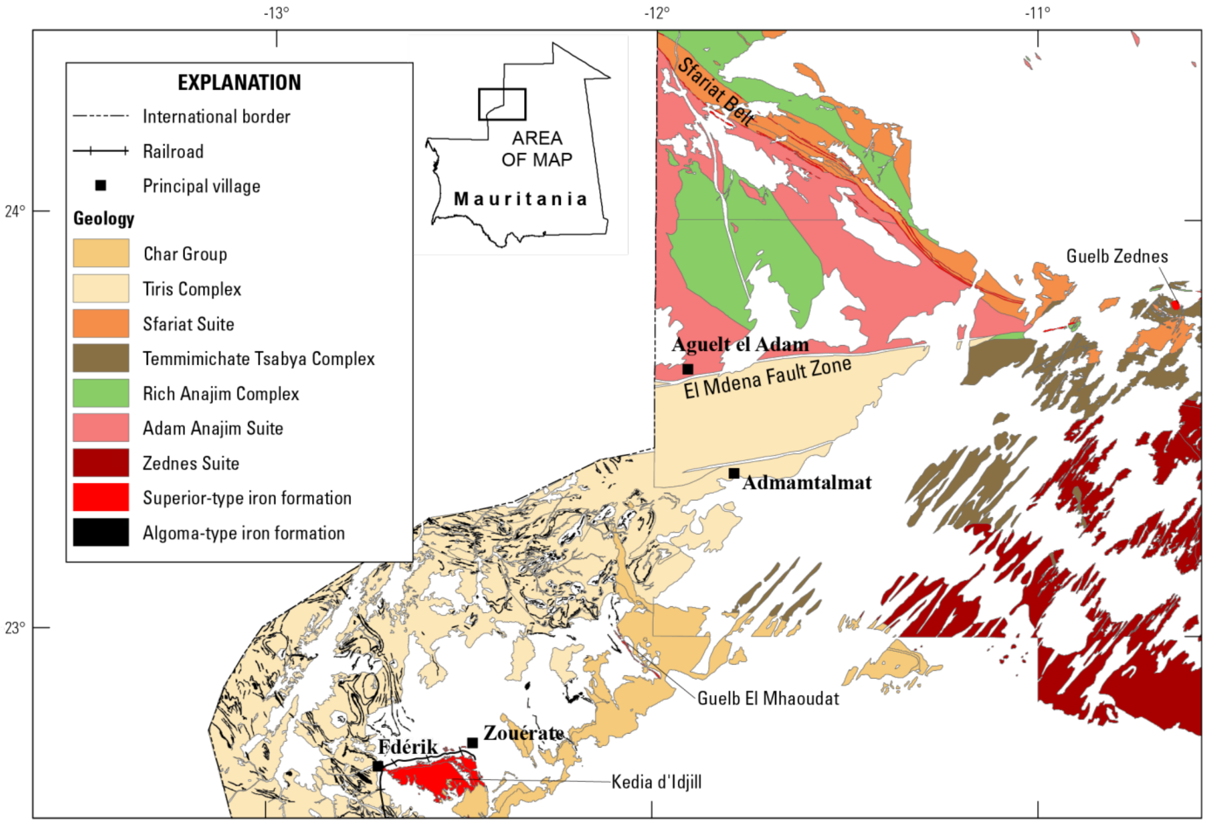

Figure 6. Geology of the northeastern margin of the Mesoarchean Rgueibat Shield showing the Paleoproterozoic suture zone marked by the El Mdena Fault and the location of the Kediat Ijil and Mhaoudat inselbergs to the southwest of the margin. Mesoarchean Algoma-type BIF is shown in black. Paleoproterozoic Superior-type BIF is shown in red.

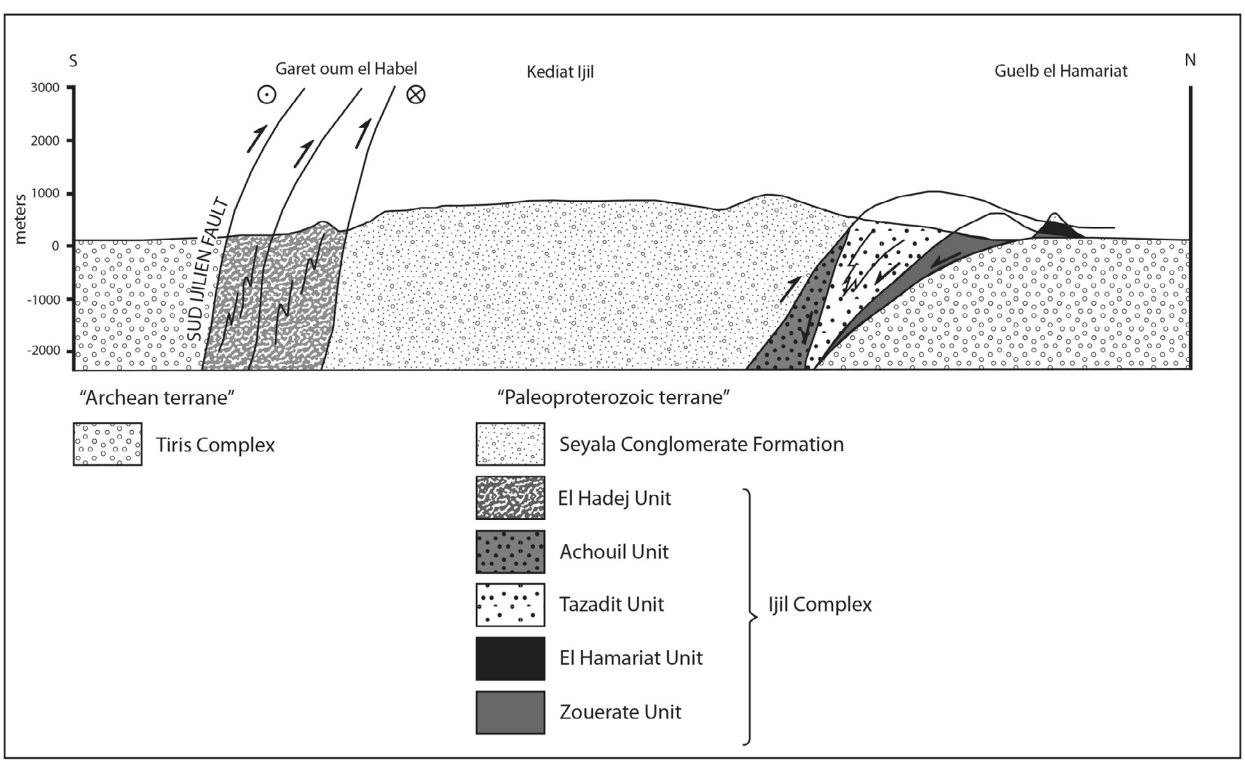

Figure 7. Schematic cross-section of the Kediat Ijil showing possible allochthonous structural relationships with the Tiris Complex basement (modified from Schofield and Gillespie, 2007).

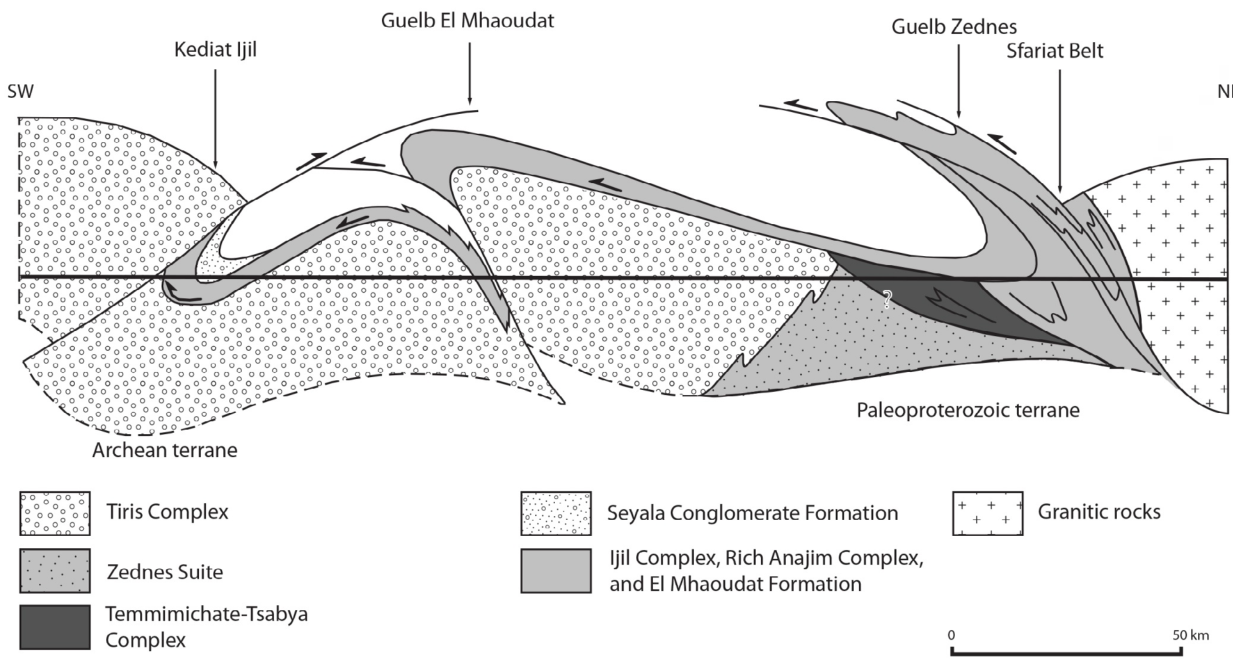

Figure 8. Schematic cross-section showing hypothetical Birimian thrust faulting relationships of Paleoproterozoic Superior-type iron formation on the northeastern margin of the Mesoarchean Rgueibat Shield (modified from Schofield and Gillespie, 2007).

The Kediat Ijil consists of six lithostructural units that occur as a series of stacked thrust nappes overlying the Tiris Complex (Bronner and Chauvel, 1979). The structurally uppermost unit is a breccia or conglomerate that is relatively undeformed and is clearly younger than the other five units. BGS work in the area (O'Conner and others, 2005) redefined the Ijil Complex to include the first five units, which have been given formation status. These include, from the base to the top: the Zouérate, El Hamariat, Tazadit, Achouil, and El Hadej Formations (fig. 7). The Ijil Complex is dominantly composed of greenschist to amphibolite facies metasedimentary rocks including quartzite, ferruginous quartzite (BIF) micaceous quartzite, and mica-quartz schist. Igneous rocks and carbonates are virtually absent.

The lowest two lithostructural units, the Zouérate and El Hamariat Formations are only present in outcrops at Guelb Hammariat and several other small inselbergs located just to the north of the Kediat Ijil and west of Zouérate (fig. 5). The Zouérate Formation, from the base upwards consists of micaceous quartzite and mica schist overlain by a thick (approximately 50 meters), concordant, sheet of metagabbroic rock, overlain by garnet-bearing muscovite-quartz schists. The metagabbro is the only known igneous rock in the Ijil Complex and appears to have been emplaced prior to the thrust stacking of the Complex. Attempts to date the metagabbro by the BGS were unsuccessful (O'Connor and others, 2005).

The central portion of the Zouérate Formation is obscured and the upper portion consists of quartzite and ferruginous quartzite that is strongly tectonized towards the top. This upper contact is strongly rodded and exhibits downdip mineral lineations. The contact is overlain by an l-tectonite breccia that represents the structural discontinuity between the Zouérate Formation and the overlying El Hamariat Formation. The El Hamariat Formation consists primarily of a quartz-pebble metaconglomerate that also preserves downdip mineral lineations and is considered an l-tectonite. Both of the formations dip moderately to the north and have been juxtaposed along a moderately inclined, north-dipping reverse fault (O'Connor and others, 2005; Schofield and Gillespie, 2007). Both formations each contain a thin carbonate horizon (calcite, ferroan calcite, dolomite and ferroan dolomite) several meters thick (Bronner and Chauvel, 1979). The upper part of the El Hamariat Formation consists of a thick (approximately 100 meters) unit of muscovite schist. The top of the El Hamariat Formation is also marked by a thrust fault that separates the formation from a unit of immature conglomerate that is assigned to the Seyala Formation that caps the Guelb el Hamariat (O'Connor and others, 2005).

The Tazadit Formation is the thickest and most voluminous unit of the Ijil Complex and due to its high proportion of BIF represents the protore as well as the host rock for the majority of the HIF resources that have been mined to date from the Kediat Ijil. It forms a narrow northern and eastern margin to the Kediat Ijil, roughly 1.6 km thick, that trends mostly east-west and dips steeply to the south. The formation wraps around and trends north-south at the eastern end of the inselberg. This unit forms the crest of the range as well as the dramatic northern scarp (figs. 5, 9, and 10).

The petrographic and stratigraphic features of the Tazadit Formation are described in detail by Bronner and Chauvel (1979) based on drill core, thin section, and the excellent outcrops exposed in the roadcut between Zouérate and the Tazadit #1 iron mine (fig. 9). The Tazadit mine road exposes a nearly continuous 1,000 meter thick sedimentary section that according to Bronner and Chauvel (1979) is composed of three repeating cycles of quartzite, mica schist, microbanded quartzite, mesobanded quartzite, mesobanded IF, and microbanded IF. Red jasper appears in the upper parts of each cycle. The lowermost two cycles are thinner than the uppermost cycle which accounts for perhaps two thirds of the thickness of the Tazadit Formation and extends from approximately mid-way between points c and d to point h on the Tazadit mine road (fig. 9, upper right) where it is overlain by the Achouil Formation (figs. 9 and 11). Portions of the stratigraphy are repeated by folding and there are several "complex" zones in which several of the above facies are intermixed and have reduced thicknesses (Bronner and Chauvel, 1979). In practice, SNIM geologists divide the Tazadit Formation into: (1) a lower member consisting of the first two cycles described above and the lower portion of the third cycle, consisting of quartzite, mica schist and the lower portion of a microbanded IF unit; and (2) an upper member consisting of a higher proportion of meso- and microbanded BIF. A fault zone near point d (fig. 9) separates the two members and is shown in figures 12 and 13. On average, lower member BIF units contain approximately 30 percent iron (figs. 14 and 15) whereas the upper member BIF units contain approximately 38 percent iron (Szymon Oksengorn, SNIM, oral commun., October, 2007). The upper member of the Tazadit Formation is therefore a better protore for the occurrence of HIF and explains why most of the exploited mines in the Kediat Ijil are hosted within the upper member (fig. 16).

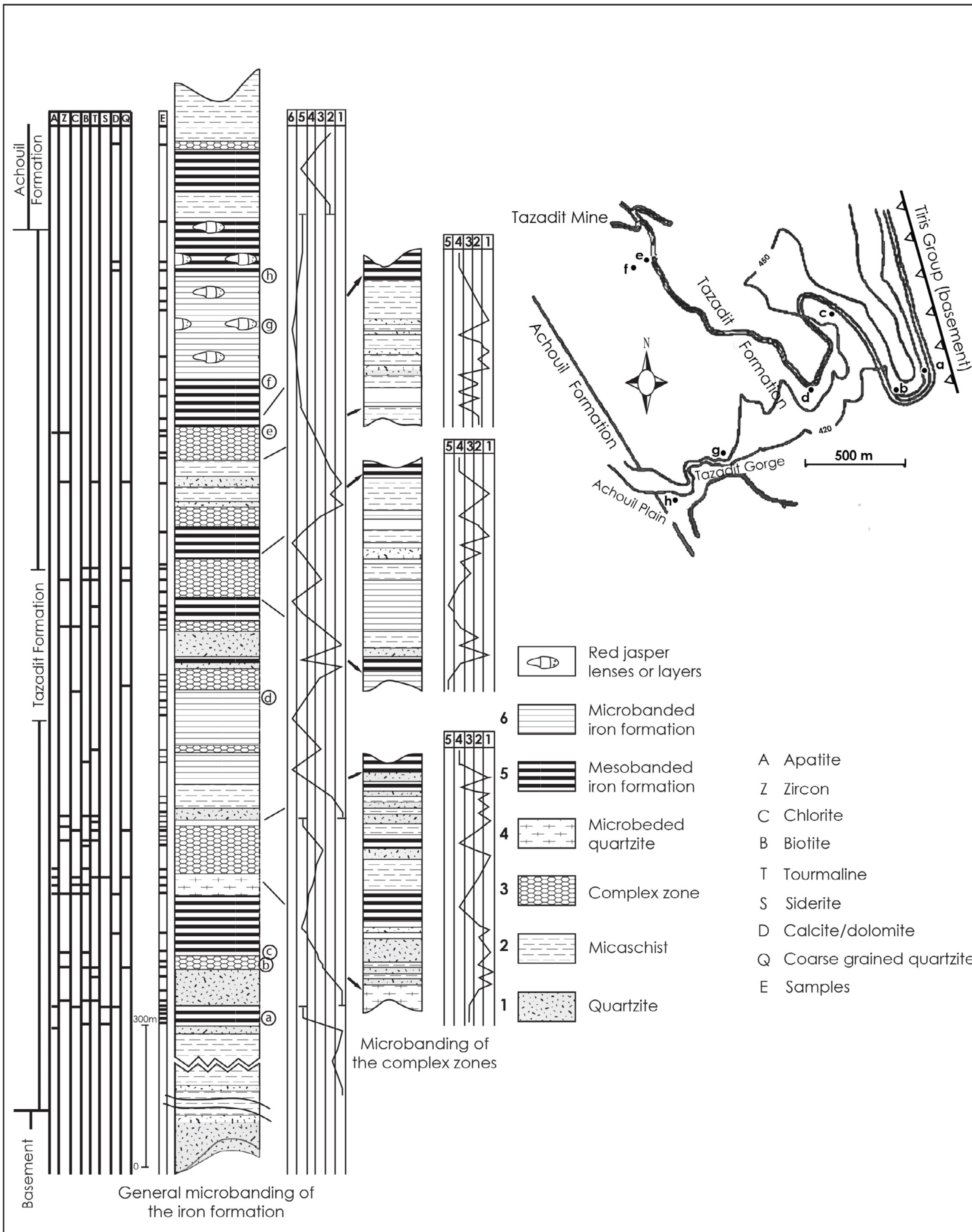

Figure 9. Lithologic column and plan map of the Tazadit Formation along the road from Zouérate to the Tazadit #1 mine (modified from Bronner and Chauvel, 1979).

Figure 10. View looking eastward at the northern flank of the Kediat Ijil from the western end of the range near F'Derik. USGS photo.

Figure 11. View southward from road to the Tazadit #1 pit, point d, of the eastern end of the Kediat Ijil showing westward-dipping BIF of the Ijil Complex-Tazadit Iron Formation and the Seyala Formation capping the horizon. USGS photo.

Figure 12. Profile through section along road to the Tazadit #1 pit, point d.Fault at right separates lower (right) and upper (left) members of the Tazadit Formation. Location of samples CT07RIM33-1 through 5. USGS photo.

Figure 13. Profile through section along road to the Tazadit #1 pit, point d.Fault at left separates lower (right) and upper (left) members of the Tazadit Formation. Location of samples CT07RIM33-1 through 5. Also location of geochronology samples DB07RIM-46a (quartzite in lower member) and DB07RIM-46b (muscovite schist in lower member for Ar/Ar). USGS photo.

Figure 14. Profile through section along road to the Tazadit #1 pit.Close-up of lower member of the Tazadit Formation, banded quartz-hematite IF. Location of sample CT07RIM33-1. USGS photo.

Figure 15. Profile through section along road to the Tazadit #1 pit.Close-up of the lower member of the Tazadit Formation, blocky quartzite interbedded with muscovite schist. Location of sample CT07RIM33-2. Also location of geochronology samples DB07RIM-46a (quartzite in lower member) and DB07RIM-46b (muscovite schist in lower member for Ar/Ar). USGS photo.

Figure 16. View along road into the Tazadit #1 pit. Upper member of the Tazadit Formation. USGS photo.

The lowermost unit within the Kediat Ijil is thought to consist of the Zouérate Formation although this relationship is entirely concealed by Cenozoic talus aprons and alluvial deposits (Schofield and Gillespie, 2007). The Tazadit Formation and the overlying nappes consisting of the Achouil, El Hadej and Seyala Formations structurally overlie the Tiris Complex basement along a sole thrust that was described by Bronner and Chauvel (1979) based on exposure in an exploration trench at the northeastern margin of the Kediat Ijil as a very thick zone of crushed rock. USGS field examination of this trench in October, 2007 was inconclusive due to lack of exposure of the critical contact with the Tazadit Formation at the top of the trench (fig. 17). However, cataclastic (fig. 18) and mylonitic textures (fig. 19) were observed in rocks of the Tiris Complex in the lower portion of the trench.

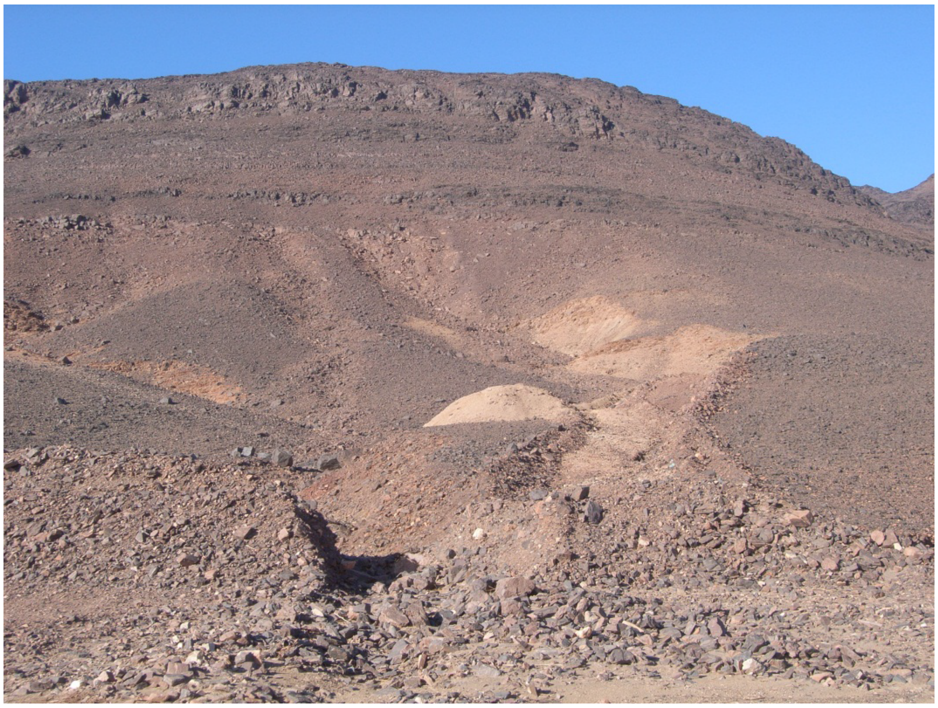

Figure 17. View looking west at trench exposing the basal thrust between the Tazadit Formation and the Tiris Complex basement.East end of the Kediat Idjil. USGS photo.

Figure 18. Cataclastic rock textures in trench exposing the basal thrust between the Kediat Idjil and the Tiris basement. USGS photo.

Figure 19. Mylonitic rock textures in trench exposing the basal thrust between the Kediat Idjil and the Tiris basement. USGS photo.

The Achouil Formation lies structurally above the Tazadit Formation and is exposed almost exclusively in the floor of the Achouil Valley that cuts through the northeastern portion of the Kediat Ijil (fig. 5). The formation contains an approximately 70-m-thick BIF unit near the base, but otherwise consists entirely of weathered, fine grained muscovite-biotite±garnet schist. The contact with the structurally overlying Seyala Formation runs along the western margin of the Achouil Valley and is mostly concealed beneath Cenozoic deposits. Where observed, this contact is strongly tectonized (O'Connor and others, 2005).

The El Hadej Formation is exposed in a series of small guelbs (guelb is the Arabic word for "hill") just south of the southern margin of the Kediat Ijil (fig. 5). The formation consists of quartzite, micaceous quartzite, mica schist, garnetiferous mica schist, hornblende-bearing mica schist and ferruginous quartzite. Ferruginous quartzite marks the crest of the guelbs which strike ESE to SE. In the vicinity of Garet Oumm el Habel the formation dips moderately (approximately 45 degrees) to the south-southwest. At Guelb el Hadej the formation curves eastward and disappears beneath Taoudeni Basin sedimentary rocks. On the north side of Garet Oum el Habel the formation dips steeply (approximately 80 degrees) to the south along a tectonic contact with the Seyala Formation. Relationships with other units of the Ijil Complex are obscured by Cenozoic cover, however, bore hole and magnetic data suggest that the Achouil and Seyala Formations are bounded to the southeast by the El Hadej Formation. Aeromagnetic data suggest that the contact between the El Hadej Formation and the Tiris Complex takes the form of a steeply dipping tectonic contact marked by abundant quartz along the southern margin of Garet Oum el Habel (Bronner and Chauvel, 1979; O'Connor and others, 2005).

The Seyala Formation is by far the most widespread unit within the Kediat Ijil. With an outcrop area of approximately 115 km^2, the Seyala Formation comprises approximately 68 percent of the main mass of the Kediat Ijil. It structurally overlies the Ijil Complex along structural contacts with the Tazadit Formation along most of its northern margin and with the Achouil Formation along the southwestern scarp of the Achouil Valley on the northeastern margin. The majority of the southwestern and southern contact with the El Hadej Formation is obscured by Cenozoic talus and alluvial deposits with the exception of the steeply dipping structural contact previously described that may represent a north-verging back thrust (O'Connor and others, 2005).

The Seyala Formation consists of a heterogeneous assemblage of clastic rock in which two major types of lithic clasts; rounded to oblate-shaped clasts of white to pale yellow quartzite and angular clasts of BIF, are set in a dark colored, fine grained matrix of iron oxide and silica (fig. 20). Clast sizes range widely from millimeter to greater than meter scale and are typically 2-60 centimeters in diameter. Proportions of clasts to matrix, types of clasts, and size range of clasts vary on the scale of an outcrop to that if the entire formation. Also, within the BIF clasts, a wide variation in the scale of banding, proportion of iron to silica, and proportion of magnetite to hematite is observed from outcrop to formation scale (O'Connor and others, 2005).

Figure 20. The Seyala Formation conglomerate in outcrop to the south of the Rouessa open pit. USGS photo.

The origin of the Seyala Formation has been the subject of a variety of interpretations. Bronner referred to it as the Ijil Breccia and suggested that it is essentially a tectonic melange (Bronner, 1970; Bronner and Chauvel, 1979). The BGS concluded that the formation is a sedimentary conglomerate based primarily on the structural setting in which it occurs (O'Connor and others, 2005; Schofield and Gillespie, 2007). They envision that the conglomerate is a proximally derived molasse or olistostrome eroded from an uplifted thrust block of the Ijil Complex. The proximal nature of the unit is reflected in the near-total lack of sedimentary features and the striking structural contrast between the polydeformed Ijil Complex and the undeformed Seyala Formation, suggesting a younger age than the structurally underlying Ijil Complex. O'Connor and others (2005) renamed the unit and gave it formational status, separate from the Ijil Complex.

5.1.2 Guelb El Mhaoudat

A second klippe or inselberg of BIF interpreted to consist of Paleoproterozoic Superior-type iron formation is located approximately 50 km to the northeast of the Kediat Ijil at Guelb El Mhaoudat. Guelb El Mhaoudat is a NW-SE trending, sinuous ridge approximately 18 km long and less than 1 km (typically 300–600 m) wide that rises above the plain of Tiris Complex basement rocks to a height of approximately 250 meters (figs. 21 and 22). Similar to the other major outcrop areas of Superior-type BIF in Mauritania, the Guelb El Mhaoudat is regarded as an allochthonous (or parautochthonous) package of rocks that formerly occupied a more northeasterly position on the northeastern passive margin of the Mesoarchean Rgueibat Shield and was transported during the Birimian orogeny to its present location. However, in contrast to the relatively flat-lying Kediat Ijil and Guelb Zednes, Guelb El Mhaoudat is a steeply dipping rock package that is interpreted to have been imbricated with the surrounding Tiris Complex during Birimian compression and thrusting as were Superior-type BIF occurrences in the Sfariat Belt (fig. 8: Schofield and Gillespie, 2007).

Figure 21. View of Guelb El Mhaoudat from the southwest. USGS photo.

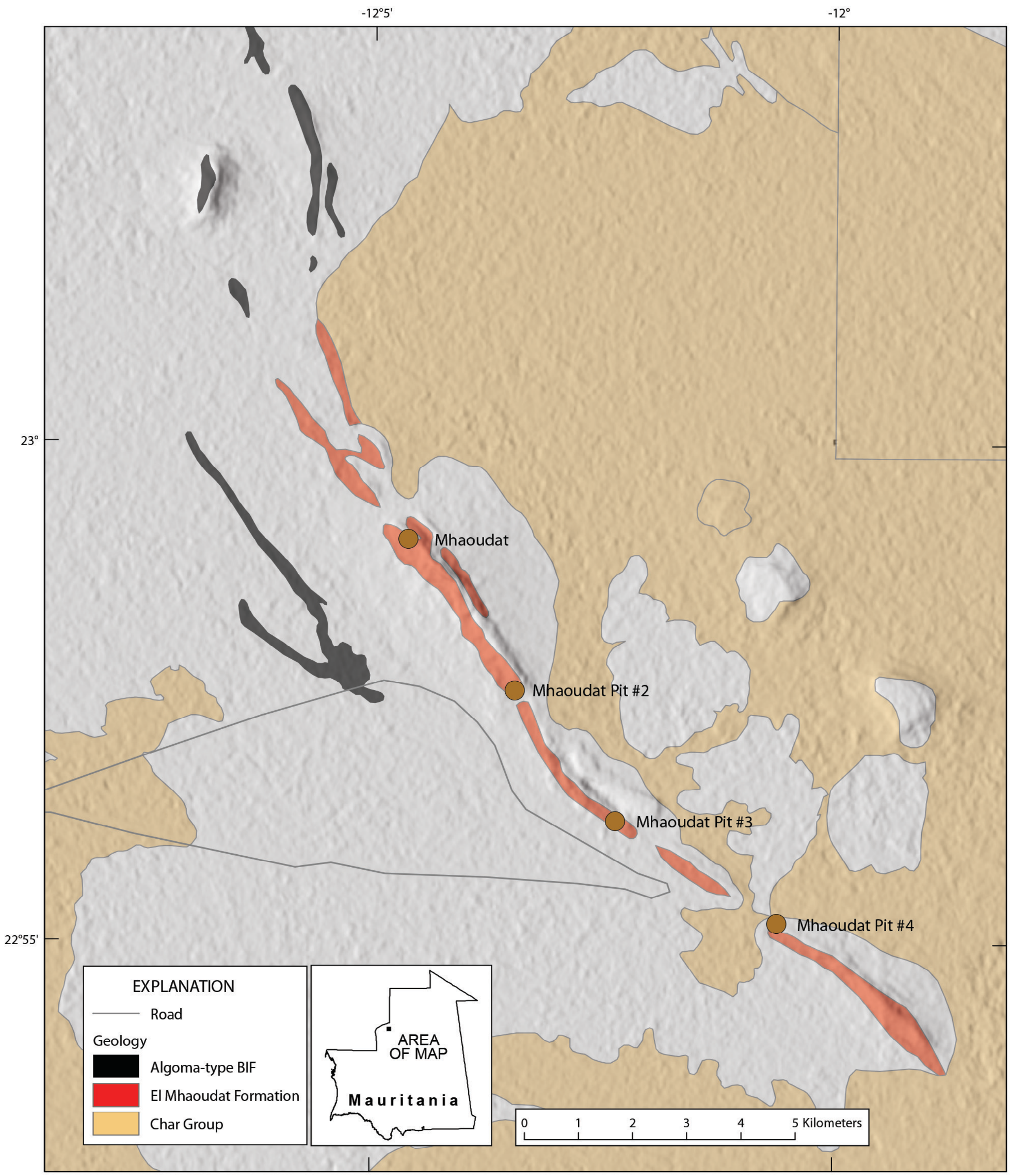

Figure 22. Geology of Guelb El Mhaoudat showing the locations of major open pits.

The entire rock package at Guelb El Mhaoudat is similar to the Kediat Ijil in that it consists mostly of ferruginous quartzite and lesser quartzites and mica schists. However, the entire Guelb is included in a single unit; the El Mhaoudat Formation. The El Mhaoudat Formation primarily contains variably micro- to mesobanded iron formation characterized by minor red jasper, hornblende, and carbonate minerals. Weakly ferruginous quartzite and quartzite with minor tourmaline or garnet is the next most abundant lithology followed by various facies of fine grained schist containing quartz, muscovite, and chlorite with variable amounts of iron oxide and tourmaline. Sedimentary facing indicators are sparse, however, Bronner (1988) concluded that grading of jasper clasts in quartzite beds indicate an up direction to the southwest. The rock package dips steeply to the northeast suggesting that it was overturned during imbrication and thrusting (O'Connor and others, 2005).

Structural interpretations suggest that the El Mhaoudat Formation is bounded on the northeast and southwest sides by steeply northeast dipping, sub-parallel fault zones (Bronner and Fourno, 1992; O'Connor and others, 2005). Bronner (1988) described a contact consisting of a 10-meter-wide zone of strongly sheared, recrystallized, and mylonitized, chlorite altered rock separating schist and quartzite of the El Mhaoudat Formation from gneiss of the Tiris Complex. USGS examination of the southwestern margin of Mhaoudat pit #2 confirmed the presence of a steeply NE dipping fault zone in chlorite altered schist in the southwestern pit wall grading into weakly ferruginous quartzite and greenschist and then into mesobanded BIF over a distance of approximately 10 meters (fig. 23). The range disappears under the Char Group sandstones to the southeast and based on Audio-magnetotelluric (AMT) and aeromagnetic data, continues into the Taoudeni basement for approximately 15 km (Bronner and Chauvel, 1979; Bronner and Fourno, 1992; Finn and Anderson, 2015; fig. 24). AMT data suggests that the El Mhaoudat Formation continues under regolith cover for an additional 6 km beyond the northwestern outcrop of the range. The steeply dipping eastern and western thrust faults merge about 10 km to the northwest of the northwestern extremity of the range placing the northeastern Archean Tiris Complex basement over the southwestern Archean basement (Bronner and Fourno, 1992).

In detail, the Guelb El Mhaoudat range is broken into a series of shorter, relatively straight segments of 2 to 4 kms in length that are separated by topographic gaps or passes (cols) through the range. Bronner (1988) and Bronner and Fourno (1992) have noted that the locations of the passes correspond to areas of thinning of the El Mhaoudat Formation and disappearance of red jasper in the ferruginous quartzites. Significantly, these passes are also the sites of upgrading of BIF to high grade hematitic ore and are the principal mine sites throughout the range (fig. 22). Thinning of the El Mhaoudat Formation and subsequent silica dissolution, oxidation, and upgrading of BIF at these locations was attributed to tensional tectonic forces and metamorphism of the range causing the formation of kilometer-scale boudins. An AMT study along four profiles across the range and supplemented by drill hole data suggests that the eastern Mhaoudat thrust fault dips to the northeast at a relatively uniform 75 to 85 degrees along the length of the range (Bronner and Fourno, 1992). However, the western thrust fault dips initially steeply but becomes progressively less steep and joins the eastern thrust at progressively greater depths along the length of the range from northwest to southeast (fig. 25). The result is a steeply dipping lens of El Mhaoudat Formation that becomes deeper and wider along the range until it disappears under the edge of the Taoudeni Basin at the southeast extremity of the range. Based on their work, Bronner and Fourno (1992) estimated that the vertical thickness (depth from surface) of the El Mhaoudat Formation is approximately 500 meters at profile P2, 700 meters at P3, and 900 meters at P4 (fig. 25). USGS geophysical studies suggest that the much of the covered extensions of the range lie at less than 700 meters depth (fig. 26: Finn and Anderson, 2015).

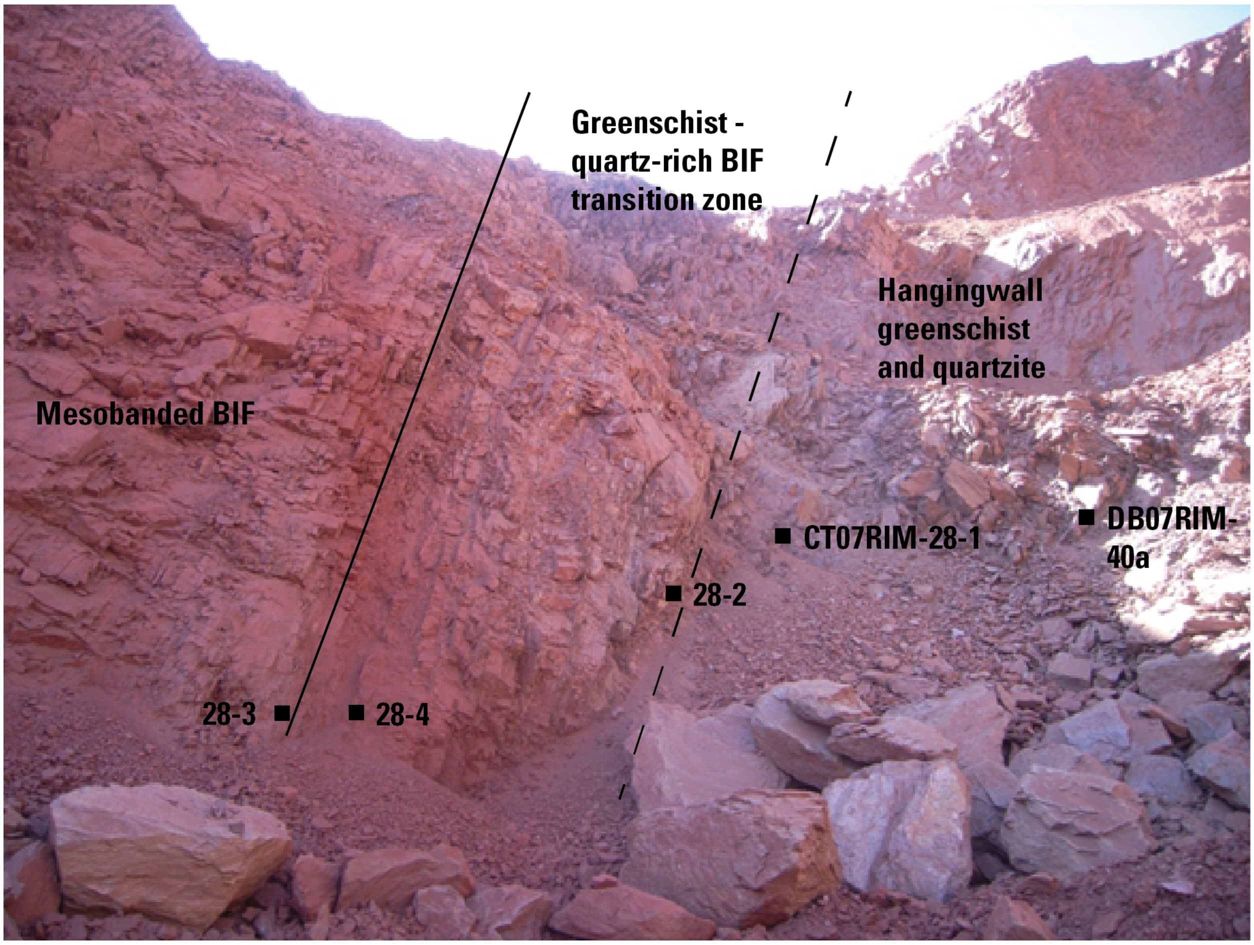

Figure 23. View looking southeast at fault zone in the southwestern wall of Mhaoudat pit #2. USGS photo.

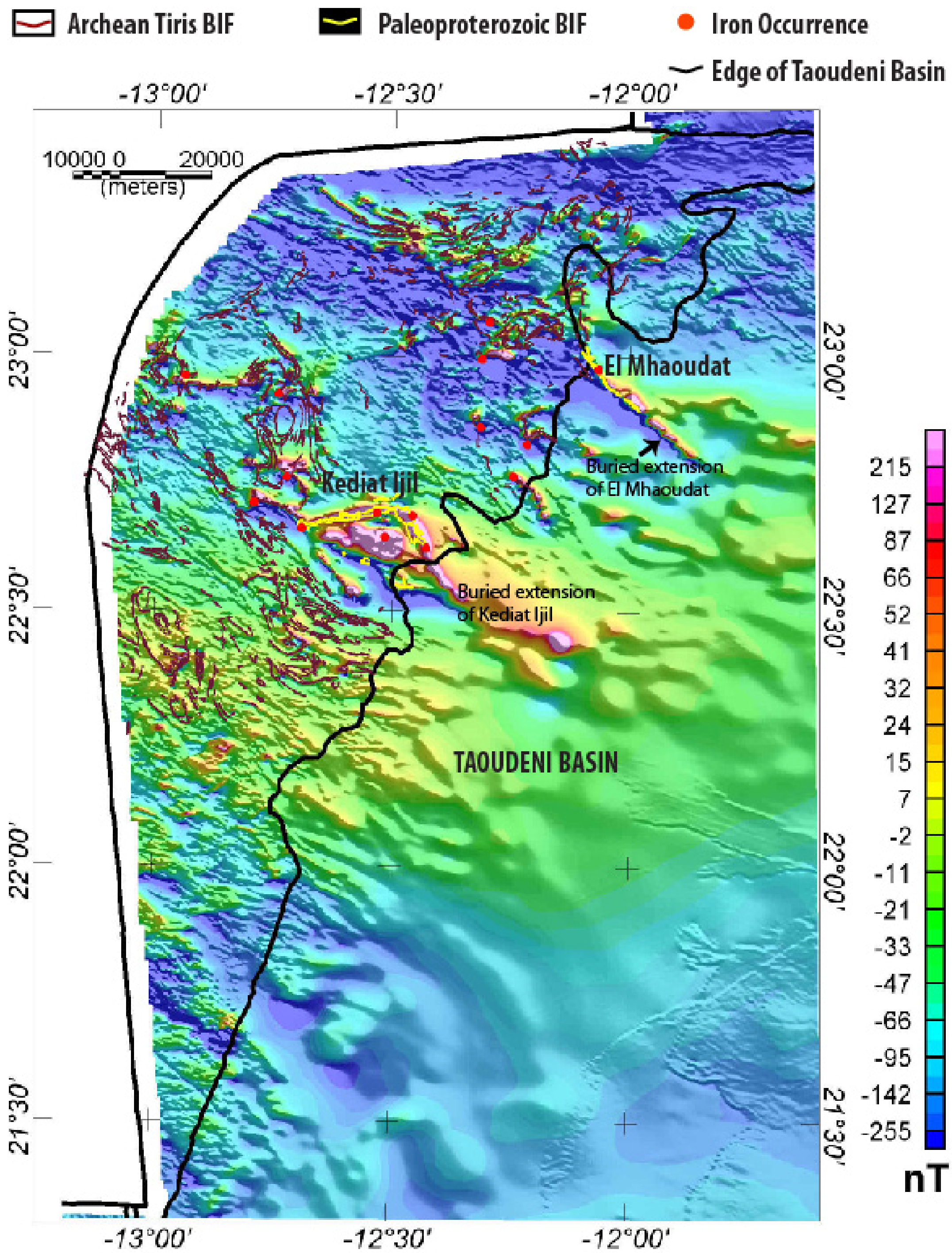

Figure 24. Color shaded relief image of the reduced to the pole magnetic data for the Tiris Complex (from Finn and Anderson, 2015) with mapped BIF units and locations of iron occurrences. Note the extension of both the Kediat Ijil and Guelb El Mhaoudat iron formation under the Taoudeni Basin margin.

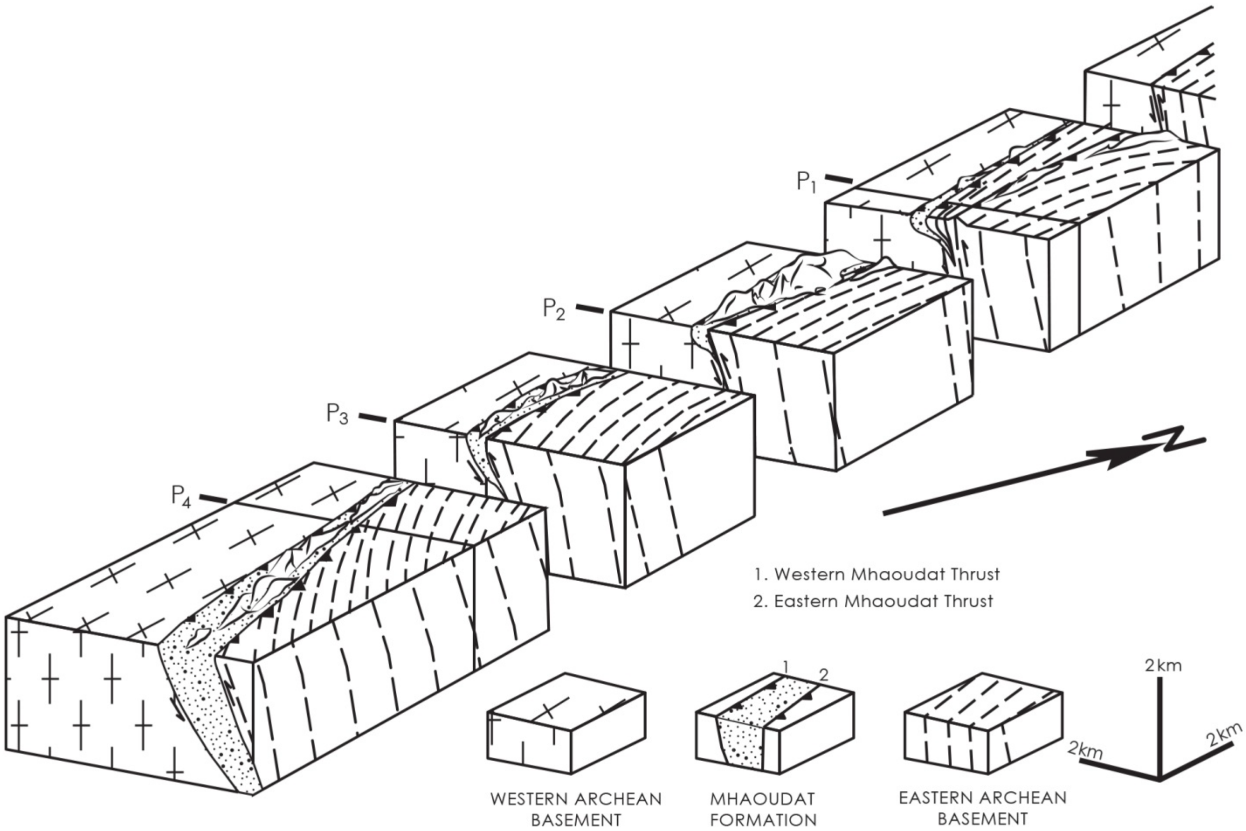

Figure 25. 3D geological interpretation showing the geometry of thrust faulting and the depth and thickness of the El Mhaoudat Formation along the length of the Guelb El Mhaoudat range (modified from Bronner and Fourno, 1992).

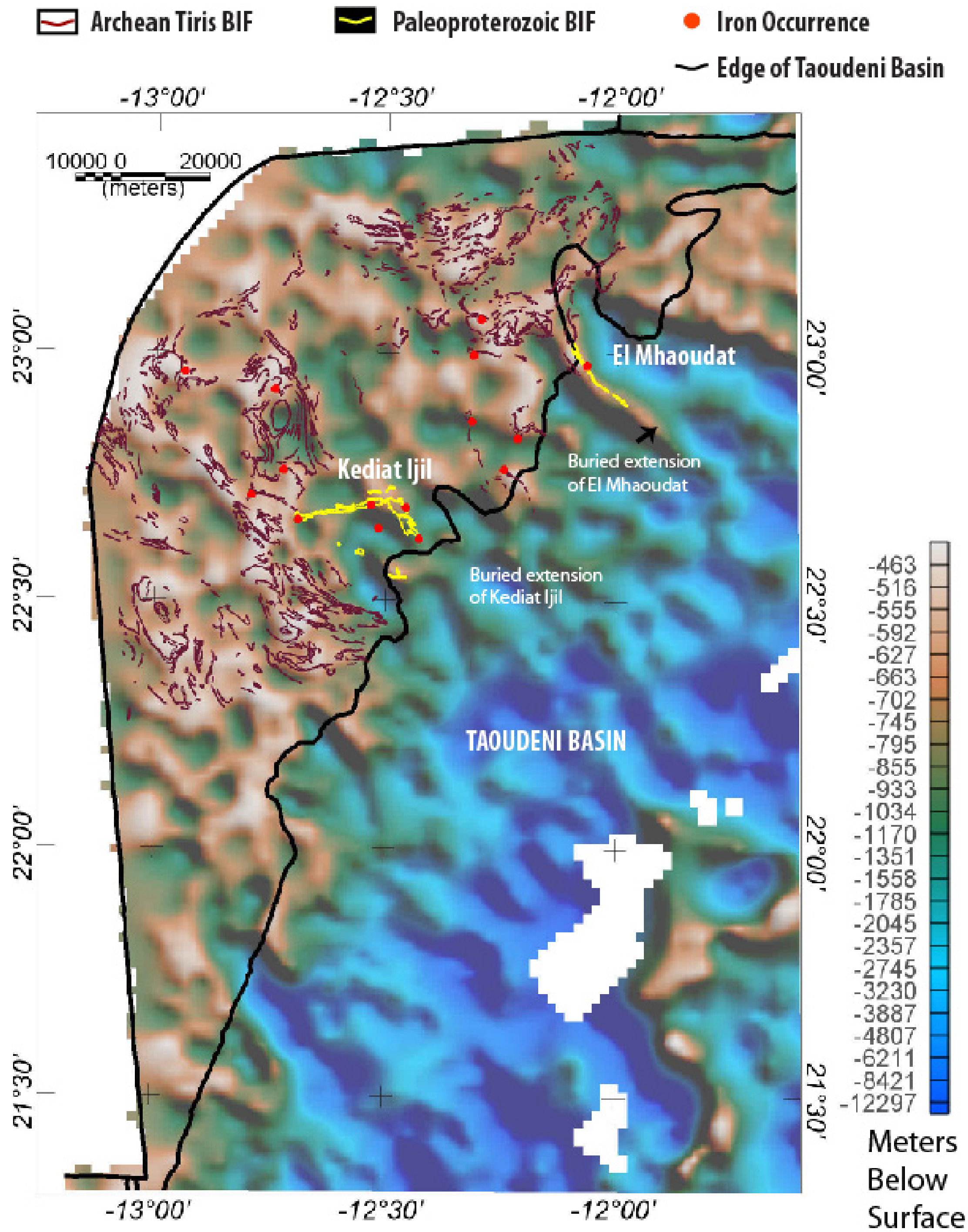

Figure 26. Color-shaded relief image of gridded depth estimates using the Extended Euler method (Phillips 2002). A structural index of 1 and a window size of 7 (3,500 m) were used with mapped BIF units and locations of iron occurrences (from Finn and Anderson, 2015).

5.1.3 Sfariat Belt and Guelb Zednes

An additional area of potential for Superior-type BIF in Mauritania consists of the Paleoproterozoic Sfariat Belt approximately 180 kms to the northeast of Zouérate, and Guelb Zednes. Four known iron occurrences are hosted in imbricated slices or klippes of iron formation along the suture zone between Mesoarchean and Paleoproterozoic rocks of the Rgueïbat Shield. Three occurrences, the Bouderga, Sfariat 1, and an unnamed occurrence are distributed along the northwest-southeast trending Sfariat Belt and are imbricated with Paleoproterozoic granitic rocks of the Adam Anajim and Sfariat Suites, and the Rich Anajim Complex. Marot and others (2003) describe the Sfariat Belt as a major zone of shearing and imbrication of all these constituent rock units that is approximately 175 kms long and up to 13 km wide. Mineral prospecting in the Belt, primarily for gold, has been concentrated on the ferruginous quartzite layers of the Rich Anajim Complex. A fourth iron occurrence is present at Guelb Zednes approximately 225 km to the east-northeast of Zouérate. Guelb Zednes is a more nearly flat-lying inselberg composed of sedimentary rocks and iron formation of the Guelb Zednes Formation of the Rich Anajim Complex that allochthonously overlies Mesoarchean rocks of the Temmimichate Tsabya Complex near the southeastern terminus of the Sfariat Suite (fig. 27).

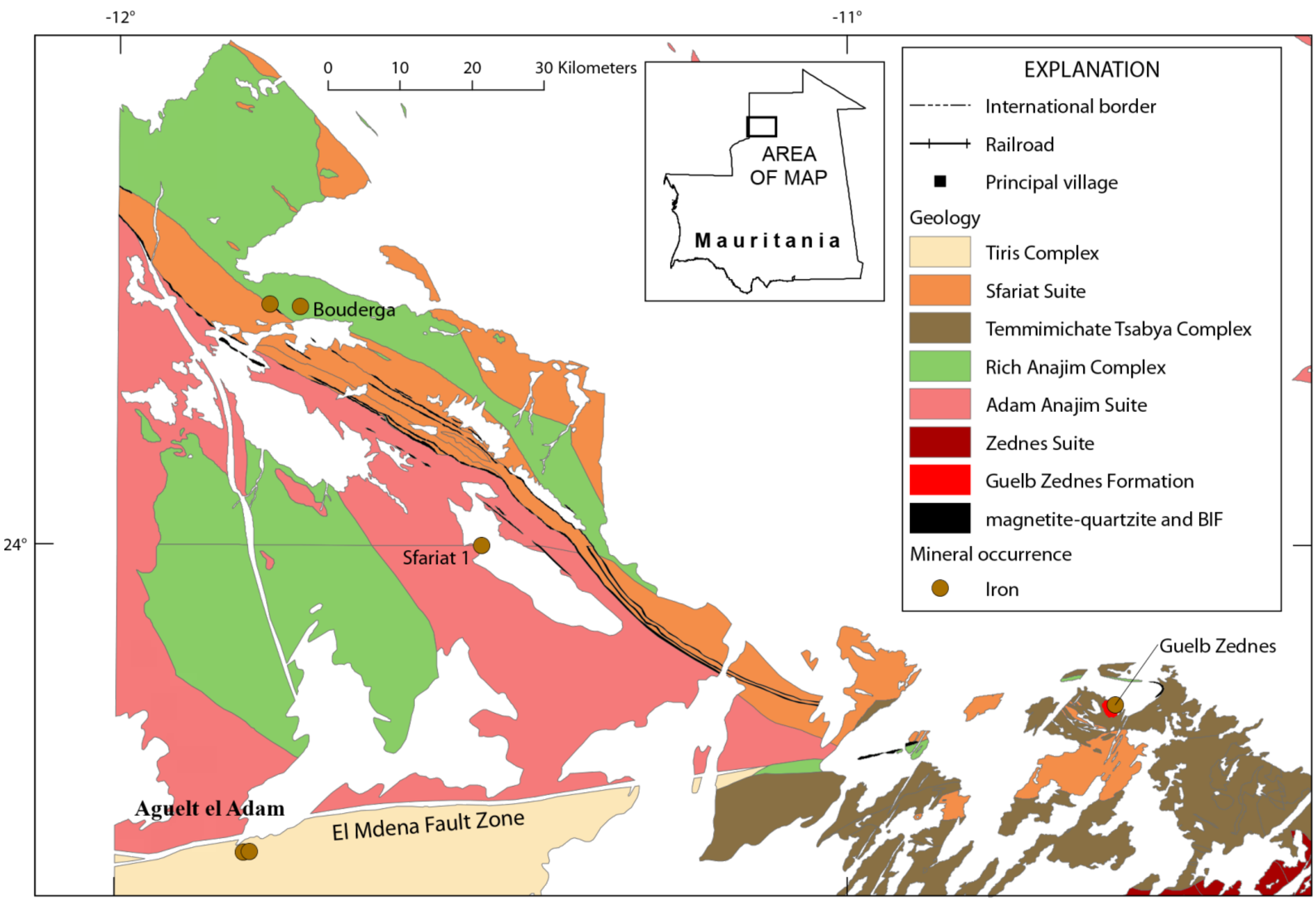

Figure 27. Simplified geology of the Sfariat Belt and Guelb Zednes showing locations of Superior-type iron occurrences.

The Rich Anajim Complex is a metamorphosed early Birimian (>2,150 Ma) group of primarily metamafic volcanosedimentary rocks consisting of metapyroxenites, amphibolites, dolomitic marbles, magnetite quarzites and migmatitic paragneiss that constitute broad mapped areas on both sides of the Sfariat belt in the southwestern portion of the Paleoproterozoic Shield. The southern outcrop area lies wholly within the granitic rocks of the middle Birimian Adam Anajim Suite and the northern outcrop area lies between the latest Birimian Sfariat Belt and granitic rocks of the Gleibat Tenebdar Suite. The Rich Anajim Complex is divisible into lithostratigraphic packages consisting of gabbros and basalts thought to be of back-arc origin, a set of closely associated ferruginous quartzites and marbles, and a paragneiss suite derived from pelitic and calcareous sandstones. The ferruginous quartzites form resistant ridges that vary from 2 to 10 meters in width and are composed primarily of magnetite, quartz, and hematite. Iron content of these BIF units ranges from 30 to 35 percent (Lahondère and others, 2003).

The latest Birimian (2,020–2,000 Ma) Sfariat Suite consists primarily of migmatitic granitoids that are interpreted to have been produced by anatectic melting of the older Rich Anajim supracrustal rocks. They outcrop primarily between the ferruginous quartzite ridges of the Rich Anajim Complex and consist of mylonitized corridors of penetratively deformed biotite-, garnet-, and cordierite-bearing granites and granodiorites. Foliation in these rocks is generally subvertical and trends west-northwest-east-southeast parallel to the ferruginous quartzite ridges (Lahondère and others, 2003).

The ferruginous quartzites (map unit RAqz; Lahondère and others, 2003) form dark colored, resistant ridges that are generally 2–10 m thick and of highly variable length, with mapped outcrops approaching 70 km in length. They are usually closely associated with impure dolomitic marbles that reach thicknesses of several tens of meters but that are laterally impersistent. The ferruginous quarzites are generally fine grained, but can reach grain sizes of several centimeters. The mineralogy consists of quartz, hematite and magnetite, minor apatite and rare detrital zircon (Bronner, 1992).The ferruginous quarzites exhibit micro- to mesobanding (mm- to cm-scale) corresponding to variations of the proportion of quartz compared to opaque minerals (Lahondère and others, 2003).

Guelb Zednes represents an outlier of the Rich Anajim Complex that rests unconformably on steeply inclined gneisses of the Mesoarchean Temmimichate Tsabya Complex. The guelb rises about 160 meters above the surrounding regolith plain and consists of gently southeastward dipping sedimentary rocks of the Guelb Zednes Formation (map unit RAgz; Lahondère and others, 2003). Like the Kediat Ijil, The basal contact of the Guelb Zednes Formation with the underlying Mesoarchean basement is strongly sheared, suggesting that Guelb Zednes is an allochthonous klippe or inselberg. The distinguishing feature of the Guelb Zednes Formation is a more than 100-m-thick unit of magnetite-rich quartzites that form the upper two thirds of the Guelb. The lower third is composed of quartz-mica-garnet-kyanite schists, brecciated metagabbros and amphibolites, and metaconglomerate (Lahondère and others, 2003; Schofield and Gillespie, 2007).

Marot and others (2003) assigned a low potential for the discovery of economic iron deposits, citing the generally low iron grades and insignificant thicknesses of the iron formation. However, Marot and others (2003) mention previous descriptions by Sougy (1952) and Rocci (1957) of potentially folded segments of iron formation in the Sfariat Belt that reach thicknesses of 80 and 100 m, respectively, and note that the magnetite-rich layer at Guelb Zednes is in excess of 100 m thick (up to 130 m). Blanchot (1975) estimated that Guelb Zednes may contain approximately 300 million tonnes of low grade iron ore in magnetite-hematite-quartzite iron formation.

Some uncertainty exists regarding the assignment of the iron formation in the Sfariat Belt to either the Algoma- or Superior-type. Early workers in the Belt (Sougy, 1952; 1953; Rocci, 1957) assigned them to the Algoma-type based on an assumed Mesoarchaean age of the surrounding granitic rocks. Current work by the BRGM has established an early Birimian age for the host supracrustal rocks of the Rich Anajim Complex (Lahondère and others, 2003) and Marot and others (2003) place the iron formation in an Algoma-type context based on their field observations in the belt during the BRGM field campaign. An Algoma-type setting is also consistent with the volcanosedimentary nature of the Rich Anajim Complex, which has been suggested to have low potential for base metal deposits of volcanogenic massive sulfides (Taylor and Giles, 2015). Consistent with an oceanic or perhaps back-arc tectonic environment for the volcanosedimentary rocks of the Rich Anajim Complex, the geochemistry of the amphibolites and metagabbros in the Guelb Zednes Formation exhibit normal mid-ocean ridge to transitional basaltic signatures (Lahondère and others, 2003).

In contrast, Bronner (1992) and recently Schofield and others (2006) and Schofield and Gillespie (2007) have assigned a Superior-type origin to the Sfariat Belt iron formation based on the descriptions of shallow marine calcareous pelitic and dolomitic protoliths of the Rich Anajim supracrustal sequence and correlation of the Sfariat Belt iron formation to that of Guelb El Mhaoudat and Kediat Ijil. Schofield and Gillespie (2007) envision imbrication and tectonic transport of Birimian passive margin terrain outliers as allochthonous inselbergs containing Superior-type iron formation to their present position along the Mesoarchean Shield margin and overlying the Tiris Complex to the southwest. For the purposes of the current summary, iron formation of the Sfariat Belt and Guelb Zednes are considered permissive of Superior-type iron deposits. However, more work is required to discern whether they are of Algoma- or Superior-type.

5.2 Algoma-Type Iron Deposits in Mauritania

In the major iron-producing region around Zouérate Algoma-type magnetite-quartzite BIF deposits are hosted in the Mesoarchean Tiris Complex. Although initially famous for the abundance of high grade hematitic iron ores shipped from Superior-type deposits in the Kediat Ijil and Guelb El Mhaoudat, declining reserves of HIF ensure that the future of iron mining in Mauritania will be dependent on the successful exploitation of the abundant Algoma-type deposits. The Guelb El Rhein deposit 25 km to the north of the Kediat Ijil currently supplies the bulk of magnetite ore production. However, plans to put the Guelb El Aouj and Askaf North deposits in production will provide additional magnetite ores for years to come.

To the south of the Tiris Complex, Mesoarchean gneisses and granulites of the Amsaga Complex also contain Algoma-type BIF, as do the Mesoarchean metavolcanic rocks of the Lebzenia (Lebtheinia) Group in the greenstone belts of the Tasiast-Tijirit terrane to the west. Late Archean and Neoproterozoic metavolcanic rocks of the Inchiri district near Akjoujt also host prospective BIFs. These rocks include the Saouda and Oumachoueima Groups at Guelb Tamagot and at El Khader, respectively, and are being prospected by an Indonesian company (PT Bumi Resources Minerals Tbk) that has obtained an exploitation permit. El Khader is unusual in that it consists of a goethite cap to an iron oxide copper-gold prospect (see below). A second project in Saouda Group BIF, ~45 km southeast of Akjoujt, is being developed by TransAfrika Resources at their Kaouat project. They estimate a resource of 370 million tonnes at 30 percent iron based upon drilling and about 1.2 billion tonnes of in-situ BIF based upon geologic mapping, gravity, and magnetic surveys. Additional occurrences of Neoproterozoic Algoma-type BIF are known in the Ijibbitene massif to the southeast of the Akjoujt nappe pile. Finally, although not currently of economic interest, correlative Neoproterozoic iron formation is present in metavolcanosedimentary rocks of the Gueneiba and Gadel Groups of the southern Mauritanides.

5.2.1 Mesoarchean Tiris Complex

The Tiris Complex of the central Rgueibat Shield is a well-known area with high potential for magnetite iron resources requiring beneficiation to reach acceptable iron grades for export. The Tiris Complex is a granulite facies Mesoarchean metamorphic terrane marked by the ubiquitous presence of Algoma-type iron formation. In general, the complex consists of granite domes and intervening keels of supracrustal rocks that are crosscut by linear belts of tight folding and steeply dipping fabrics. The complex is estimated to consist of approximately 70 percent granite with the supracrustal rocks consisting of a mixture of aluminous cordierite- and biotite-bearing paragneisses, calc-silicate rocks, metamafites, quartzites, and magnetite-quartzite BIF (Schofield and others, 2012).

Geologic mapping in the Tiris Complex by the BGS (O'Connor and others, 2005) breaks the complex into three lithodemic units defined as the El Gheicha, Mirikli, and El Khadra Formations. Although correspondence of the units is not exact, the TRla unit of the BRGM mapping equates to the El Khadra Formation and the TRle unit of the BRGM (Lahondère and others, 2003) equates to the Mirkli and El Gheicha Formations. BGS work (O'Connor and others, 2005) further identifies mappable units of Algoma-type iron formation (unit TRfe), which are ubiquitous throughout the Mirikli and El Khadra Formations, but are rare in the predominantly aluminous gneisses of the El Gheicha Formation. The El Khadra Formation is completely enclosed by the Mirikli Formation and is present in the northern Tiris Complex. It is very similar to the Mirikli Formation and consists of lithologically variable quartzofeldspathic and calc-silicate metasedimentary and metaigneous rocks, but is distinguished by the greater proportion of metasedimentary rocks and the widespread occurrence of generally close-spaced bands of BIF (Schofield and others, 2012).

An Rb-Sr whole rock age of 2,779±84 Ma on the Mirikli Formation was obtained by Vachette and Bronner (1975) at Guelb El Rhein and is interpreted as the age of migmatization of the country rocks. Recent work in the Tiris Complex suggests that there have been two main phases of intrusive activity at 2,950–2,870 and 2690–2,650 Ma involving recycling of crustal material older than approximately 3,250 Ma (Schofield and others, 2012). Thus the supracrustal rocks of the Tiris Complex, including the Algoma-type BIF, can be no younger than approximately 2.95 Ga. Early tectonism, pre-dating the first intrusive episode, imparted a flat-lying high grade metamorphic fabric with recumbent folds (Schofield and others, 2012). Bronner (1992) suggested that this early isoclinal folding and thrust imbrication of a relatively small number of BIF horizons is responsible for their widespread distribution throughout the Tiris Complex.

The ferruginous quartzites are widespread and easily distinguished by their aeromagnetic response and by their tendency to form low ridges and guelbs that range in outcrop style from simple linear ridges of low relief that may be traced for up to several kilometers, to tightly and complexly folded features that form guelbs with rugged ridges and peaks rising several hundred meters above the surrounding plains and are fringed by broad talus aprons. Individual units are typically several meters thick and range from a few centimeters to 10 meters thick (O'Connor and others, 2005).Economic deposits form where thicker BIF units are doubled or tripled by thrust stacking or folding.Delineation of such targets can be effectively accomplished by filtering of the aeromagnetic data as displayed in figure 28 and explained in the section below.Numerous targets, both in outcrop and under shallow cover remain to be prospected.

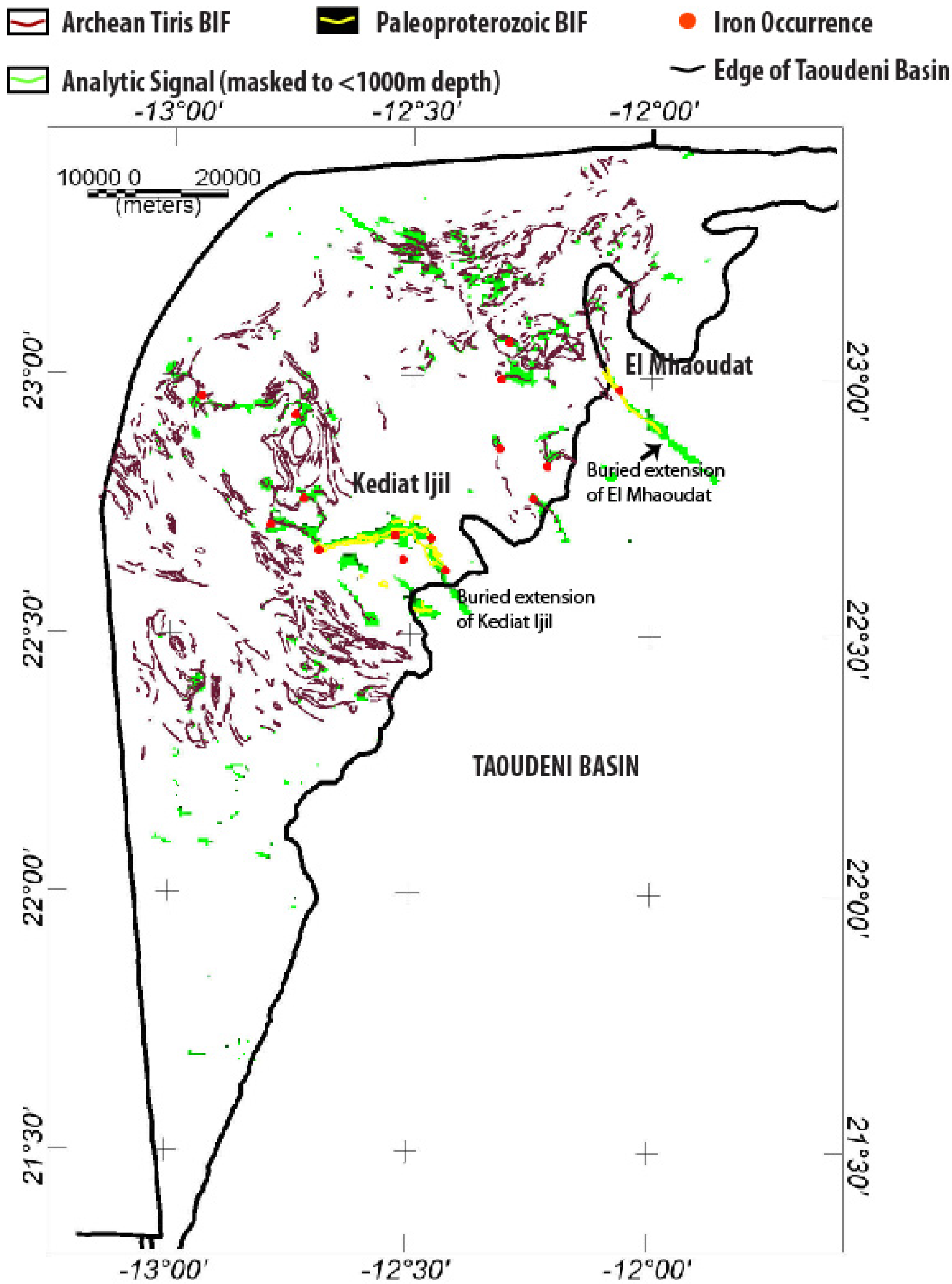

Figure 28. Analytic signal of the total field magnetic data above 0.75 (green) over regions where the depth to magnetic basement (fig. 26) is less than 1000 m with mapped BIF units and locations of iron occurrences. The green areas show new areas and extensions of mapped areas of BIF under cover.

There is an abundance of known occurrences of Algoma-type BIF in the Tiris Complex that are listed in the Mauritanian National Mineral Deposits Database (Marsh and Anderson, 2015), in addition to the producing mine at Guelb El Rhein, and the deposit nearing production at Guelb El Aouj. These include occurrences at Guelb Azouazil, Guelb Bou Derga, and Guelb

Atomai, which are generally referred to as the western guelbs, and Guelb Merizet, Guelb Oum Arwagen, Guelb El Meis and Tizerrhaf, referred to as the eastern guelbs. An additional four un-named occurrences are located approximately 60 to 75 km to the northeast of the Tizerrhaf occurrence in undifferentiated rocks of the TRle unit (fig. 4). All of these occurrences have similar short descriptive statements indicating that they all consist of bands or folded banks of magnetite-quartzite BIF hosted in high grade gneiss of the Tiris Complex. Most occurrences are described as “petite gisements”, many of which have undergone some artisanal mining. The Tizerrhaf and Guelb El Meis occurrences are perhaps the smallest. The most significant of these occurrences may be the Guelb Oum Arwagen, located to the east of Guelb El Rhein approximately half way between Zouérate and Guelb El Mhaoudat. Descriptions in the Mauritanian National Mineral Deposits Database (Marsh and Anderson, 2015) indicate that this occurrence may have been under consideration for development prior to the development of mines at Guelb El Mhaoudat. No additional information is available for these occurrences.

The Guelb El Rhein deposit is a prominent topographic feature located approximately 25 km northeast of Zouérate (fig. 29). The deposit consists of a single band of ferruginous quartzite that has been deformed into a series of tight km-scale folds that now form the crest and core of the Guelb. The ferruginous quartzite is hosted within the migmatitic gneisses of the Mirikli Formation of the Tiris Complex. A structural interpretation by Bronner (1992) shows folding of the BIF horizon into three stacked layers (fig. 30). The folded layers form an approximately north-south oriented synclinal structure that plunges gently and opens somewhat to the north. All three stacked bands are currently being mined at Guelb El Rhein in a series of open pits in successively lower levels of the Guelb (fig. 31).

Figure 29. View looking towards the southwest at Guelb el Rhein. Smoke in the foreground is from the magnetite magnetic concentration facilities and other buildings. USGS photo.

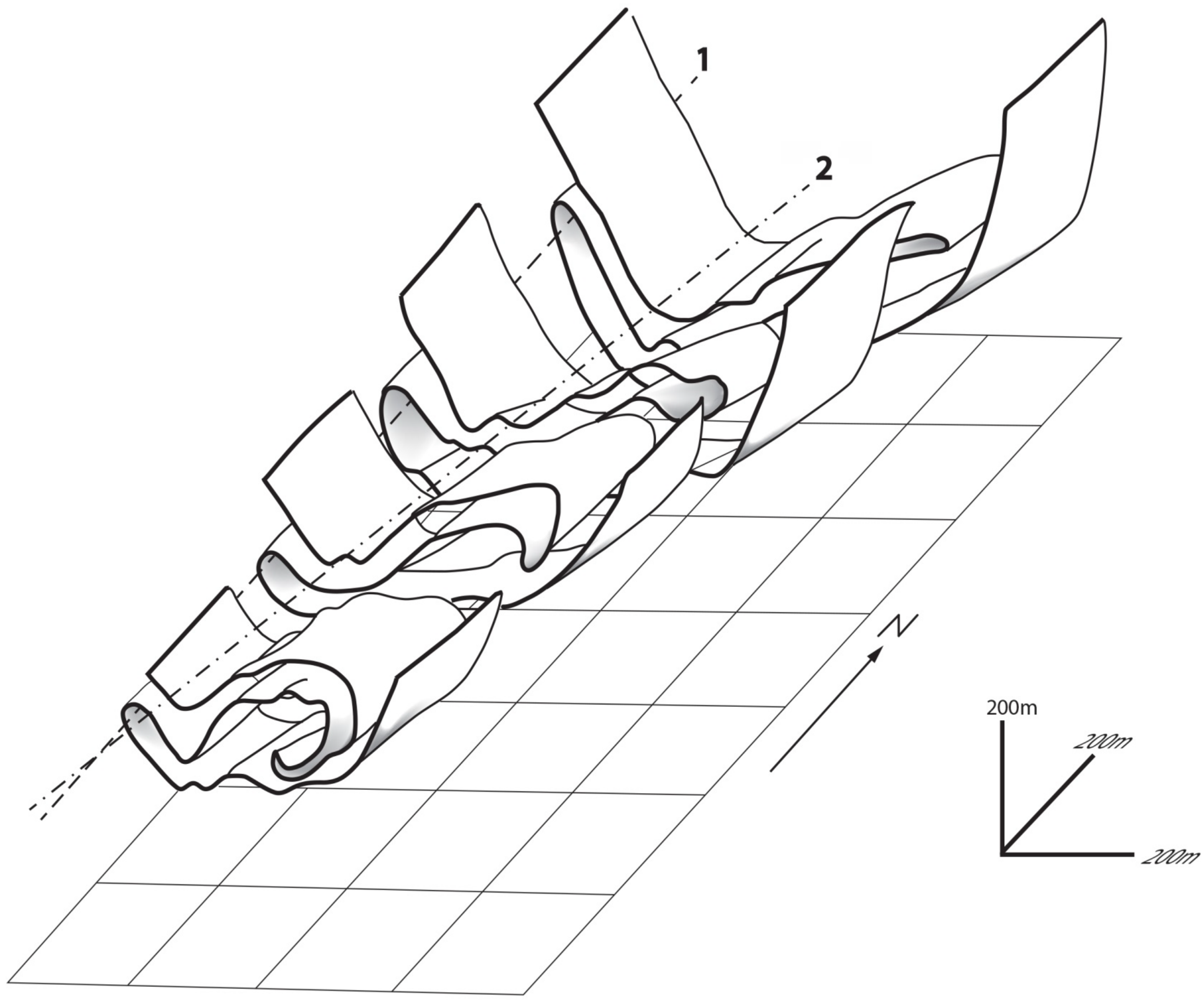

Figure 30. Structural interpretation showing the multiply folded geometry of the quartz-magnetite iron formation at Guelb el Rhein (modified from Bronner and others, 1992).

Figure 31. View of the main north-south open pit at Guelb el Rhein from the north end of the pit looking south towards the crest of the guelb. USGS photo.

Unlike the iron ore at Guelb El Mhaoudat and in the Kediat Ijil, the ore at Guelb El Rhein is relatively low grade, averaging approximately 34 to 37 percent iron, and has not been upgraded by leaching or oxidation to produce hematitic ores. A surface oxidation profile is present and extends commonly 30–50 m below the present surface and can extend to depths as great as 200 meters (Szymon Oksengorn, SNIM, oral commun., October, 2007; figs. 32 and 33). Hematite does form in the surface oxidation profile at the expense of magnetite. However, this is detrimental to iron ore recovery as the oxidized surficial ores respond less well to magnetic separation processing. In general, iron formation at Guelb El Rhein is massive and unbanded (fig. 34) and consists of approximately equal proportions of relatively coarse-grained (3–5 mm), equant, quartz and magnetite. It is accompanied by minor quantities of accessory amphibole, relict pyroxene, and rare trace sulfide minerals. Magnetite is separated from the gangue by crushing and grinding to liberate the magnetite crystals, then dry magnetic separation produces a 65 percent Fe concentrate (O'Connor and others, 2005). Annual production of crude ore is approximately 10 million tonnes, resulting in annual shipments of approximately 4 million tonnes of concentrate. Plans to install a second magnetic concentrator facility at Guelb El Rhein are expected to double these numbers (Tecsult International Ltd., 2009).

In 2001, SNIM formed a joint venture with Australia's Sphere Investments to study options for open-pit mining and beneficiation of the magnetite deposit at Guelb el Aouj (Sphere Investments Ltd, 2003; Sphere Minerals Ltd., 2012). The Guelb el Aouj deposit is located among the western guelbs approximately 35 km northwest of Zouérate (fig. 4). It consists of three distinct ridges (East, Center and West) of magnetite-quartzite and associated rocks that rise to a height of approximately 200 meters above the surrounding plain. A 2,200 m diamond drilling program was undertaken in 2004 to complement earlier drilling by SNIM in 1989 and 1990 as stage 1 of a Bankable Feasibility Study. Early attention was focused on the southern part of a tight isoclinal synform at El Aouj Center where BIF on the southwestern limb of the synform is 100–200 meters thick along a strike length of 2.4 km. The southwest limb remains open at depth along its entire strike length. Additional ore grade BIF is reported within the northeastern and northwestern limbs of the synform, which also remain open at depths greater than 50 m (O'Connor and others, 2005). Guelb el Aouj East also has a synclinal structure with magnetite-quartzite outcropping along a 4 km strike length of its thicker western limb. Guelb el Aouj West has significant magnetite quartzite outcrops over 3 km of strike length with favorable fold structures and a strong aeromagnetic signature (O'Connor and others, 2005).

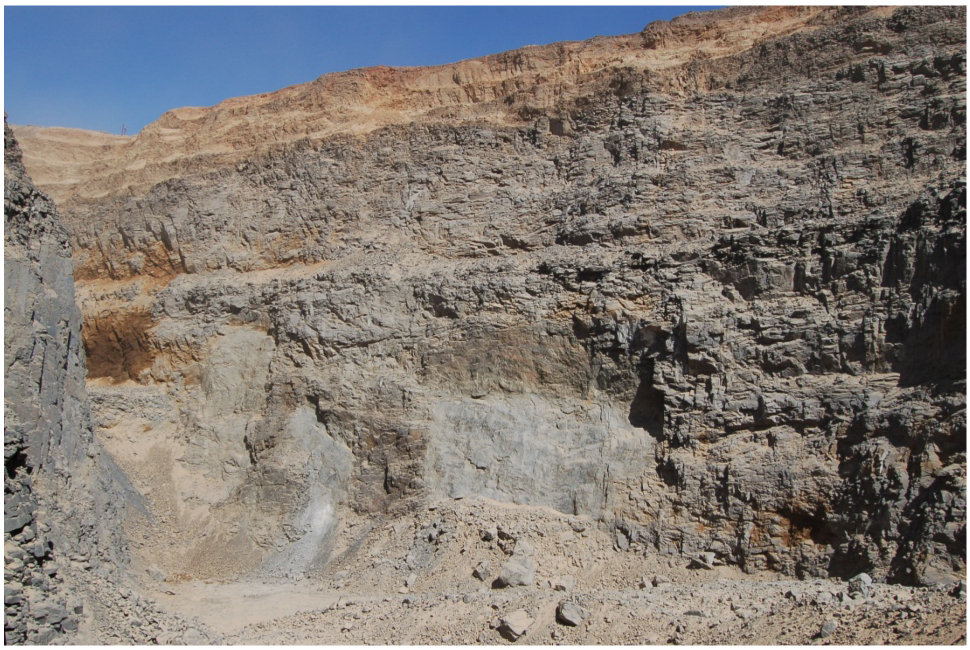

Figure 32. Northeast wall viewed from the floor of the Guelb El Rhein pit. Note prominent light orange oxidized profile extending downward approximately 30–50 meters from surface. USGS photo.

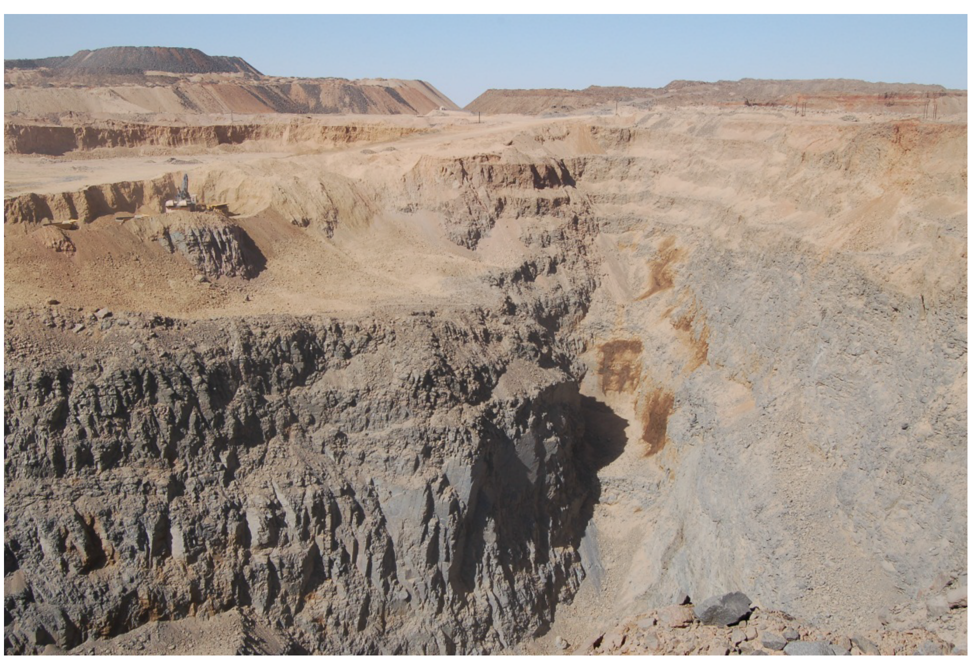

Figure 33. View looking to the northwest from the top of the Guelb El Rhein pit. USGS photo.

Figure 34. Massive, unbanded, unoxidized iron formation in west wall of Guelb El Rhein pit. Note presence of greenish pyroxene-bearing rock in footwall at left. USGS photo.

Surface mapping and drilling data show that there are three main ore types: (1) massive, unbanded, and generally coarse grained, (2) well-banded and typically fine grained, and 3) an intermediate type consisting of both fine and coarse grained magnetite-quartzite exhibiting discontinuous remnant banding. The magnetite-quartzite ore has been oxidized to a depth of about 40 m, so the weathered non-magnetic overburden is relatively thin. Other rock types associated closely with BIF at Guelb el Aouj Center are a basal (footwall) metagranite (leptynite), magnetite-bearing quartzite, and barren gray quartzite and locally magnetite-rich amphibolitic garnetiferous gneiss in the center (hanging wall) of the synform. The southwest limb is locally characterized by the presence of thin (less than 6 meter thick) concordant granitic bodies within the main magnetite-quartzite unit, particularly in its upper part. Two near-vertical basaltic dikes and one large, north-block-down normal fault cross-cut the deposit. The presence of amphibolite and the range of magnetite-bearing and barren quartzite lithologies is a fairly constant feature in the western Guelbs (O'Connor and others, 2005; Xstrata, 2011a).

Sphere Investments was granted a 30-year exploitation license on Guelb El Aouj in March, 2008. JORC-compliant reserves and resources reported by Sphere Investments in 2009 indicate proven and probable reserves at Guelb el Aouj East of 429 million tonnes grading 35.5 percent iron. Additional resources (measured + indicated + inferred) at Guelb el Aouj East total 701 million tonnes grading 36.3 percent iron with a 25 percent iron cut-off. Inferred resources are reported for Guelb el Aouj Center as 225 million tonnes grading 36 percent iron at a 20 percent iron cut-off (Sphere Minerals Ltd., 2012). As of mid-2009, Sphere Investments and SNIM planned to develop a new iron-ore mine, beneficiation plant and pelletizing plant to produce high grade direct reduction pellets for export based on the three Guelb el Aouj magnetite deposits (Center, East and West). Planned production was 7 Mt/yr of direct reduction grade pellets (Mining Journal, 2006). Two additional magnetite-quartzite occurrences to the south of Guelb el Aouj at Guelb Bou Derga (fig. 4) and Tintekrate (fig. 35) were under exploration by Sphere Investments and had a speculative resource of 800–1,050 million tonnes of magnetite-quartzite iron ore averaging between 35 and 37 percent iron. Sphere Investments Ltd. was acquired by

Xstrata in 2010 along with projects at nearby Askaf and Lebtheinia in the Tasiast-Tijirit terrane. As of December 2011, the Bankable Feasibility Study for Guelb el Aouj was under review by Xstrata (Xstrata, 2011a). Current reports mention drilling activity at Guelb Bou Derga and Tintekrate as well as continued evaluation of the Askaf project. The Askaf project encompasses a series of magnetite-quartzite guelbs to the east and west of the track leading into F'Derik from the south approximately 20 to 35 km south of F'Derik (fig. 36). Reported (JORC-compliant) resources in the Askaf project area are 394 million tonnes of magnetite-quartzite ore grading 35.7 percent iron at the Askaf North guelb. Seventy four percent of this resource is in the measured and indicated categories and there are an additional five magnetite-quartzite guelbs in the area that are under evaluation (Xstrata, 2011b).

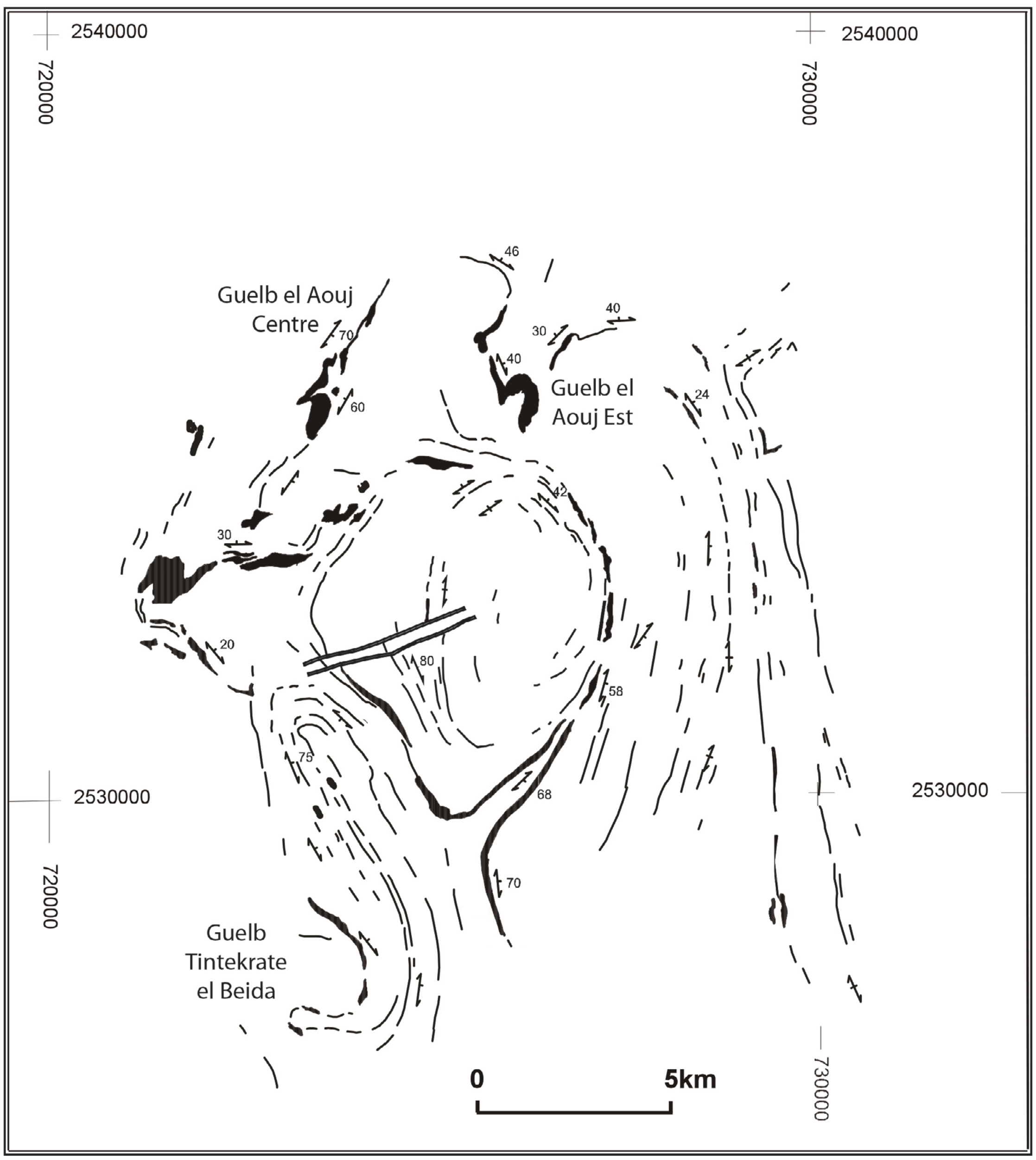

Figure 35. Sketch map of the Guelb el Aouj area showing major outcrops of Algoma-type iron formation in black, and structural trends. Location of the Tintekrat iron occurrence is also shown (modified from O'Connor and others, 2005).

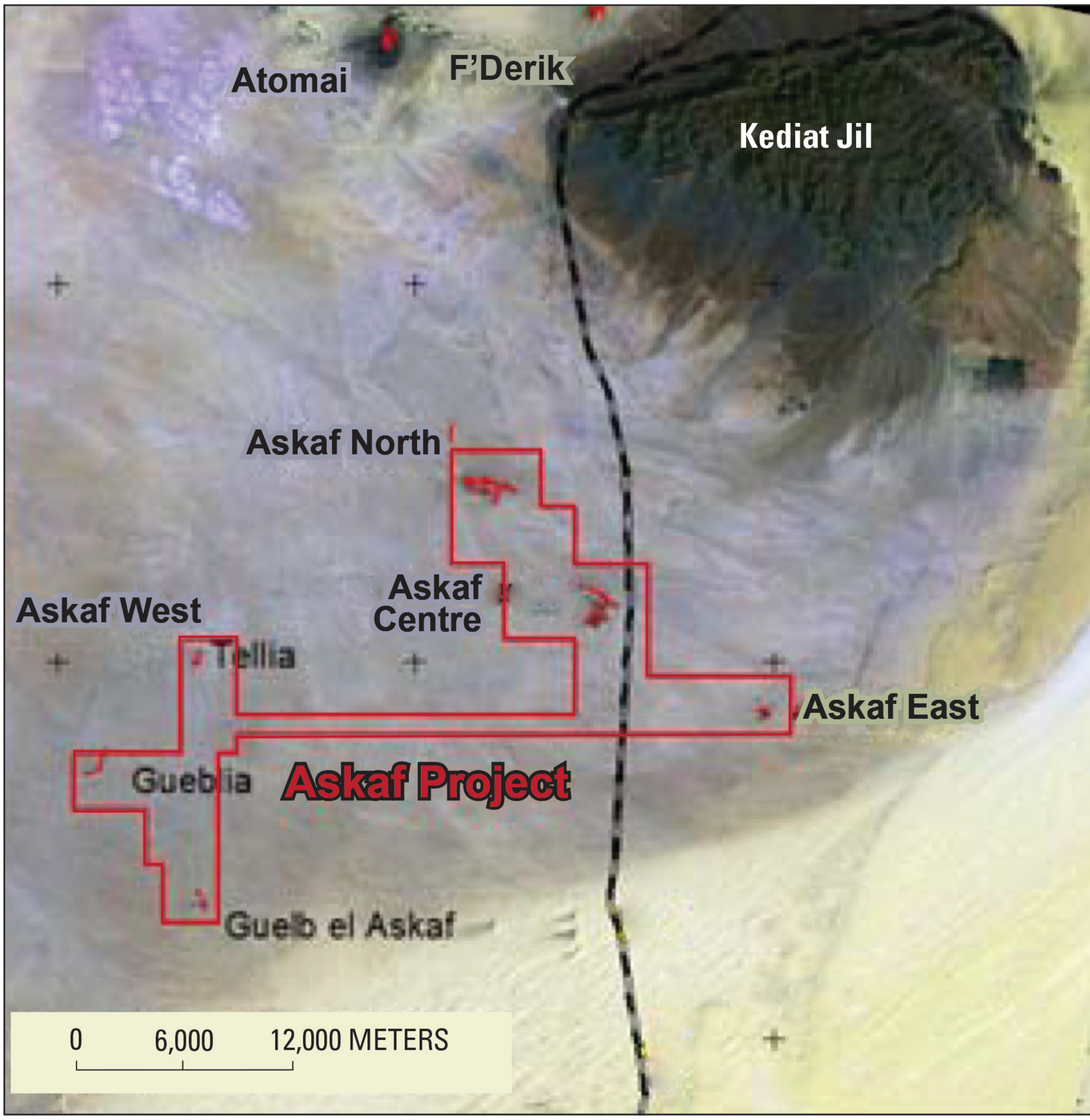

Figure 36. Location and approximate boundary of the Xstrata Askaf project area (modified from Xstrata, 2011b).

ArcelorMittal of Luxembourg also formed partnership with SNIM in 2008 and was reportedly drilling for magnetite ores at Guelb Agareb, located to the northeast of Zouérate and north of Guelb el Mhaoudat. Bronner (1992) describes two Guelbs Agareb (East and West) as synformally folded, kilometer-scale magnetite-quartzite bands that are oriented approximately northeast-southwest within a minor range of hills called the Kedia Leghnem. "Resources" of more than one billion tonnes of magnetite-quartzite may be present (Taib, 2010).

5.2.2 Geophysical Delineation of Banded Iron Formation (BIF)

The main targets for iron exploration are banded iron formations (BIFs). These can be clearly identified in aeromagnetic data whether at the surface or under sedimentary cover to depths of > 2 km. Radiometric data can help delineate surficial BIFs. Magnetite BIFs are very magnetic, with measured susceptibilities of nearly 1 SI (Finn and Anderson, 2015) and can exceed 2 SI (Clark, 1997) and produce characteristic, short (10's of km) narrow wavy high amplitude (>500 nT–3000nT) positive reduced to the pole magnetic anomalies (Finn and Anderson, 2015). The BIFs act as structural markers within deformed non-magnetic greenstone belts and therefore can represent folds. Estimates of the depth to the top of the crystalline basement have been calculated from the magnetic data (Finn and Anderson, 2015). From comparison with the mapped geology, these estimates tend to be excessively deep, by 100–300 m.

The amplitude of the 3-D analytic signal of the total magnetic field produces maxima over magnetic contacts regardless of the direction of magnetization. The absence of magnetization direction in the shape of analytic signal anomalies is a particularly attractive characteristic for the interpretation of magnetic field data near the magnetic equator. Although the amplitude of the analytic signal is dependent on magnetization strength and the direction of geologic strike with respect to the magnetization vector, this dependency is easier to deal with in the interpretation of analytic signal amplitude than in the original total field data or reduced to the pole magnetic field. High amplitudes in the analytic signal are associated with BIF. By comparing the analytic signal and mapped geology, it was possible to develop a threshold for the analytic signal such that values greater than the threshold (which varied from region to region) were clearly associated with relatively thick BIF.

Another tool for mapping BIFs is gamma ray spectrometry. Potassium and the uranium and thorium decay series possess radioisotopes that produce gamma rays of sufficient energy and intensity to be measured by gamma ray spectrometry. The depth of penetration of the radioelement data is about 30 cm, so it is most valuable as a surficial geochemical mapping tool.

Iron occurrences in the Tiris Complex relate to high amplitude magnetic highs (fig. 24).The most prominent magnetic highs are associated with Paleoproterozoic thrust sheets and overlying Superior-type BIF, most notably in Kediat Ijil and Guelb El Mhaoudat and their extensions beneath the Taoudeni Basin. Depth estimates suggest that large portions of the Paleoproterozoic rocks lie within <700 m of the surface (fig. 26). All of the rest of the linear fabric on the reduced to the pole magnetic anomaly map relates to Archean Tiris Complex BIF (fig. 24). Iron occurs in regions where the magnetic anomalies are relatively high amplitude (fig. 24). In order to determine the favorable regions for iron formation, we use the analytic signal data above a threshold (>0.75) to identify anomalies that correspond to thick BIF. We also masked these data to isolate anomalies whose sources are less than 1000 m depth (fig. 28). The masked analytic signal data show that the Kediat Ijil and El Mhaoudat and their buried extensions to be favorable for magnetite iron formation. Some of the Tiris Complex BIF may also be thick enough to be economic (fig. 28).

Many of the iron occurrences are associated with areas of low concentrations of uranium, thorium and potassium in particular in the Paleoproterozoic thrust sheets (blue colors, fig. 37). In contrast, the BIFs associated with the Tiris Complex are mainly associated with relatively enriched radiometric elements (yellow and whites, fig. 37) most likely reflecting their granitic/gneissic basement rather than the thin BIF. Areas with low concentrations of radiometric elements do not always correspond to magnetic highs related to BIF (figs. 24 and 37), and are therefore a less reliable indicator of BIF favorability than magnetic data.

The susceptibilities of the hematite BIFs are generally much lower than for the magnetite BIFs. If the hematite low susceptibility portions of the BIFs were extensive and thick they would produce magnetic lows within the highs produced by the magnetite BIFs (fig. 26). These lows are not observed, suggesting that the regions of demagnetized BIFs are small relative to the line spacing of the magnetic survey (700 m).

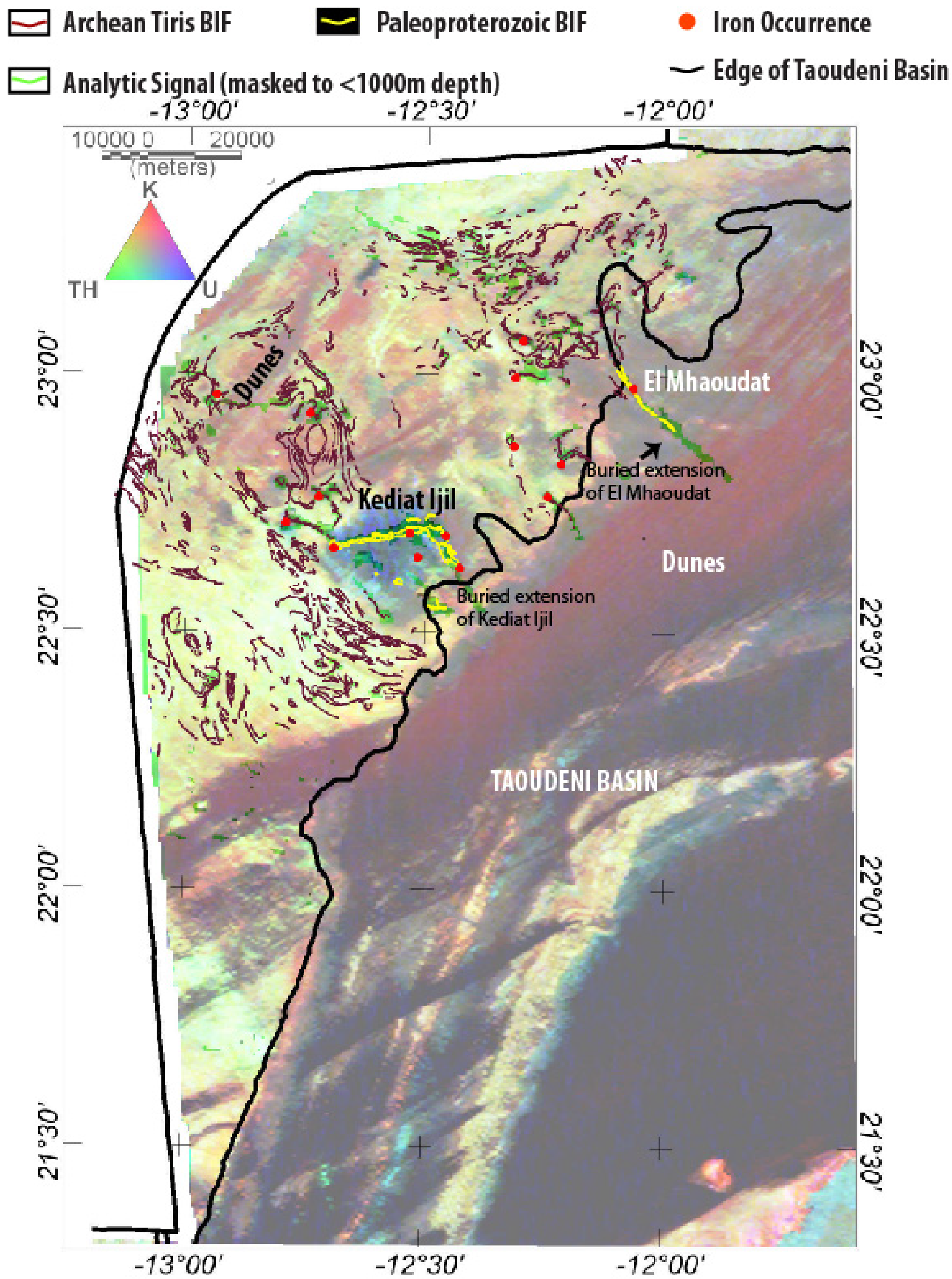

Figure 37. Color composite image red = K, green = Th and blue = U with mapped BIF units and locations of iron occurrences.

5.2.3 Mesoarchean Amsaga Complex

Banded Algoma-type magnetite-quartzite iron formation of Mesoarchean age is also present within the Amsaga Complex of the Choum-Rag el Abiod terrane to the west of Atar (fig. 38). The Rgueïbat Shield in northwestern Mauritania consists of the exposed Archean portion of the West African Craton. Recent mapping by the BGS (Pitfield and others, 2004;

O'Connor and others, 2005) divides this part of the shield into two terranes separated by a major arcuate north-northeast- to north-trending shear zone named the Tacarat-Inemmaudene Shear Zone (TISZ: Key and others, 2008).The eastern Choum-Rag el Abiod terrane consists primarily of granulite facies metamorphic rocks of the Amsaga Complex, which are as old as 3,500 Ma. These rocks are cut by major granitic, and less commonly, by mafic-ultramafic bodies, which range in age from 3,000 to 2,700 Ma. Older fragments of preserved crustal material consisting of greenstone remnants (amphibolites) in migmatitic gneisses are probably about 3,200 Ma in age. This region is interpreted as the dismembered and reworked root zone of a typical granite-greenstone assemblage (Gunn and others, 2004).

The majority of the Choum-Rag El Abiod terrane is composed of amphibolite to granulite facies granitic rocks of the Amsaga Complex that have been tectonically reworked. Ductile shearing is so prevalent that most outcrops are lozenge-shaped and consist of tectonically juxtaposed lithologies that are migmatized to a greater or lesser extent. Fissile, biotite-bearing quartzofeldspathic gneiss is the dominant lithology within which there are numerous, generally small elliptical bodies of schistose amphibolite, and lesser thinly laminated biotite-carbonate rocks that may represent sheared metabasalts, pyroxenites, metagabbro, banded calc-silicate rocks, magnetite-quartzite BIF, dunite-carbonate breccias, charnockitic gneiss, anorthosite sheets, and other unspecified ultramafic bodies. Individual lozenges of a given lithology are generally up to several hundred meters long and tens of meters thick (Pitfield and others, 2004). Individual mappable units of mylonite and ultramylonite occur in a series of long, thin lozenges that run in a sinuous pattern up the center and eastern portion of the Amsaga Complex from the southern thrust contact with overlying Neoproterozoic rocks of the Inchiri district to the northern border near Choum. These mylonites are "flower structures" (Pitfield and others, 2004) related to the TISZ, which constitutes the western border of the terrane (figs. 38 and 39).

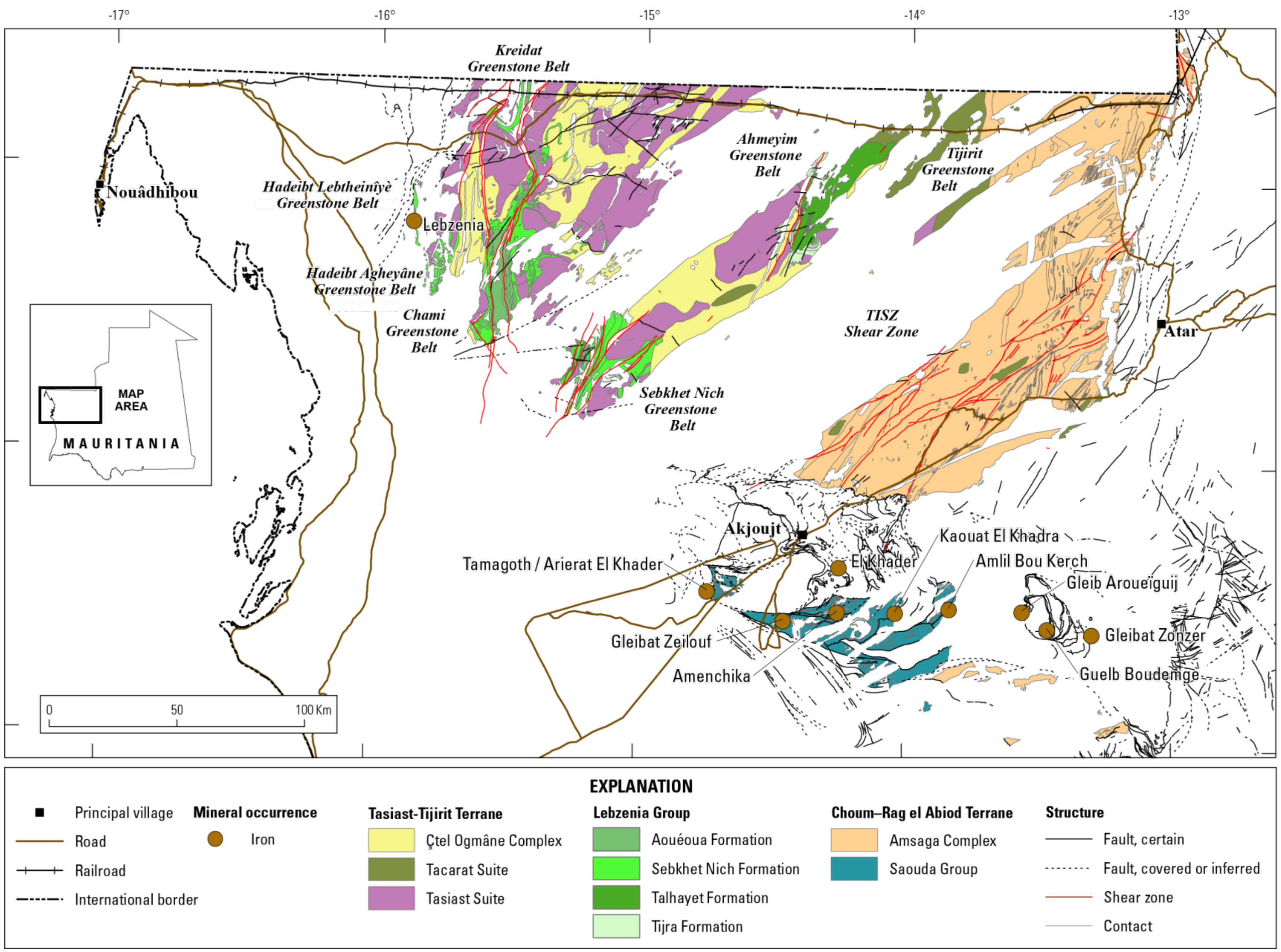

Figure 38. Simplified geologic map of the southwestern Rgueïbat Shield showing the Choum-Rag el Abiod and Tasiast-Tijirit terranes. The principal greenstone belts and Algoma-type BIF discussed in the text are shown.

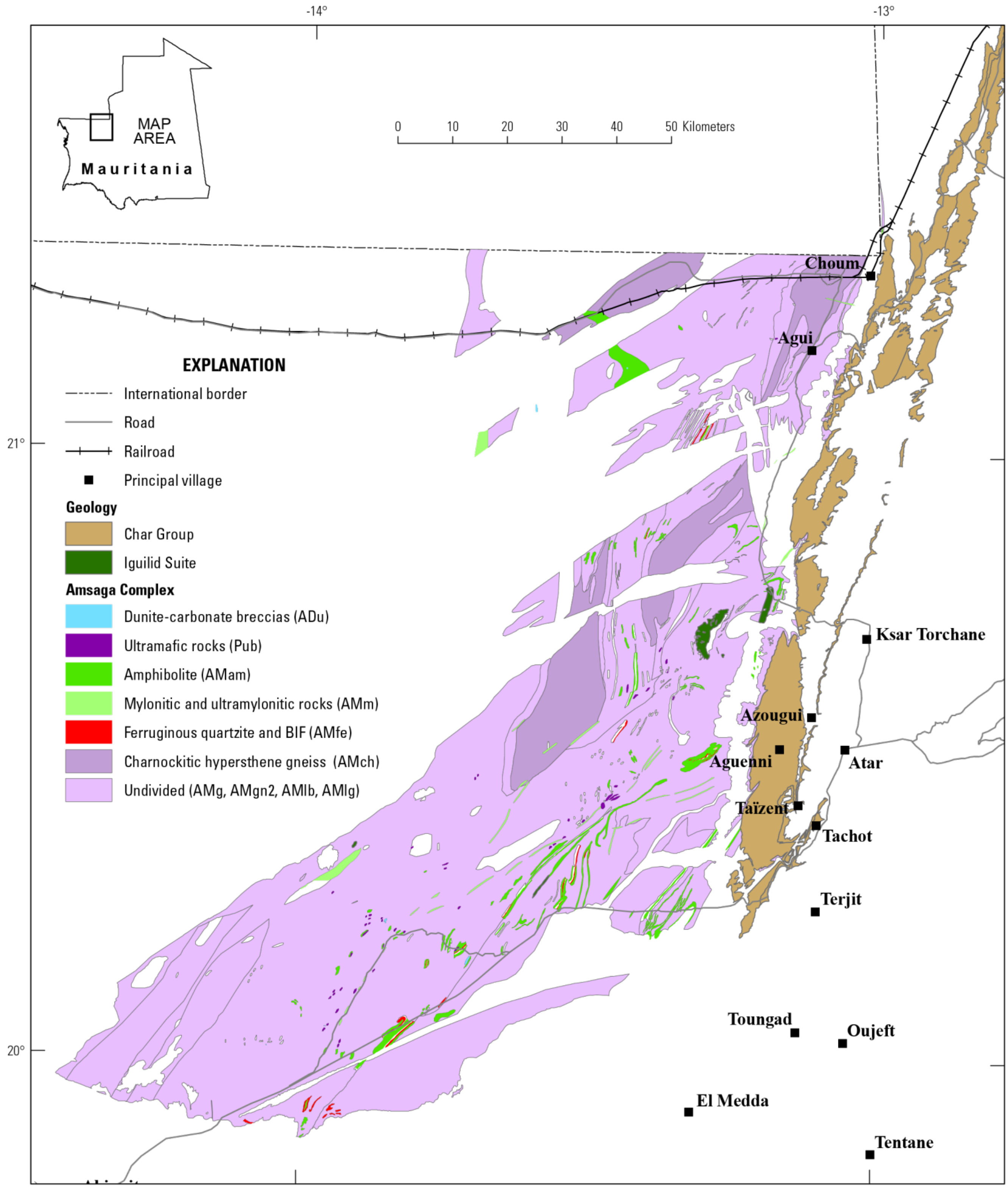

Figure 39. Simplified geology of the Amsaga Complex showing distribution of supracrustal rocks and magnetite-quartzite iron formation.

There are currently no known iron occurrences in the National Mineral Deposits Database (Marsh and Anderson, 2015) that are located in the Amsaga Complex, and the outcrops of iron formation are not as numerous, thick, or persistent as similar iron formation in the Tiris Complex to the north. However, the presence of iron formation associated with other supracrustal rocks such as amphibolites, carbonates, metapelites, and various ultramafic rocks suggest that the Amsaga Complex should be regarded as permissive of Algoma-type iron formation.

Iron formation is mapped as discrete units within the Amsaga Complex primarily in the southern half of the Complex and to the east of the mylonite flower structures (fig. 39). They occur as elongate low ridges parallel to foliation and as rounded hills in areas of fold closures usually in association with amphibolites and less commonly with marbles. Thickness of the iron formation is difficult to estimate due to deformation, however, it is generally tens of meters thick and well under 100 meters thick. Individual ridges can be traced for up to 8 km. Fresh BIF in the Amsaga Complex is strongly magnetic and is composed of centimeter-scale bands of magnetite and chert. Weathered outcrops consist of massive to sponge textured quartz-limonite breccias with clasts consisting of angular quartz fragments less than 30 centimeters in size (Pitfield and others, 2004).

Aeromagnetic data should provide extensions of mapped iron formation under cover. Inspection of the aeromagnetic data highlights the occurrence of a large magnetic anomaly in the sub-Taoudeni Basin basement to the east of the Adrar Escarpment south of Atar. Stratigraphic thickness of the overlying sedimentary rocks is probably less than 200 meters (fig. 40).

Aeromagnetic data collected along 500 meter spaced flightlines over the Amsaga Complex show an intricate pattern of magnetic anomalies (fig. 41). The RTP map shows broad magnetic anomaly highs associated with the charnockite gneiss that is in contrast to magnetic lows associated with the garnet quartzofeldspathic gneiss. Linear northeast trending magnetic highs correlate with mapped magnetite-quartzite BIF and amphibolite units, whereas a north trending magnetic high correlated with the metacarbonate unit. Several mapped ultramafic bodies broadly correlate with RTP anomaly highs. The metagabbro associated with the Iguilid massif is associated with a strong, arcuate RTP anomaly high.

The analytic signal calculates the gradient of the magnetic field and can be used to simplify the interpretation of magnetic anomalies (Nabighian, 1972; Roest and others, 1992). The analytic signal over the Amsaga Complex shows several highs that indicate areas where the magnetic field is rapidly changing. Analytic signal highs correlate with the metagabbro of the Iguilid massif, the linear metacarbonate unit, and BIFs. Several of the smaller mapped ultramafic units also correlate with analytic signal highs. Several isolated analytic signal highs occur within the garnet quartzofeldspathic gneiss which may indicate the presence of more BIF or ultramafic rocks in the region than is depicted on the geologic maps (fig. 41).

Magnetic anomalies with amplitudes greater than 1,000 nanoteslas (nT) were identified along flightlines. Such anomalies may represent magnetic material, such as BIF or ultramafic rock, within less magnetic material. There is a risk that strong magnetic anomalies may be subdued during gridding processes, therefore, use of original flightline data to map their distribution is preferred. All of the magnetic anomalies identified correlate with analytic signal highs. These areas may be further focused, by selecting the regions within the analytic signal highs where the most magnetic units occur. Comparing the mapped geology, RTP, analytic signal, and magnetic anomaly picks may help indicate where the more favorable areas for BIF within the Amsaga Complex occur (fig. 41).

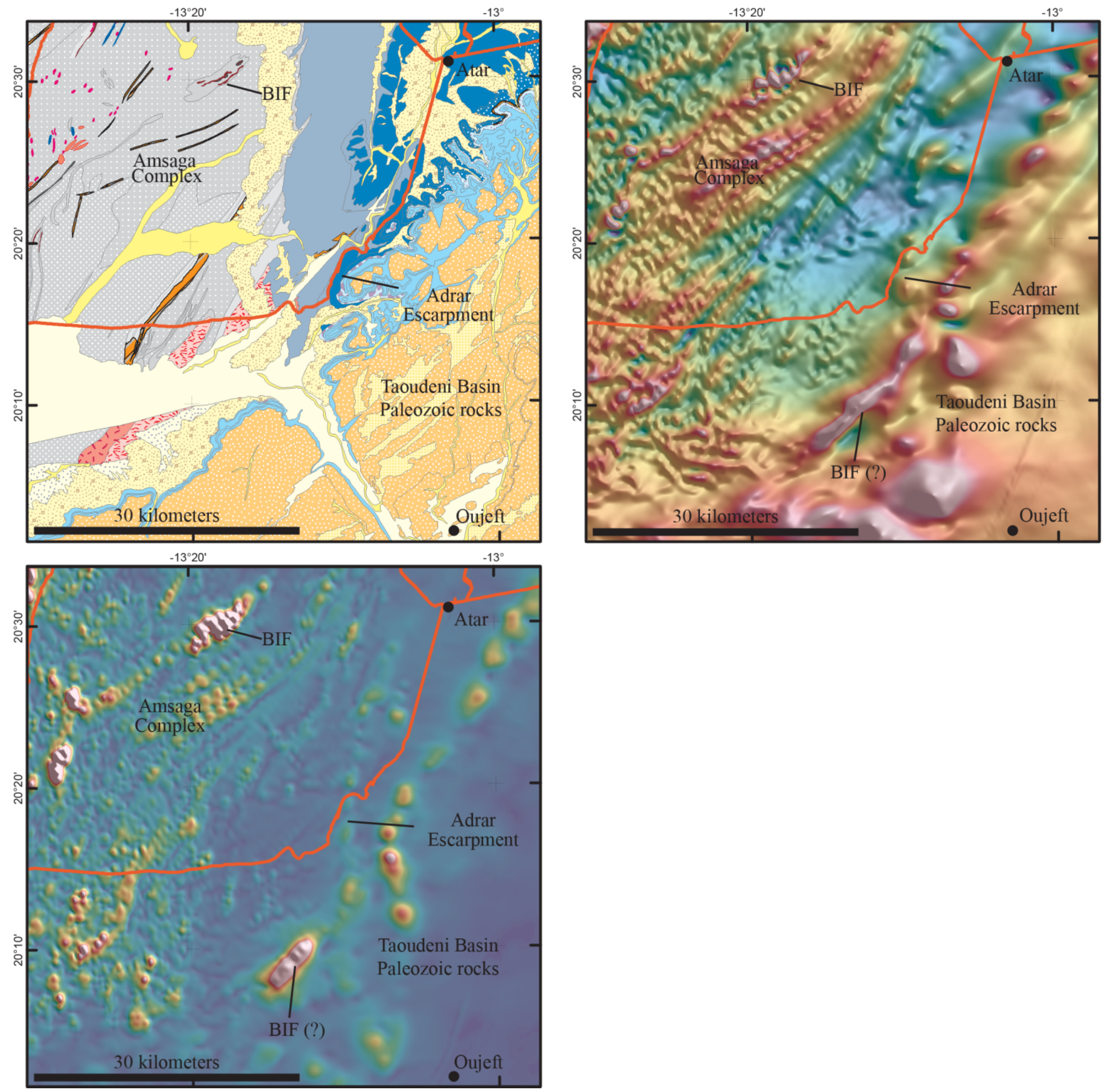

Figure 40. Aeromagnetic data showing a large magnetic anomaly in the sub-Taoudeni Basin basement to the east of the Adrar Escarpment south of Atar that is probably due to BIF in the basement. Stratigraphic thickness of the overlying sedimentary rocks is probably less than 200 meters.

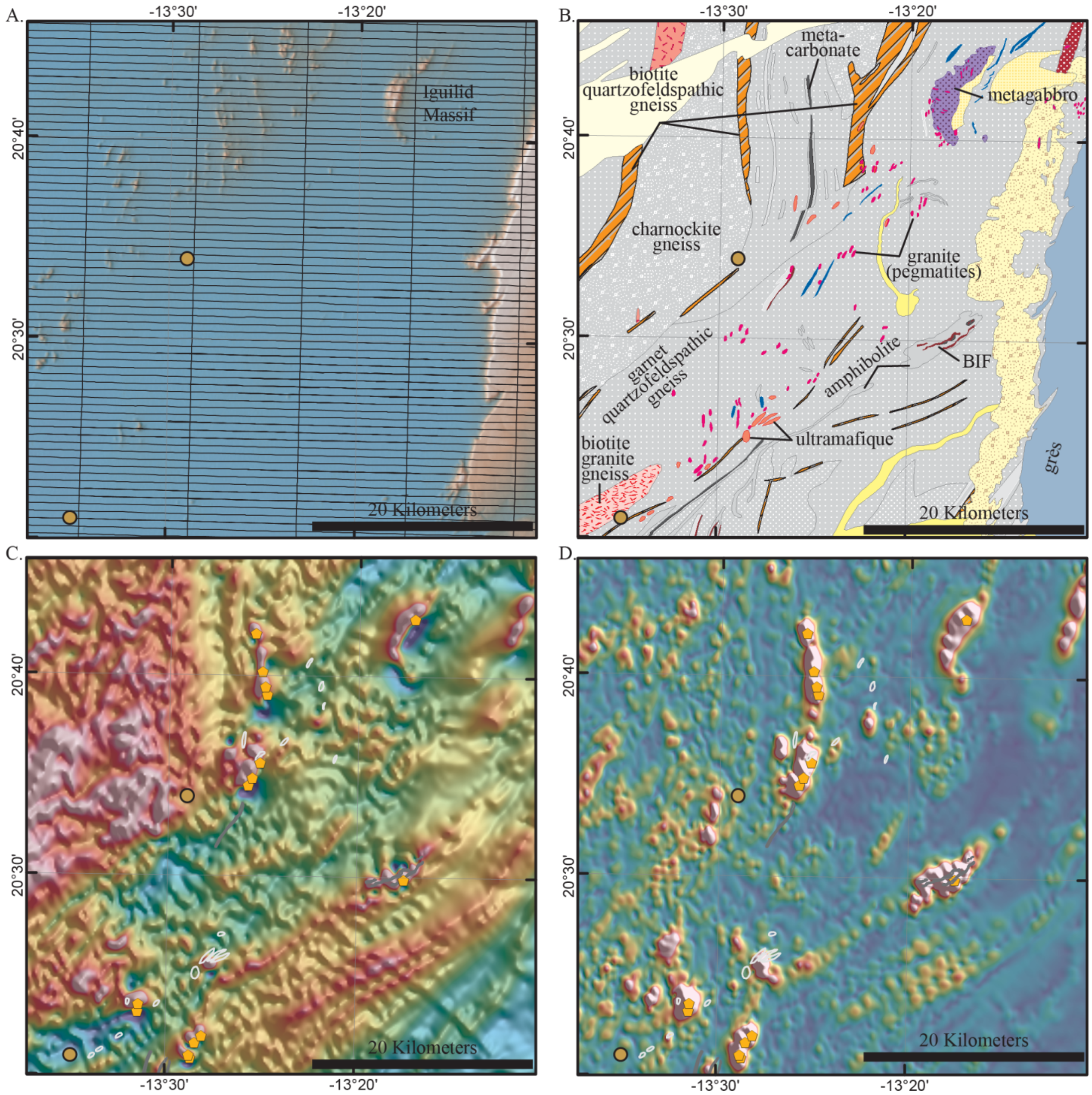

Figure 41. Generalized geology, reduced-to-pole (RTP), and analytic signal maps over the Amsaga Complex. *A,* Shaded-relief of digital elevation model and flightline location for the area. *B,* Generalized geologic map showing the distribution of magnetite-quartzite BIF mostly within the garnet quartzofeldspathic gneiss. *C,* RTP map showing a broad magnetic anomaly high associated with the charnockite gneiss in the west. Several linear magnetic anomalies correlate with BIF units (gray polygon) and ultramafic rocks (white polygons). Orange markers indicate magnetic anomalies >1,000 (nT) nanoteslas along flightlines. Magnetic highs and lows are shown as warm and cool colors, respectively. *D,* Analytic signal highlighting several areas where the magnetic field is rapidly changing. Orange markers indicate magnetic anomalies >1,000 nanoteslas along flightlines. Analytic signal highs and lows are shown as warm and cool colors, respectively.

5.2.4 Mesoarchean Tasiast-Tijirit terrane

Banded Algoma-type magnetite-quartzite iron formation of Mesoarchean age is also present within the Tasiast-Tijirit terrane in the northwestern portion of the Mesoarchean Rgueïbat Shield (fig. 38). As described above, recent mapping by the BGS (Pitfield and others, 2004;

O'Connor and others, 2005) divides this part of the Shield into two terranes separated by a major arcuate north-northeast- to north-trending shear zone, the TISZ (Key and others, 2008). The western Tasiast-Tijirit terrane consists of a typical Archean granite-greenstone assemblage exposed at shallower levels than the Choum-Rag el Abiod terrane and are thus much less sheared and tectonized than the similar-age rocks to the east. The oldest rocks are variably migmatized tonalitic gneisses that are cut by younger granitic phases and tectonically or unconformably underlie the greenstone belts (fig. 38).

The Tasiast-Tijirit terrane consists of three major lithologic groups: (1) migmatitic gneisses of the Çtel Ogmâne Complex that are the oldest rocks in the terrane and underlie the greenstone belts, (2) greenstone belt lithologies, and (3) younger granitoid intrusions consisting of gneissic granites, biotite-tonalites-granodiorites (including rocks with abundant secondary epidote) as well as late xenolithic, leucocratic biotite-granites of the Tasiast Suite and gneissic granites of the Tacarat Suite (fig. 38).

The main greenstone belts in the Tasiast-Tijirit terrane are named, from east to west, the Tijirit, Ahmeyim, Sebkhet Nich, Kreidat, and Chami. Two smaller greenstone belts to the west of the Chami Belt are called the Hadeibt Agheyâne and Hadeibt Lebtheinîyé and are collectively referred to as the Lebzenia Greenstone Belts (fig. 38). Note that multiple spellings of the proper names Lebzenia, Lebtheinîyé, and Lebtheinia are used in various literatures. We have retained Lebzenia for the group name, following BGS usage (Pitfield and others, 2004), as well as for the iron occurrence listed in the Mauritanian National Mineral Deposits Database (Marsh and Anderson, 2015). However, we use Lebtheinia for the various project and occurrence names used in the Xstrata company literature (see below). These greenstone belts consist predominantly of mafic metavolcanic and siliciclastic metasedimentary rocks metamorphosed at low- to medium-grades. Banded iron formation (BIF) and ultramafic rocks are locally common and intermediate to felsic metavolcanic rocks are rare. The greenstone belts are locally intensely sheared especially along competency contrasts between lithologic units, and major ductile shear zones control both the current shape of the belts as well as folds within the belts.

The greenstone belts are characterized by low to medium-grade metamorphic mineral assemblages in an assortment of metavolcanic and metasedimentary strata. Altered basalts and gabbros that include amphibolite schists, siliciclastic rocks and banded ironstones dominate the various greenstone belts. Ultramafic rocks are locally common (for example, Sebkhet Nich Greenstone Belt). Ferruginous quartzites and banded ironstones are common in the Sebkhet Nich, Chami, and Lebzenia Greenstone Belts. Actinolite schists are most common near contacts with intrusions such as syenites, gabbros and late-stage granites. Metasedimentary rocks are locally recrystallized to actinolite-chlorite-quartz, and sericite-quartz schists. The belts are locally intensely sheared with individual shear zones preferentially following specific lithologies.

Lithologies in the various greenstone belts are lumped into the Lebzenia Group. Four formations are recognized within this group and include: the Talhayet Formation and Tijraj Formation in the Ahmeyim Greenstone Belt, the Aouéoua Formation in the Chami Greenstone Belt, and the Sebkhet Nich Formation from the greenstone belt of the same name. The Tijraj and Aouéoua Formations are dominated by metasedimentary rocks with a significant felsic to intermediate volcanic component. The Talhayet and Sebkhet Nich Formations are characterized by basaltic greenstones and ultramafic rocks with synvolcanic intrusive sheets. The Talhayet Formation and Tijraj Formation in the Ahmeyim Greenstone Belt are not known to contain significant thicknesses of BIF. Therefore, they will not be discussed further. The Aouéoua Formation forms the fault-bounded synformal core to the contiguous Chami and Kreidat Greenstone Belts and appears to overlie the mafic-ultramafic rocks of the Sebkhet Nich Formation. In the Sebkhet Nich Greenstone Belt, the greenstone sequence is characterized by metasedimentary units structurally overlain by metabasaltic lavas and mafic sheets that are in turn overlain by ultramafic rocks. This same greenstone association flanks the Aouéoua Formation in the Chami and Kreidat Greenstone Belts and characterizes the volcanosedimentary succession in the Hudeibt Agheyâne and Hadeibt Lebtheinîyé Greenstone Belts as well. Thus, the most likely depositional sequence assuming no overthrusting or inversion would place the Sebkhet Nich Formation beneath the Aouéoua Formation (dated at 2,968±2Ma; Pitfield and others, 2004).

Ferruginous quartzites and banded ironstones are thick enough in the Sebkhet Nich, Chami, and Lebzenia Greenstone Belts to appear as mappable units. They tend to form ridges and low hills of competent, quartz-rich ferruginous rock with abundant magnetite. The iron formation generally consists of equigranular quartz separated into bands up to several centimeters in thickness by mm-thick bands of iron oxide. Hematite as well as magnetite occurs in the iron oxide bands with secondary hematite infilling fractures. The banding is generally folded into microfolds and is locally lenticular. Cross-folding of the banding is common. Brittle fractures are generally infilled by secondary silica (quartz and chert). Secondary limonite is common as a replacement of iron oxides. Sulfides are generally not present either as primary or secondary minerals (Pitfield and others, 2004). However, Algoma-type BIF is a well-known favorable host rock for orogenic gold deposits worldwide and is one of the several rock types hosting gold mineralization at Tasiast in the Chami Greenstone Belt. Low grade (0.5–1.0 grams per tonne) gold ore in BIF at Tasiast contains pyrrhotite and carbonate replacing magnetite bands (Kinross Gold Corp., 2011; Goldfarb and others, 2015).

Currently only one iron occurrence in the Tasiast-Tijirit terrane, named Lebzenia, is listed in the Mauritanian National Mineral Deposits Database (Marsh and Anderson, 2015). The occurrence is shown as occurring in the Hadeibt Lebtheinîyé Belt about midway between the north and south ends of the mapped, iron formation sub-unit of the Sebkhet Nich Formation (fig. 42). This iron occurrence is part of the Lebtheinia Iron Ore Project initiated by Sphere Investments and SNIM following their 2001 work agreement, which is now held by Xstrata. In October 2009, Sphere announced JORC-compliant indicated and inferred resources of 2,179 and 354 million tonnes, respectively, of unoxidized magnetite BIF (at 32.3 and 32.4 percent iron, respectively) and an additional inferred resource of 209 million tonnes of partially oxidized magnetite ore grading 30.7 percent iron for the Lebtheinia Center deposit (Sphere Investments Ltd., 2009; Sphere Minerals Ltd., 2012). The Lebtheinia Center deposit is one of four magnetite iron formation targets within the license areas held by Sphere including the Lebtheinia North, Center, and South targets located in the Hadeibt Lebtheinîyé Greenstone Belt and the Lebtheinia East target in the Chami Greenstone Belt north of the Tasiast mine (fig. 42).

In the Hadeibt Lebtheinîyé Greenstone Belt, the magnetite iron formation sub-unit of the Sebkhet Nich Formation is oriented north-south and is exposed over a total strike length of approximately 24 km. A slight en-echelon bend separates the North occurrence and Center deposit into segments each approximately 10 km long, whereas the South occurrence consists of a separate and much smaller exposure of BIF approximately 3 km long (fig. 42). The BIF unit does not form prominent topographical features and in general the terrain is gentle with significant portions of the Lebtheinia Center deposit covered by laterite and colluvium consisting mostly of BIF fragments (Sphere Minerals Ltd., 2012). In the Chami Greenstone Belt, BIF is present as a sub-unit of the Aouéoua Formation and forms several north-south trending persistent exposures. The westernmost BIF is approximately 33 km long and contains the Lebtheinia East deposit, which is essentially the northernmost 5–7 km of the BIF. The Tasiast gold mine is hosted in BIF and mafic metavolcanic rocks of the Aouéoua Formation approximately 15 km to the south of the Lebtheinia East iron occurrence.

Magnetite iron formation at the Lebtheinia Center deposit averages approximately 240 m in thickness (maximum 320 m thick) and dips uniformly to the west at approximately 40 degrees between a variable hanging wall of quartzite, amphibolite, altered amphibolite (clay/saprolite), and rhyolite, and a footwall of quartzite or amphibolite (Sphere Minerals Ltd., 2012). The iron formation is well banded (mesobanded; 5–10 mm) and the banding is homogenous on an outcrop scale and at depth as confirmed by drilling in 2008. Drilling indicates that ore grade BIF extends to a depth of 400 meters vertically below surface and remains open at depth. The main BIF unit splits into two units in the southern part of the deposit where it is separated by approximately 25 meters of gray quartzite and mylonitized leucocratic quartz-feldspar schist. The BIF is also crosscut by a series of northeast-southwest to north-northeast to south-southwest trending, sub-vertical basaltic dikes that are exposed at surface and have been shown by drilling to persist at depth (Sphere Minerals Ltd., 2012).

The depth of oxidation at Lebtheinia Center is variable and averages approximately 50 meters. Generally, areas of higher BIF topography are covered by laterite. The degree of oxidation within the weathered profile is variable as expressed by magnetic susceptibility measurements, with the lower two-thirds of the profile having higher magnetic responses. This lower oxidation zone constitutes the additional inferred resource of 209 million tonnes of partially oxidized magnetite ore grading 30.7 percent iron (Sphere Investments Ltd., 2009; Sphere Minerals Ltd., 2012).

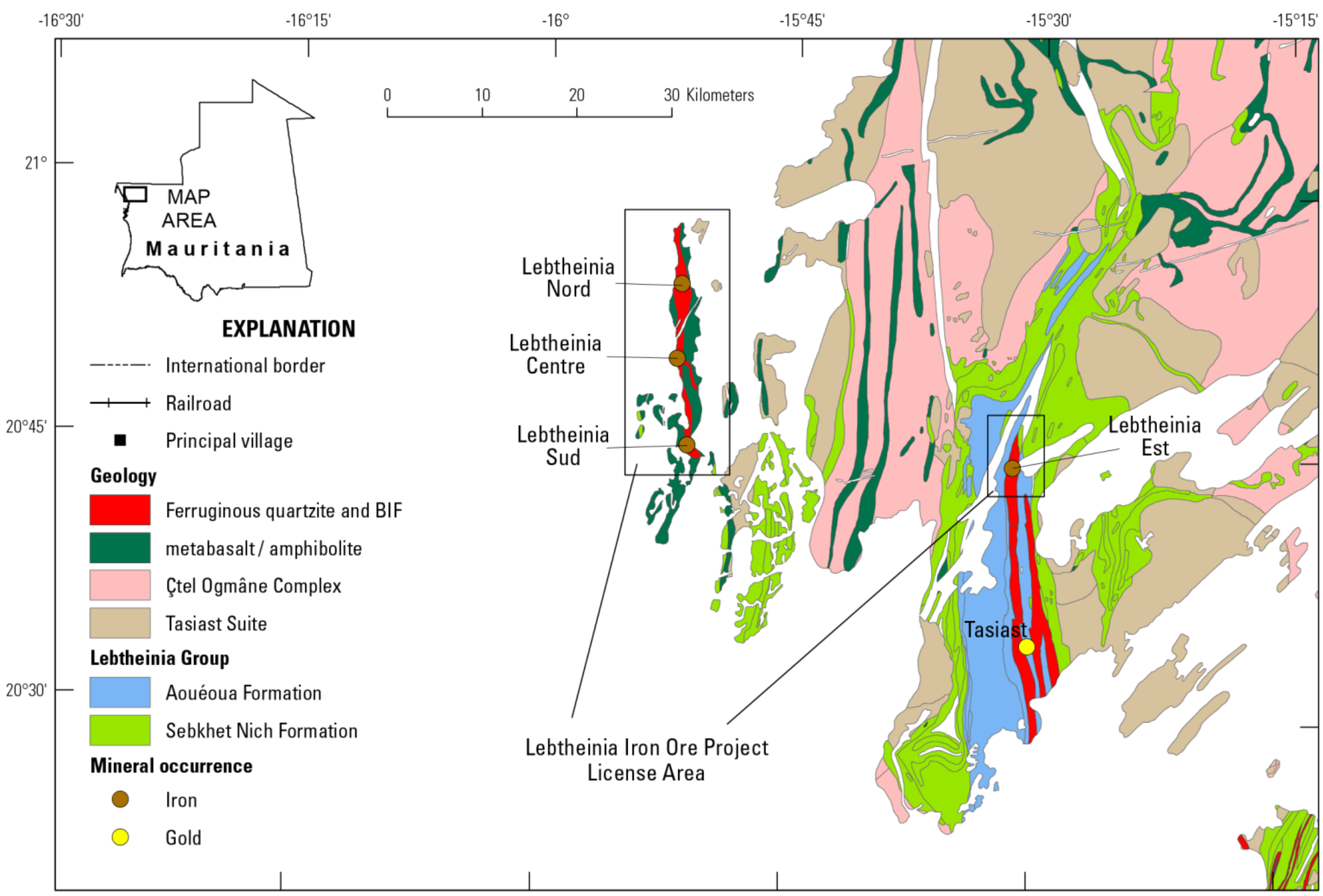

Figure 42. Simplified geology and locations of the Lebtheinia Project North, Center, South, and East targets in relation to mapped iron formation and the Tasiast gold mine.

5.2.5 The Inchiri district

The Inchiri district is defined by a variety of mineral deposits in the Akjoujt area, which for the purposes of this paper is considered as part of the central Mauritanides. Mineralized host rocks in the district are dominantly Neoproterozoic through lower Paleozoic supracrustal rocks consisting of metabasalts, metasedimentary rocks, banded iron formation, and lesser intermediate to felsic metavolcanic rocks of the Oumachoueima Group. These rocks are host to a large number of copper and gold occurrences thought to be of the iron oxide copper-gold type (IOCG), including the Guelb Moghrein mine that is currently in production (see Fernette, 2015). Other mineral occurrences in the Inchiri district include tungsten and pegmatite (Marsh and Anderson, 2015) and the district is regarded as permissive of orogenic gold, volcanogenic massive sulfide, and Cu-Ni-PGE-Cr deposits (Goldfarb and others, 2015; Taylor and Giles, 2015; Taylor and others, 2015). Similar to the southern Mauritanides, this region was affected by Pan-African through Hercynian deformation that produced a structurally complex zone of thrust nappes, together referred to as the Akjoujt nappe pile, that juxtaposes slices of the Mesoarchean basement and associated supracrustal rocks with slices of the Proterozoic supracrustal sequence (fig. 43). Several different BIF units of Mesoarchean and Neoproterozoic age are present in the district and are thick enough to appear as discrete mappable units (Pitfield and others, 2004). However, there are currently no known iron occurrences listed in the Mauritanian National Mineral Deposits Database (Marsh and Anderson, 2015) in the Neoproterozoic rocks of the Akjoujt nappe pile. In contrast, three known occurrences (Gleib Aroueiguil, Guelb Boudemge, and Gleibat Zonzer) are hosted in Neoproterozoic BIF of the Ijibbitene Group and six occurrences (Tamagoth/Arierat El Khader, Gleibat Zeilouf, Amenchika, Kaouat El Khadra, Amlil Bou Kerch, and Aftout De Faye) are hosted in BIF of the Mesoarchean Saouda Group. Thus, all of the predominantly magnetite-quartzite BIF units in the Inchiri district are regarded as permissive of Algoma-type iron deposits. Recent private company evaluations of Algoma-type iron formation at Guelb Tamagot, Kaouat El Khadra, and an unusual goethite-rich gossan capping the IOCG occurrence at El Khader suggest that economic deposits of iron ore may be present within the district.

Current understanding of the age constraints on the supracrustal rocks of the district are conflicting and raise the possibility that both the host rocks and mineral occurrences could be as old as Mesoarchean to as young as Neoproterozoic.Until the ages of these rocks are resolved, the relationship of the central Mauritanides to either the greenstone belts of the Tasiast-Tijirit terrane or to the younger rocks of the southern Mauritanides remains in question.

Rocks in the Inchiri district are an allochthonous package consisting of Mesoarchean to Paleoproterozoic gneisses and metamafic volcanosedimentary rocks in tectonic windows within an imbricated supracrustal nappe pile of Paleoproterozoic to Neoproterozoic rocks of wide-ranging lithologies. This infrastructural allochthon (Pitfield and others, 2004) was emplaced over autochthonous to para-autochthonous rocks of the Amsaga Complex and foreland basin sedimentary rocks of the Taoudeni Basin during the Pan African through Hercynian Mauritanide orogeny. The allochthon consists of four internally imbricated nappes (fig. 43).

The Agoualilet Group, consisting of a mafic melange interspersed with siliciclastic sedimentary rocks, form the root zone and regionally extensive basal nappe of the allochthon. It forms a western block at the southwestern edge of the Akjoujt nappe pile and an eastern block well to the southeast of the Ijibbitene nappe (fig. 43). Although these rocks are regarded as permissive of VMS deposits (Taylor and Giles, 2015), they exhibit a total absence of BIF in the western block and contains only rare BIF in the Treïfiyat Formation of the eastern block. Rocks of the basal nappe are therefore not considered permissive for the occurrence of Algoma-type iron deposits and will not be discussed further.

The Tamagot basement window or tectonic inlier, together with the Bou Kerch nappe, are located along the eastern edge of the Agoualilet Group root zone southwest and south of the village of Akjoujt. These rocks consist of the Tamagot orthogneiss and mafic igneous rocks, banded iron formation (BIF), and sedimentary rocks of the Saouda Group that together exhibit characteristics of an Archean granite-greenstone association. They are the oldest rocks in the allochthon and are thought to be an eastward-transported southern section of the Mesoarchean Tasiast-Tijirit terrane. In the Bou Kerch nappe, rocks of the Saouda Group tectonically overlie and are imbricated with quartzitic metasediments of the Agoualilet Group (fig. 43; Pitfield and others, 2004).

The current understanding of the Saouda Group in the Tamagot window and Bou Kerch nappe (fig. 43) suggests that these predominantly mafic metavolcanic rocks with ubiquitous BIF represent an Archean (?) granite-greenstone sequence that may be related to the Tasiast-Tijirit terrane. The granite-greenstone-like geometry is primarily based on the complexly interfolded nature of the Saouda Group greenstones with orthogneiss in the Tamagot window and is extrapolated to the mafic metavolcanosedimentary succession of the Bou Kerch nappe. Available geochronologic data on these rocks are sparse and are limited to ^{40}Ar-^{39}Ar studies (Dallmeyer and Lecorche, 1990). A total gas age of 2,035±11 Ma was obtained for an amphibole concentrate from Saouda Group rocks of the Bou Kerch nappe. Argon dating of muscovites from a garnet-mica schist and a leucocratic gneiss from the Saouda Group gave mixed Mesoproterozoic and upper Paleozoic ages, however these data display internally discordant spectra that suggest thermal disturbance of mineral systems as old as 2,600 Ma (Pitfield and others, 2004). Correlation of mafic metavolcanic rocks in the Zemzem tectonic window of the southern Mauritanides with the Saouda Group of the Inchiri district and a U-Pb zircon age of 2,683±22 Ma on an associated Zemzem metamicrogranodiorite strengthens the probability that rocks of the Bou Kerch nappe are at least Neoarchean age (Pitfield and others, 2004). However, as discussed above, the greenstone successions of the Tasiast-Tijirit terrane are Mesoarchean in age and are approximately 300 million years older than rocks of the Saouda Group. Thus, the association of greenstones of the Saouda Group with comparable rocks in the Tasiast-Tijirit terrane is tenuous. No geochemical data are available for comparison.

There are currently six known Algoma-type iron occurrences hosted by rocks of the Saouda Group (Marsh and Anderson, 2015). The dominantly metamafic assemblage contains two major lithologies: amphibolites and metamafites, and chloritic schists. The presence of ubiquitous thin and impersistent BIF and lesser metachert layers throughout both major lithologic assemblages indicate that seafloor exhalative processes responsible for Algoma-type iron formation were operative during deposition of the mafic volcanosedimentary succession. Therefore, the entire Saouda Group must be regarded as permissive of Algoma-type iron deposits.

As summarized by Gunn and others (2004), exploration for iron ore in the Inchiri district dates back to the 1950s and was coincident with the search for additional copper resources similar to Guelb Moghrein. The Bureau Minier de la France d'Outre-Mer (BUMIFOM) was intermittently engaged in iron exploration in the Tamagot area, along the southwest side of the Akjoujt nappe pile, and at El Khader from 1951 to 1957. In 1955 a low resolution aeromagnetic survey by BUMIFOM to search for magnetite-bearing copper deposits revealed the widespread presence of BIF throughout the Inchiri district as well as additional copper and tungsten prospects (Gunn and others, 2004). Surface exploration during this period resulted in more detailed work at the El Khader copper-gold- (iron) prospect (described below) in the Legleitat El Khader area to the southeast of Akjoujt (Allon, 1957).

Of the six occurrences in the Saouda Group (Tamagoth/Arierat El Khader, Gleibat Zeilouf, Amenchika, Kaouat El Khadra, Amlil Bou Kerch, and Aftout De Faye) current activity is occurring at the Tamagoth/Arierat El Khader and Kaouat El Khadra occurrences. The Tamagoth/Arierat El Khader occurrence is named for a prominent topographic feature easily visible approximately 3 km northwest of the Nouakchott-Akjoujt highway and approximately 41 km southwest of Akjoujt. The license area is currently held by an Indonesian company (PT Bumi Resources Minerals Tbk, hereafter referred to as Bumi Minerals) that seeks to develop iron ore from a total of three areas including the Tamagot, West Tamagot, and Sfariat-Zednes areas (consisting of 1,298, 1,440, and 1,238 km^2 areas, respectively). Resource figures published by Bumi Minerals in their Annual Reports (PT Bumi Resources Minerals Tbk, 2010; 2011) claim an aggregated "estimated mineral inventory" from the three areas of 100 million tonnes grading approximately 58 percent iron. Bumi Minerals plans to mine direct shipping iron ore from an open pit in the Tamagot area that will not require further beneficiation on-site. Analyses of drilled samples from their Otoy Main and

Kabayan prospects in the Tamagot area suggest iron grades of between 46 and 58 percent. Production from the open pit covering these two prospects and a third, Otoy North prospect, will be trucked to the Port of Nouakchott over existing roads and then shipped from new loading facilities constructed for the purpose (PT Bumi Resources Minerals Tbk, 2010).

Uncertainty exists at the time of this writing regarding the exact location of the Bumi Minerals exploration activities and prospects in the Inchiri district. We assume that the three prospects named above in the Tamagot area correspond to the Tamagoth/Arierat El Khader occurrence listed in the Mauritanian National Mineral Deposits Database (Marsh and Anderson, 2015). We also assume that the location of Bumi Minerals Tamagot license area and the various named prospects and occurrence named above corresponds to the Guelb Tamagot topographic feature rising 50–75 meters above the regolith (fig. 44). Guelb Tamagot rises 50–75 meters above the surrounding regolith plain and is composed of a thickened north-south trending exposure of BIF of the Saouda Group within the Tamagot tectonic window (fig. 45). An eastward bend in the mapped exposure of BIF at Guelb Tamagot may indicate folding, resulting in the thickened BIF at the Guelb. The BIF consists of meso- to microbanded magnetite and ferruginous quartzite. The magnetite bands are partially replaced by hematite (fig. 46). A 1–2 m thick breccia horizon near the base of the Guelb is of uncertain origin and may represent a near-horizontal fault plane (fig. 47).

Regionally, the Saouda Group BIF is a ubiquitous and characteristic feature of the Saouda Group. It is dominantly composed of magnetite-rich oxide-facies BIF with subordinate carbonate- and sulfide-facies assemblages. The oxide-facies BIF is a feature-forming unit within the Saouda Group greenstones and is usually associated with flaggy to massive metaquartzites. BIF horizons are meters to tens (maximum of 30) of meters thick and consist of iron gray to black, mesobanded to thinly laminated and contorted ferruginous quartzite and iron oxides. Magnetite-bearing carbonate-facies BIF is locally present in the footwall of more erosion-resistant silicate-oxide facies BIF and is rarely more than a few meters thick. Geologic mapping at 1:200,000 scale by the BGS only shows thicker exposures of BIF, however, thin BIF layers (1–4 m thick) are ubiquitous throughout the Saouda Group and comprise approximately 5 percent of the sequence (Pitfield and others, 2004).

The Kaouat El Khadra occurrence is located approximately 47 km southeast of Akjoujt in Saouda Group BIF of the Bou Kerch nappe (fig. 43). Sparse descriptive information suggests that the occurrence consists of magnetite-hematite quartzite with trace chalcopyrite and malachite in Saouda Group schist and amphibolite (Marsh and Anderson, 2015). The occurrence lies within Prospecting Permit 273B1, an east-west elongated block covering an area 130 × 11 km in size held by Transafrika Resources Limited (hereafter referred to as Transafrika; Transafrika Resources Limited, 2010; 2011). The permit encompasses the area of the Gleibat Zeilouf occurrence near its western boundary to the Gleibat Zonzer occurrence on the east side of the Ijibbitene massif near its eastern boundary (figs. 43 and 48). Within this permit Transafrica has identified an area 11 × 6 km in size, at and to the west of the 200-m-high Kaouat el Khadra topographic feature, which contains five separate mapped outcrops of Saouda Group BIF. This portion of the permit is referred to by Transafrika as the Kaouat Iron Project (fig. 49). Oucrops in the southern and western part of the project consist of shallowly dipping, gently folded BIF, whereas exposures in the north (the Zerga and Zerga Extension) dip at approximately 45 degrees to the north and consist of BIF and BIF breccia (fig. 49). A third ferruginous rock type present consists of magnetite-bearing schist. Mineralogy consists primarily of hematite, magnetite, goethite, and quartz (Transafrika Resources Limited, 2010). In April, 2010 Transafrika had completed mapping of approximately 60 km^2, gravity and magnetic surveys over the eastern portion of the Project, 20 reverse circulation drill holes in the western, central, and eastern parts of the Project and nine diamond drill holes in the Zerga Extension to test the BIF breccias. Based on this work, Transafrika suggested a potential resource of 1.2 billion tonnes of BIF at an average grade of 30 percent iron (Transafrika Resources Limited, 2010).

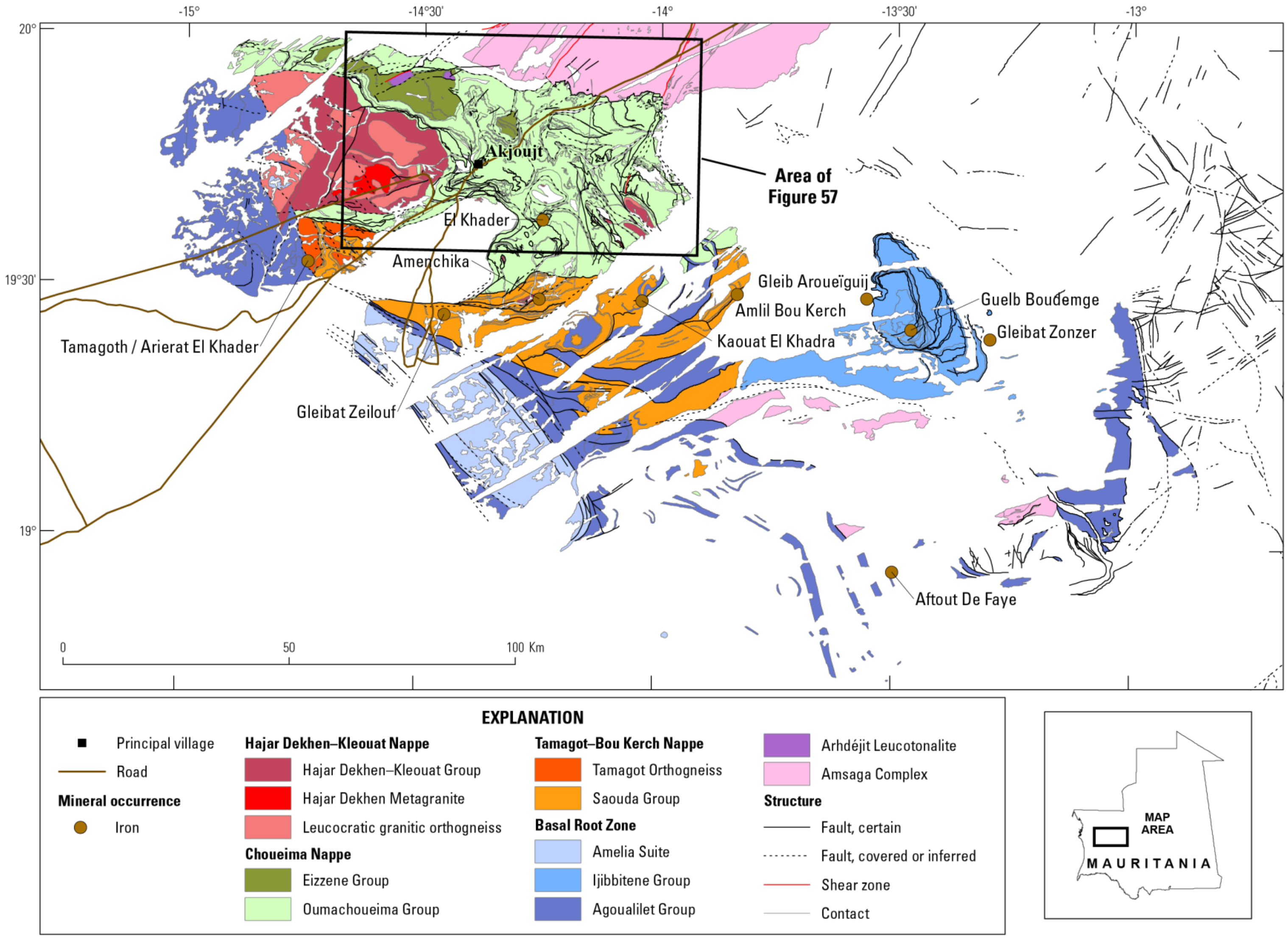

Figure 43. Simplified geology of the of the Inchiri district showing the various nappes and tectonic windows of the Akjoujt nappe pile and deposits and mineral occurrences discussed in text.

Figure 44. View looking north along the west side of Guelb Tamagot approximately 41 kilometers to the southwest of Akjoujt in the Inchiri district. Dark colored blocks in the foreground are composed of Saouda Group BIF. USGS photo.

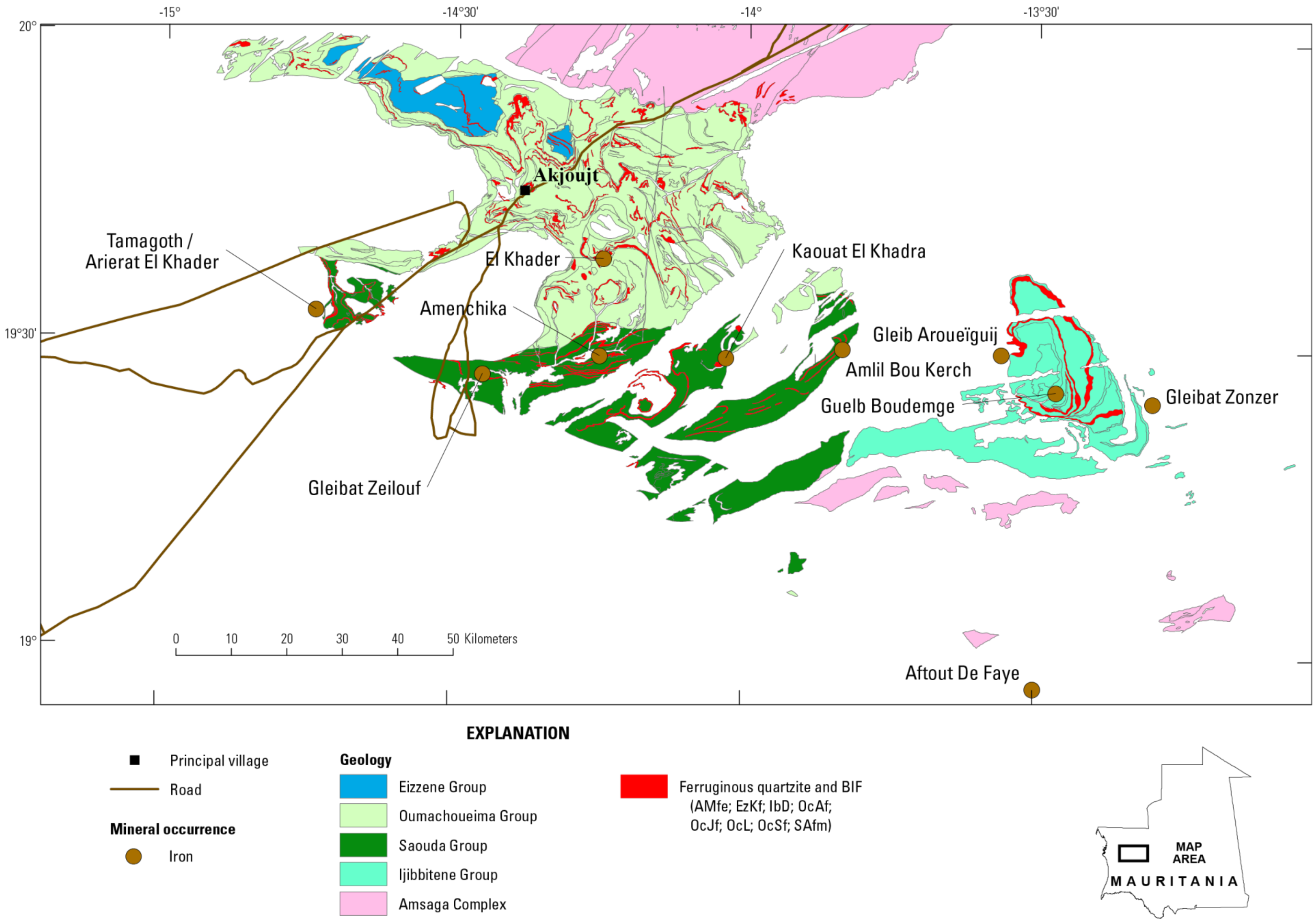

Figure 45. Simplified geology of the Inchiri district showing BIF units and locations of iron occurrences described in text.

Figure 46. Close-up showing meso- to microbanded BIF of the Saouda Group at Guelb Tamagot. USGS photo.

Figure 47. Breccia horizon near the base of Guelb Tamagot is of uncertain origin and may represent a near-horizontal fault plane in BIF of the Saouda Group. USGS photo.

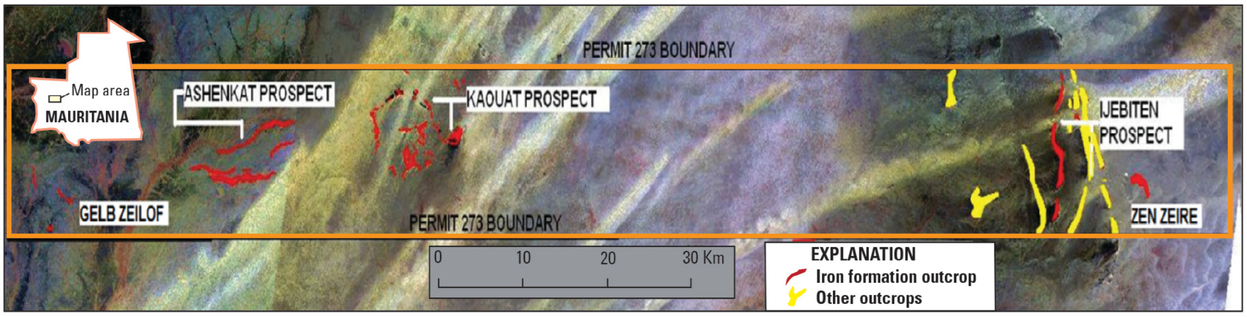

Figure 48. Satellite image of Prospecting Permit 273B1 showing the location of the Kaouat Iron Ore Project and other occurrences in the southern Inchiri district (modified from Transafrika Resources Limited, 2011).

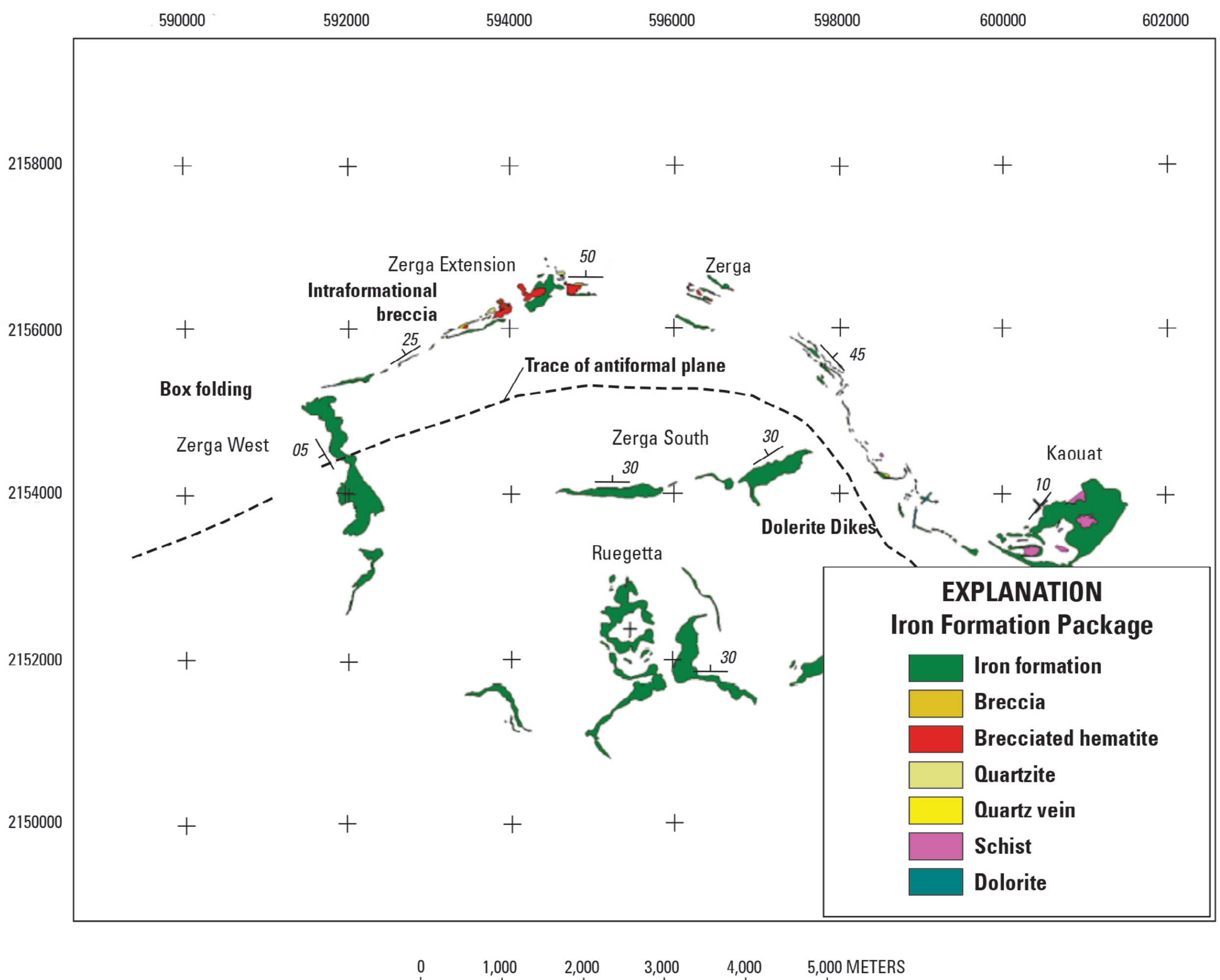

Figure 49. Geologic map of the Kaouat Iron Ore Project area (modified from Transafrika Resources Limited, 2011).

Subsequent exploration in the permit area by Transafrica noted the presence of an additional four prospects named (from west to east) Gelb Zeilof and Adhem Ashenkhat to the west of the Kaouat Iron Project, and the Ijibbitene and Zen Zeire prospects to the east, within and off the southeastern margin of the Ijibbitene massif (fig. 48; Transafrika Resources Limited, 2011). Comparison of the locations of the Transafrica prospects with those of occurrences recorded in the Mauritanian National Mineral Deposits Database (fig. 43: Marsh and Anderson, 2015) suggest that the Gelb Zeilof and Adhem Ashenkhat prospects hosted in Saouda Group BIF correspond to the Gleibat Zeilouf and Amenchika occurrences. There is no corresponding Transafrika prospect at the location of the Amlil Bou Kerch occurrence to the east of Kaouat El Khadra. The Zen Zeire prospect location corresponds to the Gleibat Zonzer occurrence hosted in Proterozoic rocks of the Ijibbitene Group off the southeastern margin of the Ijibbitene massif. The Ijebiten prospect is described as a number of discontinuous outcrops of iron formation, some consisting of quartz-hematite rock, approximately 11 km long located 80 km east of the Kaouat Iron Project (Transafrika Resources Limited, 2011). This prospect may include the Guelb Boudemge occurrence, which also is hosted in Proterozoic rocks of the Ijibbitene Group within the Ijibbitene massif. The setting of BIF in the Ijibbitene Group is briefly described in the section on Proterozoic BIF below.

Based on additional work conducted in 2011, Transafrika has suggested that the 273B1 permit area has the potential to hold as much as 5 billion tonnes of BIF at an average grade of 30 percent iron (Transafrika Resources Limited, 2011). The highest potential for development of an economic deposit exists at the Kaouat Iron Project (described above) and at the Adhem Ashenkat prospect. At Adhem Ashenkat, Saouda Group BIF outcrop occurs continuously for over 9 km along strike prompting Transafrika to suggest a potential exploration target of 400 million tonnes of BIF at grades similar to those encountered at the Kaouat Iron Project. Aeromagnetic data are interpreted by Transafrica to suggest that there may be an additional 11 km of BIF buried under sand between the Kaouat Iron Project and the Adhem Ashenkat prospect. Transafrika has conducted geologic mapping and sampling at the Gelb Zeilof and Adhem Ashenkhat prospects and reconnaissance work at the Ijebiten and Zen Zeire prospects (Transafrika Resources Limited, 2011).

Additional exploration work in Prospecting Permit 792, a 960 square kilometer area immediately to the north of and adjacent to the Kaouat Iron Project, is currently being conducted by Charter Pacific Corporation Limited (hereafter referred to as Charter Pacific) who refer to the permit area as "Kaoua El Khadhra" (Charter Pacific Corporation Limited, 2012). Similar to permit 793B1, permit 792 is an east-west elongate block approximately 60 × 18 km in size. Much of the western end of the permit is covered by sand of the northeast-trending Amatlich dune field and the eastern end encompasses the northwestern portion of the Ijibbitene massif (fig. 50). The geology of the permit is complex and includes portions of the Choueima nappe in the northwest and center, the Bou Kerch nappe in the southwest and south-center, and the Ijibbitene nappe in the eastern parts of the permit area. Similar to Transafrika, Charter Pacific seeks to develop magnetite-quartzite BIF of any age that can be magnetically concentrated and trucked to the coast for export. Therefore, current exploration efforts are focused on prospects in both Mesoarchean Saouda Group BIF as well as Neoproterozoic BIF of the Ijibbitene Group (described below).

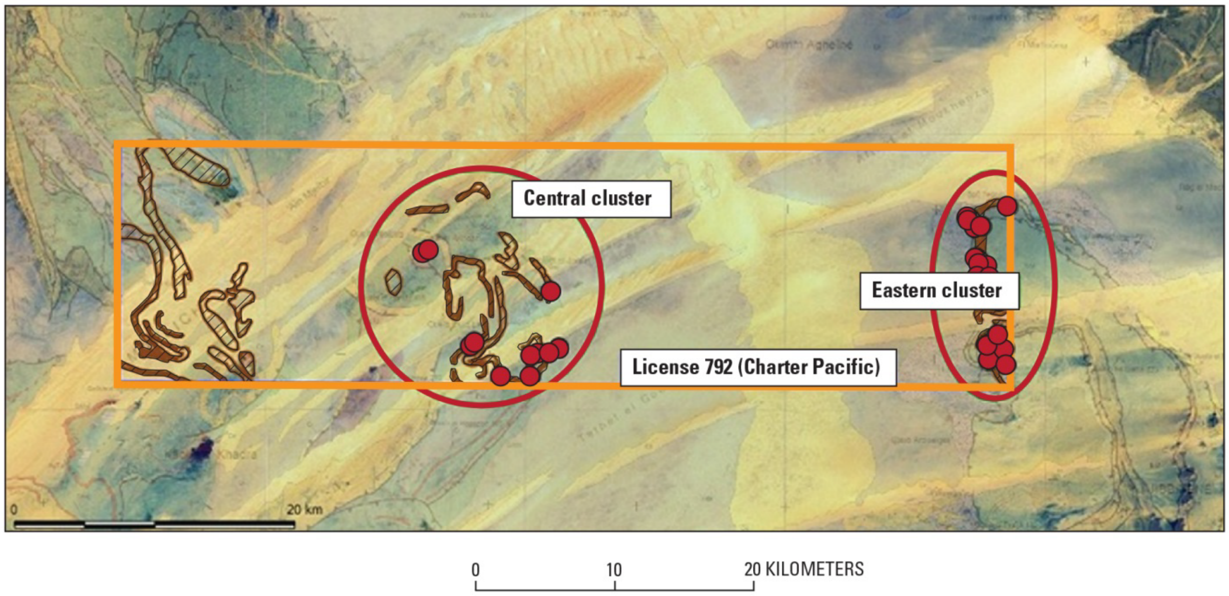

Figure 50. Satellite image of Prospecting Permit 792 showing the locations of clusters of BIF within the Charter Pacific Kaoua El Khadhra Project area in the southern Inchiri district (modified from Charter Pacific Resources Limited, 2012).

During 2012, Charter Pacific carried out detailed ground magnetic surveys in the permit area resulting in the extension under cover of intermittently outcropping BIF in their Central Cluster within Saouda Group rocks, and in their Eastern Cluster within Neoproterozoic BIF of the Ijibbitene group. The location of sampling in the Central Cluster corresponds approximately with the location of the Amlil Bou Kerch occurrence listed in the Mauritanian National Mineral Deposits Database (Marsh and Anderson, 2015). Additional magnetic targets were identified under sand cover in the western part of the permit area. Site visits in the eastern area resulted in the observation of extensive non-magnetic (hematite-rich?) iron formation in a 2 square kilometer exposure within the Neoproterozoic Jbeliat and Teniagouri Groups (Byrne, 2012). This target is located approximately 3 km north of a known iron occurrence, which we suggest is probably the Gleib Aroueiguil occurrence (fig. 43; Marsh and Anderson, 2015). If sampling confirms the presence of elevated iron content in these rocks, it will significantly increase the exploration potential of the Jbeliat and Teniagouri Groups for iron resources. These rock groups have not previously been known to host significant occurrences of iron in Mauritania. Based on their recent ground-based magnetic studies and analyses of samples collected Charter Pacific suggests that their permit area potentially contains 2.6 to 4.4 billion tonnes of BIF at grades of 18 to 39 percent iron (Byrne, 2012; Charter Pacific Corporation Limited, 2012).

Very little is known about iron occurrences hosted in the Saouda Group at Gleibat Zeilouf, Amenchika, Amlil Bou Kerch, and Aftout De Faye. The Mauritanian National Mineral Deposits Database (Marsh and Anderson, 2015) contains short descriptions suggesting that all consist of magnetite-hematite bearing oxide-facies BIF variably hosted within greenschists, amphibolites, and quartzites. Amlil Bou Kerch apparently consists of a horizon of ferruginous quartzite overlying carbonate rocks. Gleibat Zeilouf and Amenchika were discovered in the mid-1950s and Amlil Bou Kerch and Aftout De Faye in the mid-1960s (Marsh and Anderson, 2015). As described above, we speculate that most if not all of these occurrences are currently being prospected under different names by Transafrika and Charter Pacific.

To the east and north, the Tamagot window and Bou Kerch nappe are overthrust by the Choueima nappe, which comprise the volcanosedimentary host rocks to numerous mineral occurrences of the Inchiri district. The nappe is centered on the village of Akjoujt (fig. 43) and consists of the Eizzene and Oumachoueima Groups separated by an angular unconformity. The older Eizzene Group consists of a lower sequence of mafic volcanic rocks, the Raoui Formation, overlain by the Khmeiyat Formation. The Khmeiyat Formation is marked by a regionally extensive BIF at the base (figs. 51 and 52) followed by an entirely metasedimentary succession characterized by low-grade, pelitic to semi-pelitic schist-phyllites with psammitic subgraywackes, quartzites, and intermittent thin BIF (Pitfield and others, 2004).

Figure 51. Outcrop of the Eizzene Group, Khmeiyat Formation BIF about 14 kilometers northwest of Akjoujt. USGS photo.

Figure 52. Close-up of Eizzene Group, Khmeiyat Formation BIF showing meso- to microbanded silicates and oxide-facies BIF. USGS photo.

The second volcanosedimentary succession of the Choueima nappe consists of the Oumachoueima Group (fig. 43), which hosts the majority of known mineral occurrences of the Inchiri district. It is the most aerially extensive rock unit present in the district and occupies the majority of the center, northern, and northeastern portion of the Akjoujt nappe pile (fig. 43). It overlies the Amsaga terrane above a major sole thrust fault along the northern margin of the district and is in thrust contact with the overlying Hajar Dekhen-Kleouat nappe along a curvilinear western boundary. From its unconformable basal contact with the Eizzene Group, the Oumachoueima Group passes upwards from siliciclastic through pelitic sedimentary rocks into andesite-dacite derived volcaniclastic and proximal volcanic rocks followed by submarine basaltic flows and synvolcanic intrusions. BIF units occur at several stratigraphic levels within the Group (Pitfield and others, 2004).

The Oumachoueima Group commences with the Atilis Quartzite member of the clastic Irarchene El Hamra Formation and then transitions into dominantly quartz-chlorite±muscovite schists. The Irarchene El Hamra Formation is overlain by volcanogenic sedimentary rocks and BIF of the Atomai Formation, which is dominantly composed of volcanogenic siltstone and graywacke metamorphosed to chlorite±sericite+quartz±carbonate schists with quartz-carbonate-magnetite BIF horizons ranging up to several tens of meters in thickness. The BIFs vary in composition but are dominated by Fe-carbonate and quartz with unevenly distributed magnetite. Tabular to podiform coarse-grained ankeritic Fe-Mg carbonate±quartz and magnetite occur sporadically within or adjacent to the iron formations (figs. 53 and 54). Fine grained, massive, millimeter- to centimeter-scale banded, oxide facies hematite-magnetite-quartzite BIF±muscovite, chlorite, and tourmaline is also present and contains introduced calcite and Fe-carbonates. Thin units of locally pillowed metabasalt and metamicrogabbro sills occur sporadically in the upper part of the formation (Pitfield and others, 2004).

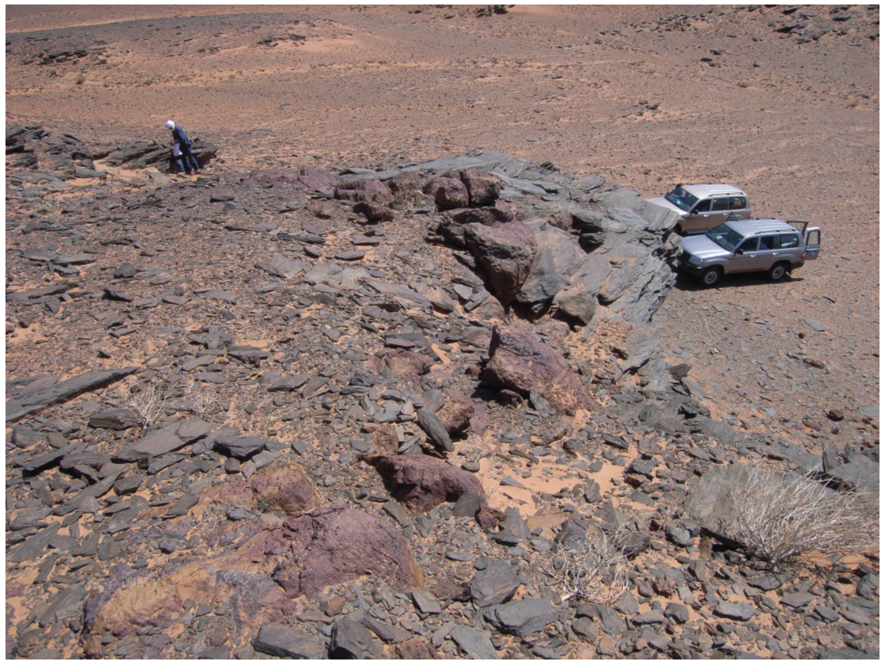

Figure 53. Large pod of coarse-grained ankeritic Fe-Mg carbonate ± quartz and magnetite occupying the contact between thin-banded cherty iron formation of the Oumachoueima Group, Atomai Formation (left of vehicles) and the overlying volcanosedimentary rocks of the St. Barbe Formation (not visible in photo). USGS photo.

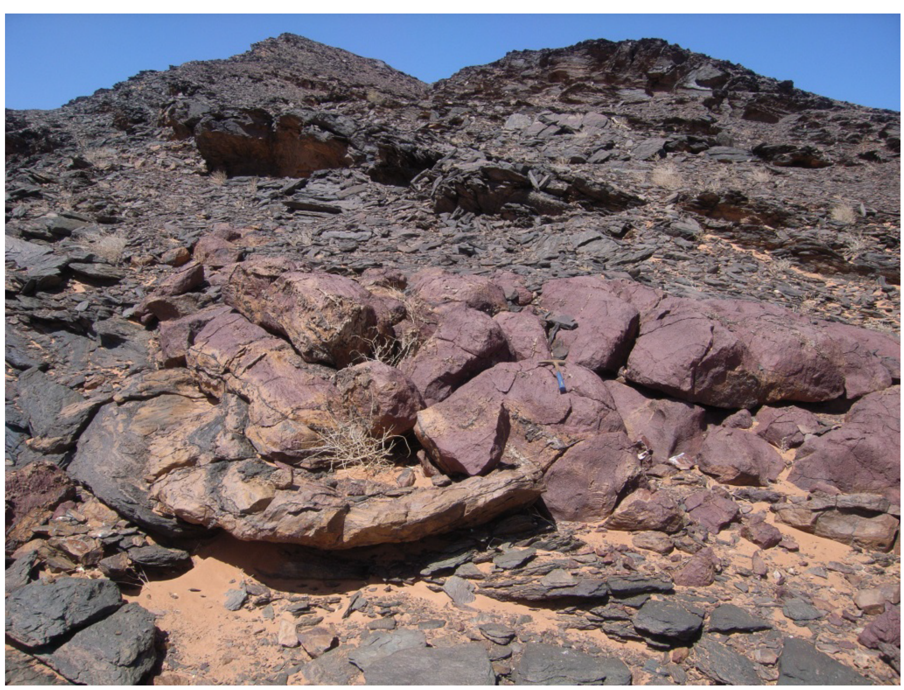

Figure 54. Large pod of coarse-grained ankeritic Fe-Mg carbonate ± quartz and magnetite occupying the contact between thin-banded cherty iron formation of the Oumachoueima Group, Atomai Formation and the overlying volcanosedimentary rocks of the St. Barbe Formation. USGS photo.

The Atomai Formation is overlain by proximal volcanic to distal volcaniclastic rocks of dominantly intermediate composition of the Sainte Barbe Formation (fig. 54). The Sainte Barbe Formation is capped by a widespread marker unit consisting of chert and BIF of the Lembeitih Formation. The Lembeitih Formation (figs. 55 and 56), which is generally less than 10 meters thick andvaries from recrystallized pyritic chert in the Guelb Moghrein mine, to quartz-magnetite or hematite iron formation towards Loueibda, and quartz-carbonate-magnetite banded iron formation in the El Joul-El Khader area.The stratigraphy culminates in a monotonous pile of submarine basalts and related microgabbroic intrusive rocks of the Akjoujt Formation (Pitfield and others, 2004). Detailed geology of the Akjoujt nappe pile is shown in figure 57. The stratigraphy of the Akjoujt nappe pile and possible correlations to other rocks described in this section is shown in figure 58.

Figure 55. Outcrop of the Oumachoueima Group, Lembeitih Formation BIF about six kilometers north-northeast of Akjoujt. USGS photo.

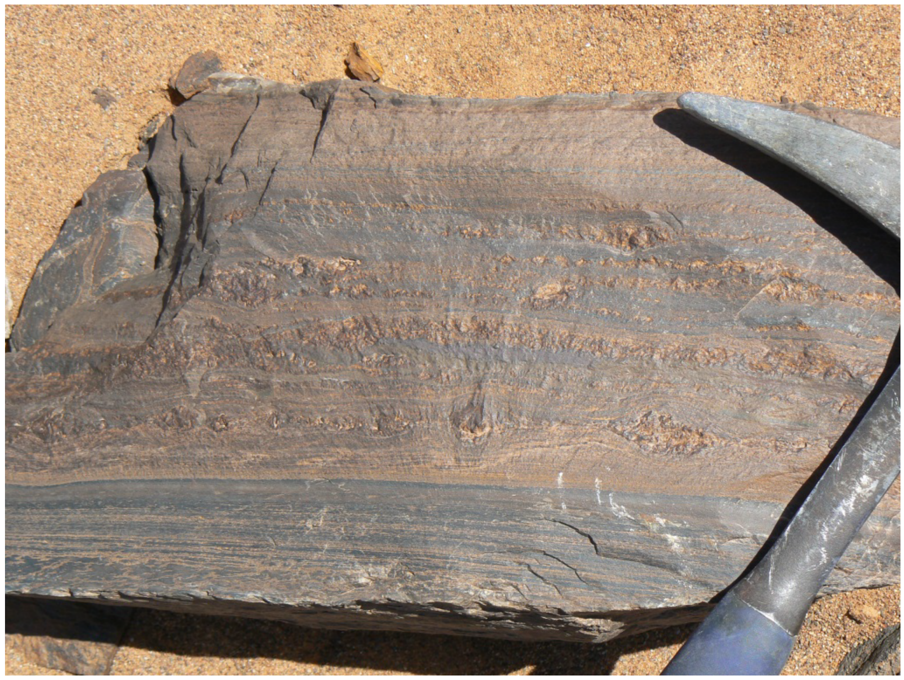

Figure 56. Close-up of Oumachoueima Group, Lembeitih Formation BIF showing microbanded oxide-facies BIF with cm-scale clots of iron carbonate. USGS photo.

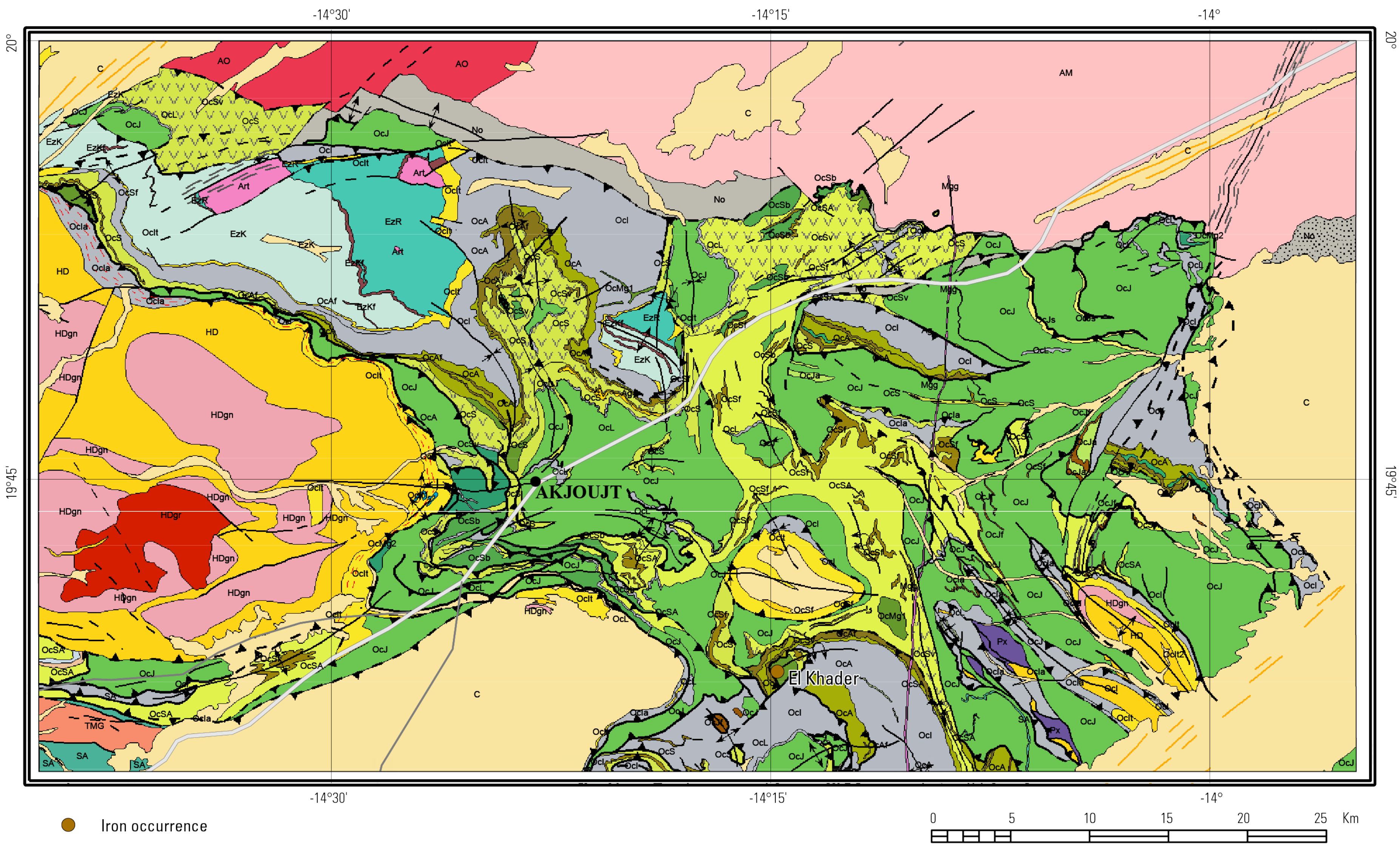

Figure 57. Detailed geology of the Akjoujt nappe pile (from Pitfield and others, 2004).

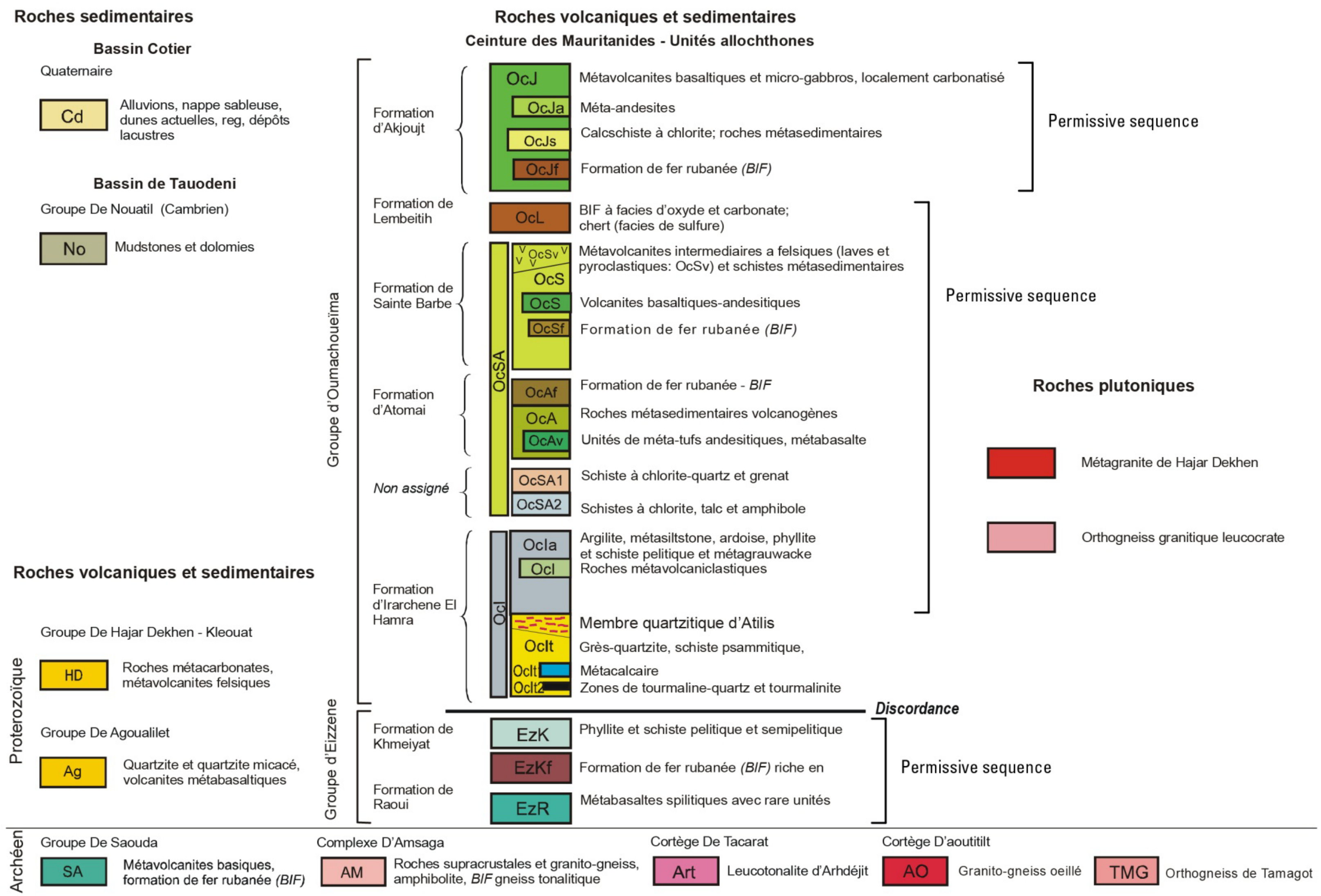

Figure 58. Stratigraphic section and correlation diagram of rocks in the Akjoujt nappe pile (from Pitfield and others, 2004).

The structurally highest nappe in the Akjoujt nappe pile is the Hajar Dekhen-Kleouat nappe that overlies the Choueima nappe primarily to the west of Akjoujt (fig. 43). Rocks of the Hajar Dekhen-Kleouat Group consist of amphibolite facies supracrustal metamorphic and granitic rocks and are not known to contain Algoma-type BIF. Previously thought to consist of overthrust basement, the nappe also contains rocks of the Eizzene and Oumachoueima Groups. Correlation of rocks in the Hajar Dekhen-Kleouat nappe depends on the age and correlation of the Eizzene Group (Pitfield and others, 2004).

An additional nappe is located to the east of the Akjoujt nappe pile and consists of metavolcanosedimentary rocks of the Ijibbitene Group (fig. 43). Rocks of the Ijibbitene Group in the Ijibbitene nappe are tentatively correlated with the lower part of the Choueima nappe (for example, the Eizzene Group; Pitfield and others, 2004). Descriptions of the constituent formations of the Ijibbitene Group indicate that the El Mbehteh Formation and especially the Bou Demje Formation contain magnetite-quartzite BIF known to host iron occurrences.

Despite the widespread occurrence of iron formation in multiple stratigraphic levels of the Eizzene and Oumachoueima Groups throughout the Choueima nappe, there are currently no known BIF-hosted iron occurrences in the nappe. To the best of our knowledge, there has been little historical exploration interest in the Neoproterozoic BIF of the Akjoujt nappe pile. Similarly, with one exception, all current iron exploration is focused on the Mesoarchean BIF of the Saouda Group and the presumed Neoarchean BIF of the Ijibbitene Group. The exception is the unusually thick and well exposed iron oxide cap over the El Khader Cu-Au occurrence located in a range of hills approximately 19 km southeast of Akjoujt named the Legleitat El Khader (fig. 43; Marsh and Anderson, 2015). As described above, El Khader was discovered by BUMIFOM during exploration for iron and copper-gold deposits similar to Guelb Moghrein in the early 1950s. Although initially evaluated as an iron resource, the primary exploration at El Khader over the last 50 years has been for IOCG deposits. El Khader is located within the Tamagot permit area held by Bumi Minerals and the iron resource there is included within the resource figures estimated by Bumi Minerals for their holdings in Mauritania. Gunn and others (2004) provide an excellent description of the El Khader Cu-Au occurrence and iron deposit based on their review of previous work and fieldwork during the BGS program in 2003. The description below is based on their work and is augmented by additional observations resulting from USGS fieldwork in October, 2007.

The El Khader iron deposit is located in a domal structure at the intersection of a north-east-trending asymmetric antiform with a north-northwest-trending antiform that is imposed on a complex system of early, stacked thrust sheets. The dome (the Legleitat El Khader) is approximately 4 km^2 in size and rises about 100 m above the surrounding plain. The dome is bounded to the southeast by metasiltstone and greywacke of the Irarchene el Hamra Formation and to the southwest, west, and northwest by BIF and tuffaceous siltstone of the Atomai Formation. The northeastern side of the dome is bounded by quartz-sericite-altered felsic volcaniclastic rocks assigned to the Sainte Barbe Formation. Metamicrogabbro occurs widely in the core of the dome, although exposure is obscured by extensive areas of supergene ironstone. The Cu-Au occurrence is chiefly related to an area of Fe-Mg carbonate stockwork and veining, which extends up to 2 km in maximum dimension. Supergene oxidation of this carbonate has given rise to a massive silica-iron oxide cap, up to 60 m thick, consisting primarily of goethite and hematite. At depth, the abundance of carbonate decreases and is restricted to narrow veins within altered metamicrogabbro country rock. Sodic alteration of the microgabbro is present as almost pure andesine rock in contact zones, with carbonate and disseminated albite further from the veins. Quartz-sericite alteration is widespread in the felsic volcaniclastic rocks, while silicification and quartz veining are locally important (Gunn and others, 2004).

Modern exploration commenced at El Khader in 1953 when it was examined as a potential source of iron ore. Between 1953 and 1957, about 75 shafts were excavated (total depth 1,843 meters) and nine diamond drill holes (810 m) were drilled leading to the definition of a proven resource of 11 Mt around 51 percent Fe. There are no data available on the Au and Cu contents of this resource. Further drilling and pitting by the Société des Mines de Cuivre de Mauritanie (MICUMA) in 1958 yielded an estimated possible resource of 18 Mt (Maurin, 1993). Subsequently Charter Consolidated carried out surface sampling and trenching for copper in 1970. Further drilling was carried out by SNIM in 1975 (Gunn and others, 2004).

Subsequent investigations by BRGM in 1992 and by BRGM in joint venture with OMRG in 1995 and 1997, and the OMRG-BRGM-GGISA consortium in 1997, focused mainly on Au and associated Cu and Co. These studies are discussed more thoroughly in the context of IOCG exploration elsewhere (Gunn and others, 2004; Fernette, 2015). However, the presence of scheelite and tourmaline in sediment samples from oueds draining the dome and elevated Cu, Mo, W, As, and Sn in rock samples from the northern sector of the dome supports the interpretation that the El Khader Cu-Au occurrence is unlike other supposed IOCG occurrences in the district and that an underlying felsic intrusion may be present (Gunn and others, 2004; Pitfield and others, 2004). However, drilling in 1997 in the northern sector of the dome intersected a succession of schists, quartz-schists and ferruginous quartzites, with variable amounts of carbonate, underlain by green 'metadiorites'. The most recent activity at El Khader prior to the current phase of iron exploration by Bumi Minerals was a limited and unsuccessful drilling program for primary Cu-Au mineralization in the northern sector in 2000 by Normandy LaSource (Strickland and Martyn, 2002; Gunn and others, 2004).

In October 2007, a USGS field team made a one-kilometer-long traverse of the Legleitat El Khader along a dry oued exiting the western margin to the highest point of the dome approximately 300 m south of the published location of the Cu-Au occurrence (Marsh and Anderson, 2015). Country rock at the start of the traverse consists of thin-bedded siltstones of the Atomai Formation that progresses immediately into a zone of quartz-carbonate stockwork veining and hematite-rich BIF breccia at the flank of the dome (fig. 59). Minor amounts of green malachite, brochantite (hydrous copper sulfate), tetrahedrite or chalcocite, and black hematite occurs as matrix in quartz-rich breccias. Quartz-carbonate stockwork veining and brecciated blocks of Atomai Formation BIF and siltstone interspersed with white quartz vein fragments persist for a distance of approximately 50 to 100 meters into the dome and then are covered by the extensive silica-iron oxide cap that characterizes all outcrop exposure to the summit of the dome (fig. 60). Numerous sample sites, drill hole collars, short adits and shafts, drill roads and various areas of surface disturbance are visible over most of the upper slopes of the dome (fig. 61), attesting to the over 50 years of interest in both iron as well as Cu-Au resources at El Khader. In outcrop and hand specimen the cap consists of massive, dense to highly porous mixture of reddish brown to black silica, hematite, and goethite (fig. 62). Mineral textures range from bladed to fibrous, and commonly in botryoidal clusters with individual goethite balls in the centimeter to decimeter size range (fig. 63). However, amorphous reddish-brown massive to slightly porous, ochreous exposures of iron oxide-silica characterize the bulk of the cap.

As described above, there are three occurrences (Gleib Aroueiguil, Guelb Boudemge, and Gleibat Zonzer) hosted in BIF the Neoproterozoic Ijibbitene Group located to the southeast of the Akjoujt nappe pile in the Ijibbitene nappe (fig. 43). Similar to the tectonic setting of the Akjoujt nappe pile, the Ijibbitene nappe is an allochthonous package of Neoproterozoic supracrustal rocks that has been thrust eastward against the western margin of the Taoudeni Basin during Pan African and Hercynian orogenies. The presence of BIF is reported in two units of the Ijibbitene Group; it is a common feature of the El Mbehteh Formation and is the major component of the

Bou Demje Formation. Individual massive BIFs are rarely more than five meters thick, however, multiple decimeter- to meter-scale BIF horizons frequently occur within any given stratigraphic interval. They commonly have transitional ferruginous schists in the footwall (Pitfield and others, 2004).

Figure 59. Quartz-carbonate stockwork veins and BIF breccia in Atomai Formation siltstone at the western margin of the Legleitat El Khader. USGS photo.

Figure 60. View looking west at the western margin of the Legleitat El Khader and the extensive iron oxide-silica cap covering all exposures in the interior of the dome. USGS photo.

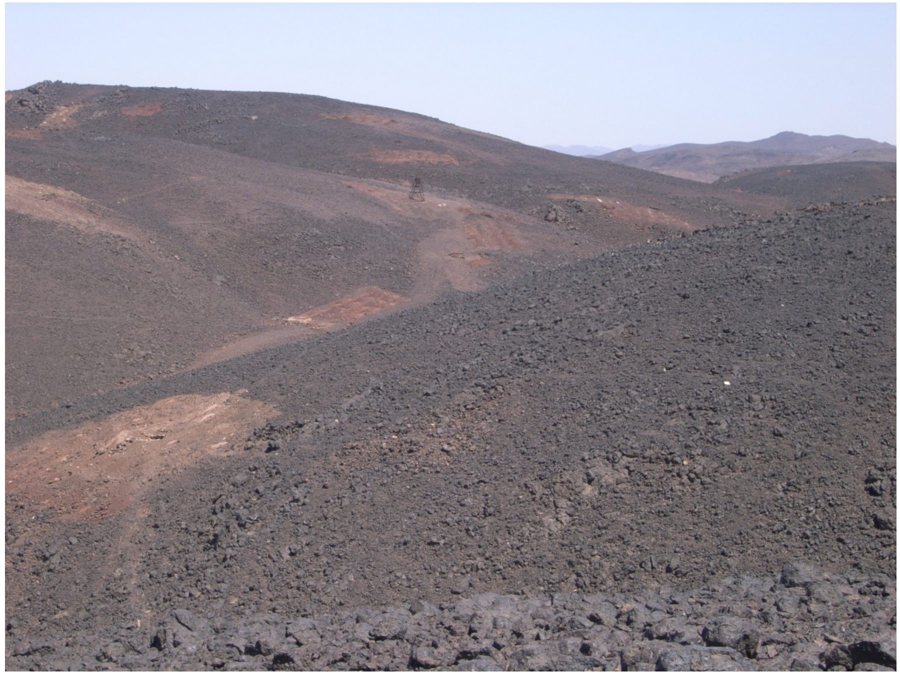

Figure 61. View looking north across the Legleitat El Khader iron oxide silica cap from the summit of the dome. Note the light colored cemented drill hole collars in the left foreground and center, the metal headframe in upper center, and the numerous light brown areas of gridded bulk sampling. USGS photo.

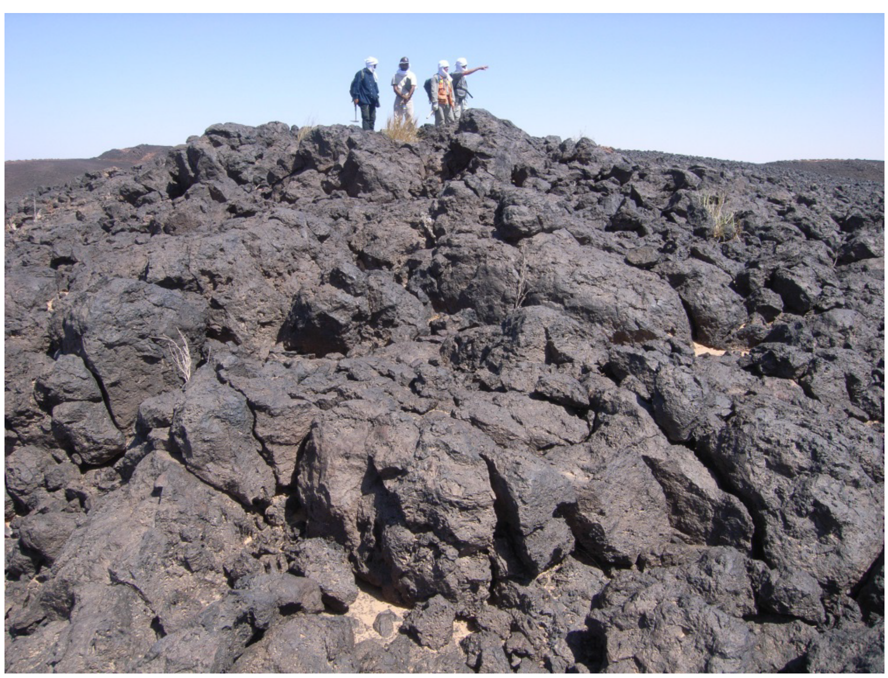

Figure 62. Exposure of massive to porous iron oxide-silica at the summit of Legleitat El Khader. USGS photo.

Figure 63. Botryoidal goethite in the iron oxide-silica cap at Legleitat El Khader. USGS photo.

The BIF is composed of alternating bands of millimeter- to centimeter-thick recrystallized white siliceous and brown or black iron-rich bands. Magnetite-rich oxide facies iron formation is most common with rare pyrite+/-pyrrhotite-bearing sulfide facies BIF occurring as thin units of <0.5 meters thickness. Carbonate-facies BIF of the type present in the Akjoujt nappe pile (Atomai Formation) has not been reported. The thick oxide facies units commonly exhibit an upward gradation from slaty (or platy) BIF with micaceous partings of muscovite and Fe-biotite to massive to slabby and finely laminated BIF. The slaty structure is commonly associated with shearing along the footwall (Pitfield and others, 2004).

The Guelb Boudemge occurrence (Marsh and Anderson, 2015) is located near the center of the Ijibbitene massif in schists and quartzites of the Ed Dab'a Formation. Brief descriptive information suggests that the occurrence consists of ferruginous quartzites. No additional information is available. Similarly, there is very little descriptive information for the information for the Gleibat Zonzer and Gleib Aroueiguil occurrences. The Gleibat Zonzer occurrence is located in an area mapped as Quaternary regolith off the southeastern margin of the Ijibbitene massif and is described as ferruginous quarztites in a sequence of Ijibbitene Group quartzites and schists (Marsh and Anderson, 2015). Interestingly, the Gleib Aroueiguil occurrence is located just off the west side of the massif in an area mapped as undifferentiated volcanosedimentary rocks and tillites of the Teniagouri and Jbeliat Groups. Sparse descriptive information suggests that the occurrence consists of quartz, specular and amorphous hematite, and fluorite in metasedimentary rocks of the Teniagouri Group (Marsh and Anderson, 2015). No other information is provided.

In summary, BIF units in the Inchiri district that are permissive of Algoma-type iron deposits include the Mesoarchean Saouda Group, and Neoproterozoic BIF horizons in the Khmeiyat Formation, the Atomai Formation, the Sainte Barbe Formation, the Lembeitih Formation, and the Akjoujt Formationin the Akjoujt nappe pile and the El Mbehteh and Bou Demje Formations in the Ijibbitene nappe. Six known iron occurrences are present in the Saouda Group BIF with the occurrences at Tamagoth/Arierat El Khader and Kaouat El Khadra the subjects of current evaluation projects. There are currently no known iron occurrences defined in the numerous Neoproterozoic BIF horizons in the Akjoujt nappe pile. Although BIF in both the Khmeiyat and Lembeitih Formations are tens of meters thick and regionally persistent, traceable units, they do not form any known guelbs or ridges where mineable quantities are present due to fold or thrust duplication and thickening as in the F'Derik region. BIF of the Atomai, Sainte Barbe, and Akjoujt Formations, despite being tens of meters thick, contains sulfide and carbonate facies minerals in addition to oxide facies and are thus of lower iron grade and not economically attractive. The hematite-goethite-silica deposit covering the Cu-Au occurrence at El Khader is an unusual type of iron deposit unrelated to Algoma-type BIF. BIF units in the Ijibbitene nappe are host to three known occurrences of Algoma-type iron formation and are currently the subject of private company interest.

5.2.6 Southern Mauritanides

Although not currently the subject of private industry exploration for iron resources, Neoproterozoic iron formation is present in metavolcanosedimentary rocks of the Gueneiba and Gadel Groups of the Gorgol Noir Complex in the southern Mauritanides. The area here referred to as the southern Mauritanides consists of the Mauritanide orogen from about latitude 17^{o} south to the border with Senegal. The host rocks in the southern Mauritanides are dominantly Neoproterozoic through Cambrian metasedimentary and metavolcanic units that were accreted to and thrust upon the Gondwanan continental margin during early Paleozoic Pan-African tectonism in West Africa. Collision with the North American craton during Hercynian times (approximately 330–270 Ma) reactivated many of the structures from this earlier collisional orogen and formed the Appalachian-Mauritanian belt, which later broke apart during Triassic rifting.

The southern Mauritanides consist of a north-south trending pile of thrust slices of allochthonous and parautochthonous units juxtaposed against the Neoproterozoic to Paleozoic rocks of the western Taoudeni Basin foreland sequence (Le Page, 1988; Pitfield and others, 2004).The parautochthonous zone lies between the foreland and the infrastructural allochthonous zone to the west and consists of deformed sedimentary rocks of the Adrar Supergroup imbricated with local basement inliers or tectonic windows (such as the Zemzem window). The infrastructural allochthonous zone consists of imbricated ophiolites, continental margin rift-facies and calc-alkaline igneous complexes. Two major tectonostratigraphic divisions are recognized in the southern Mauritanides; (1) the western side of the allochthon consists of calc-alkaline metavolcanic and metasedimentary supracrustal rocks with mainly greenschist facies mineral assemblages, collectively termed the Mbout Supergroup, and (2) an eastern belt consisting of a tectonic melange and associated metavolcanic and intrusive rocks, termed the Gorgol Noir Complex, typified by greenschist to high- pressure amphibolite facies mineral assemblages (fig. 64; Pitfield and others, 2004). The Mbout Supergroup does not contain appreciable amounts of iron formation and will not be described further.

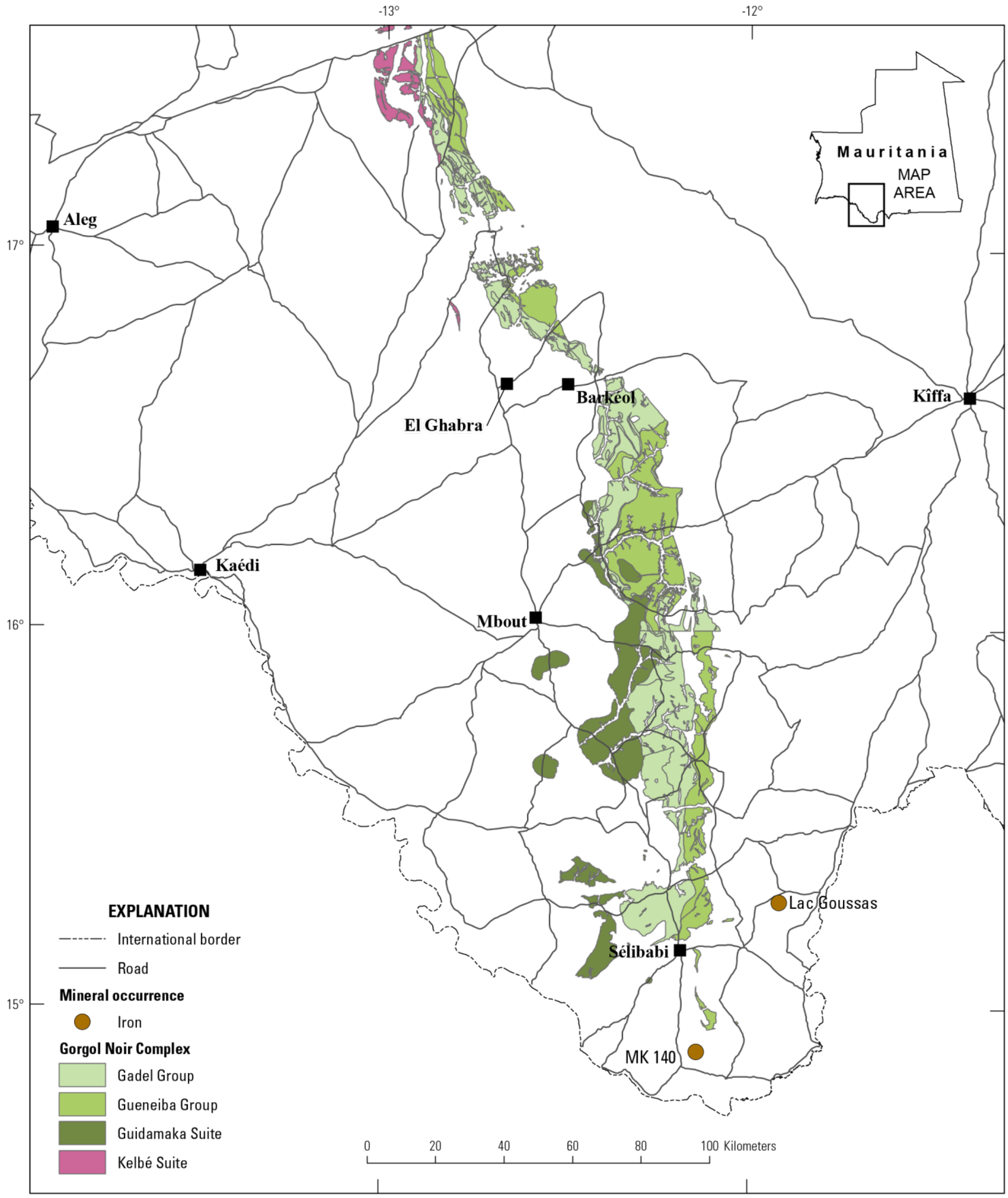

Figure 64. Simplified geology of the Gorgol Noir Complex in the southern Mauritanides.

The Gorgol Noir Complex consists of ophiolite and continental margin–rift facies sequences divided into three tectonically imbricated groups, each with characteristic lithologies (fig. 64). First, the upper western Guidamaka Suite consists of massive gabbro and associated more felsic intrusive rocks. The intrusive suite has many of the characteristics of a plagiogranite association but is metasomatically altered and exhibits some crustal inheritance. This intrusive suite has no potential for iron formation and will not be discussed further. Second, the lower eastern El Gueneiba Group consists of a middle-upper greenschist facies oceanic lithospheric or ophiolitic association dominated by metabasaltic rocks. The metabasic rocks have characteristics of submarine tholeiitic basalt but exhibit a more alkaline or transitional within-plate chemistry. Finally, the central Gadel Group is interpreted as a melange composed of a range of lithologies including serpentinite and quartzite (Pitfield and others, 2004). It consists of an internally imbricated middle to lower amphibolite facies, continental margin rift-facies association containing major tectonic rafts of the El Gueneiba Group. The melange is tectonically intercalated with deformed parautochthonous sedimentary rocks of the Taoudeni Basin in the extreme south. The Gadel Group melange occurs structurally below as well as above the El Gueneiba Group, which suggests that the metavolcanic rocks form one or more very large units in the form of frontal klippen within the melange (Pitfield and others, 2004).

Lithologies within the Gadel Group consist of two major associations: (1) a predominantly magmatic association including ultramafic rocks (serpentinites), metabasalts, ferruginous jaspilites, garnet amphibolites, albitites, metagabbros, greenschists, and metacarbonate rocks, and (2) a siliciclastic metasedimentary association consisting of muscovite and kyanite quartzites with or without garnet and staurolite, and pelitic mica schists. Because the Gadel Group is a tectonically imbricated melange, no lithostratigraphic or tectonostratigraphic succession can be defined. However, in general, a simplified succession of serpentinites associated with talc schists, greenschists, ferruginous quartzites, amphibolites and jaspilites in the west transition eastward into kyanite-staurolite-garnet quartzites and micaschists, muscovite quartzite, muscovitic schists and local amphibolites (Pitfield and others, 2004). The serpentinite bodies form the main areas of high relief in the group and have a wide range of appearances and variable primary and secondary mineralogy. They are commonly capped by birbiritic gossans that have secondary chert and carbonate filling fractures that separate clasts of the host serpentinite. The serpentinites are usually sandwiched between mylonitic, variably ferruginous quartzites and/or quartz-muscovite/sericite-schists. Talc-schists invariably form lenticular bodies that are rarely more than several hundred meters in length and are always enclosed by serpentinite. Geochemical profiles for the serpentinites suggest a within plate, non-arc environment of formation. Ferruginous jaspilites and subordinate BIF are common within the Gadel Group melange and form resistant, black- weathered low ridges. They are mostly associated with the pelitic schists, mafic and ultramafic rocks (Pitfield and others, 2004).

No direct U-Pb zircon dates are reported for rocks of the Gadel Group. $^{40}Ar/^{39}Ar$ incremental release ages for hornblende and muscovite concentrates suggest that post-metamorphic cooling occurred following distinct Neoproterozoic tectonothermal events at approximately 700–720 Ma and 640–650 Ma (Dallmeyer and Lécorché, 1989). The younger episode is related to the Pan-African 1 continental collision and broadly corresponds to U-Pb dates obtained for the syn- to post-kinematic granitoid suites of Guidamaka (665 Ma) and Selibabi (637 Ma; Pitfield and others, 2004). Muscovite within Gadel Group lithologies cooled through argon closure temperature between approximately 570 and 595 Ma (Pitfield and others, 2004). The Gadel Group melange is interpreted to represent a major tectonic suture. The ultramafic rocks represent tectonized oceanic lithosphere. They are commonly associated with ferruginous jaspilites and metacarbonate rocks. The mafic rocks have two distinct geneses: one suite is comparable to the El Gueneiba Group metabasaltic rocks (described below) with a within-plate chemistry whereas the amphibolites have a composition more typical of a subduction-related volcanic arc derivation. Their association with distal turbidites is consisted with their oceanic origins (Pitfield and others, 2004).

The El Gueneiba Group is imbricated with and locally incorporated within the Gadel Group (fig. 64). It is characterized by calc-chlorite schists, chlorite±talc±amphibole schists and deformed metabasalts (pillow lavas and breccias) metamorphosed to middle-upper greenstone facies. The group remains undifferentiated in the southern Mauritanides with the exception of intrusive suites of the Guidamaka Suite (fig. 64). Less common lithologies include quartz-sericite-phyllites, chlorite-quartz-schists, deformed metabasalts with quartz-carbonate segregations associated with pillow breccias, ferruginous jaspilites, metakeratophyres, and massive, fine-grained marble with pyritic clots. Local intercalations of BIF lithologies are present and consist of millimeter-thick iron-rich seams with magnetite and (or) hematite separated by thicker siliceous bands of quartz and chert. Quartz veins are extremely common and a veneer of vein quartz gravel covers large portions of the outcrop area (Pitfield and others, 2004).

Geochemical profiles of major lithologies of the El Gueneiba Group show wide variation from patterns consistent with alkaline, within plate tectonic settings to subduction-related volcanic arc patterns. The presence of pillows in the metabasaltic volcanic rocks suggests deposition in a submarine setting. The El Gueneiba Group is interpreted to consist of a disrupted ophiolite consistent with the rest of the Gorgol Noir Complex. Intrusive (?) relationships with dated granitic rocks of the Guidamaka Suite suggest a minimum age of 665±2.7 Ma (Pitfield and others, 2004).

Based on the above descriptions there are numerous features of the Gadel and El Gueneiba Group rocks such as pillow basalts, co-genetic mafic and ultramafic intrusive bodies, ferruginous jaspilites, BIF, malachite-bearing volcaniclastic rocks and pelitic schists that are permissive of seafloor exhalative processes and specifically Algoma-type iron formation. The presence of a number of known Cu±Au occurrences that are interpreted to represent VMS occurrences (Taylor and Giles, 2015) increases the favorability of the permissive rock sequences.

Numerous metallic mineral occurrences are present in the southern Mauritanides and include a variety of mineral deposit types such as VMS (see Taylor and Giles, 2015) orogenic gold (see Goldfarb and others, 2015), Guelb Moghrein-like IOCG (see Fernette, 2015), Cu-Ni-PGE-bearing magmatic sulfide deposits, and podiform chromite±PGE deposits (see Taylor and others,2015). Due to the recognized potential of the region, the area has been the subject of multiple exploration campaigns dating to the first surveys by the BRGM from the mid-1960s to the mid-1970s, followed by various collaborations of the OMRG with the BRGM and a German private company, Otto Gold, through the mid-1990s. In 1995, exploration rights to the M40 concession area consisting of a 20,000 km^2 section of the Southern Mauritanides from just north of the Bou Zrabie and Kadiar occurrences to the border with Senegal. Their work included stream sediment, panned concentrates and BLEG sample surveys, and detailed studies at 28 prospects, using shallow soil sampling, trenching/pitting, rock chip sampling, geophysical surveys and geological mapping. RC drilling (51 holes, 4,180 m) was carried out at several targets with limited diamond drilling (5 holes, 808 meters) at a few localities. Over 20,000 geochemical samples were ultimately collected and analyzed (Gunn and others, 2004). As a result of these various programs, the basic geological relationships at many of the more important mineral occurrences have been documented. Gunn and others (2004) provide excellent descriptions of many of the known prospects based on their review of previous work and fieldwork during the BGS program in 2003.

Despite the multiple periods of exploration in the southern Mauritanides for a variety of mineral deposit types, there are no known iron occurrences in the southern Mauritanides listed in the Mauritanian National Mineral Deposits Database (Marsh and Anderson, 2015). However, the widespread presence of BIF in rocks of the Gueneiba and Gadel Groups of the Gorgol Noir Complex indicate that they are permissive of Algoma-type iron deposits. Permissive tracts have therefore been drawn on these units, however, they are regarded as having low potential for the occurrence of economic iron deposits.

5.3 Oolitic Ironstone Occurrences in Mauritania

Phanerozoic oolitic ironstones are present in two locations in Mauritania. The largest known accumulations of this type are located on the southern flank of the Tindouf Basin. Both the Black Zenmour and North Yetti sub-basins of the Tindouf Basin contain oolitic ironstones within Silurian and Devonian platform sedimentary rock sequences. Within the Black Zenmour sub-basin ironstone occurrences are present at the Bir Aidiate, Tighirt, Oumat el Ham, and Khang Leghouat occurrences. The North Yetti sub-basin contains the western portion of the Gara Djebilet West deposit, which is part of the Gara Djebilet field that straddles the border with Algeria. A second occurrence is located near the border with Western Sahara at Oued el Hamra. A second area of oolitic ironstone is present on the western margin of the Taoudeni Basin north of Tidjikja.

5.3.1 Oolitic Ironstones of the Tindouf Basin

The Tindouf Basin is a post-Silurian west-southwest to east-northeast trending asymmetrical basin covering over 120,000 km^2 and bounded to the north by the Moroccan Anti-Atlas mountains, on the south by the Rgueïbat Shield, to the West by the El Aioun depression, and to the east by the Erg Chech depression. The majority of the basin is in Algeria with portions in Western Sahara, Morocco, Algeria, Mauritania, and Libya. The basin consists of Cambro-Ordovician to Carboniferous marine sedimentary rocks overlain by continental Cretaceous sedimentary rocks and Cenozoic cover (Guerrak, 1989). Numerous oolitic ironstone deposits are present within Silurian and Devonian sedimentary rocks along the gently northward dipping southern margin of the Basin. Together they define the North African Paleozoic oolitic ironstone belt that stretches approximately 3,000 km along the northern flank of the Rgueïbat Shield from the Black Zenmour sub-basin to Libya (Guerrak, 1989). Small portions of the southernmost margin of the Tindouf Basin are present within Mauritanian territory in the Black Zemmour sub-basin to the northwest of Bir Moghrein and in the North Yetti sub-basin in the northernmost tip of Mauritania along the road to Tindouf, Algeria. Guerrak (1989) has estimated that the ironstone belt may contain as much as 10.7 billion tonnes (1.5 billion in Silurian and 9.2 billion in Devonian rocks) of oolitic iron formation.

Of the several major oolitic ironstone deposits located along the southern margin of the Tindouf Basin, only the Gara Djebilet field contains iron resources within Mauritanian territory. The Gara Djebilet field is the westernmost of two small depositories in the North Yetti sub-basin that are separated by uplifts (fig. 65). The Djebilet depository developed on the western flank of the Aouinet uplift. The Gara Djebilet field is developed in the Early Devonian (Lochkovian and Pragian) Gara Djebilet Formation (of Algeria) that extends east-west for a distance of about 60 km. Oolitic ironstone resources are developed in the uppermost cycle of the Early Devonian Gara Djebilet Formation (fig. 66) in three main deposits; Gara Djebilet West, Center, and East. The Gara Djebilet West deposit straddles the Algeria-Mauritania border and extends along strike into Mauritania for approximately 13 km (fig. 67). The Gara Djebilet West deposit (in Algeria) is approximately 14 × 4 km in size and 6-30 meters thick (Guerrak, 1988).

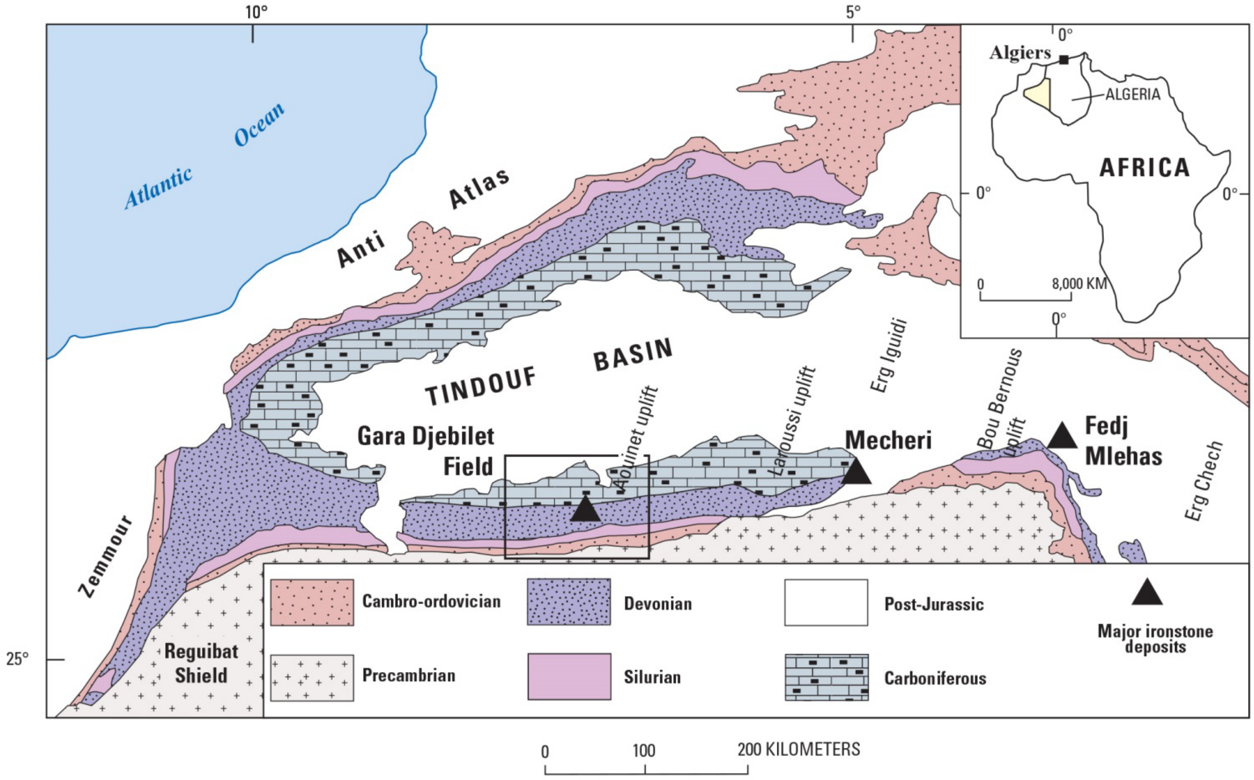

Figure 65. Location of the Tindouf Basin and the major oolitic ironstone deposits of southern Algeria. The Gara Djebilet field straddles the border with Mauritania (modified from Guerrak, 1988).

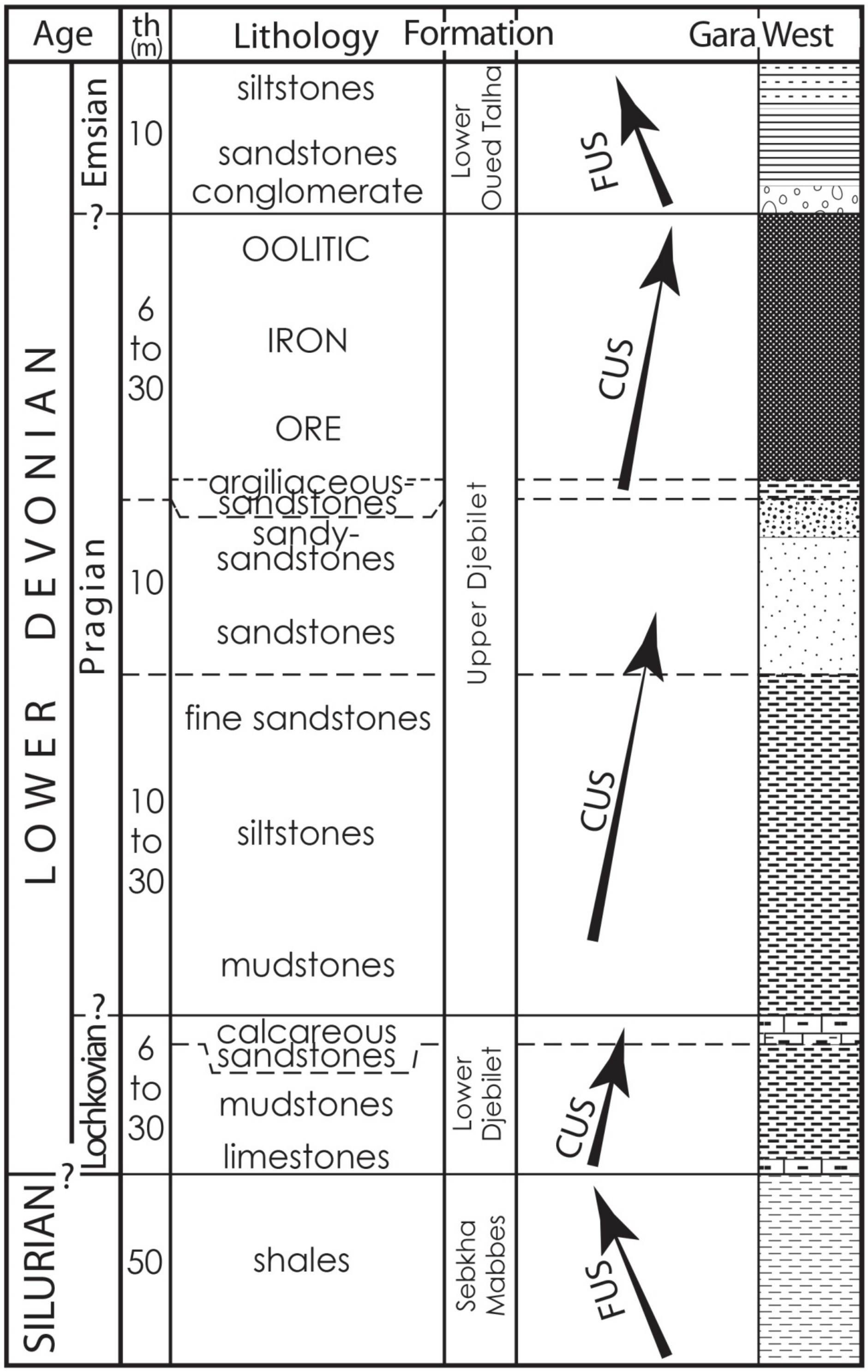

Figure 66. Lithostratigraphic column at the Gara Djebilet West deposit. CUS = coarsening-upwards sequence, FUS = fining-upwards sequence (modified from Guerrak, 1988).

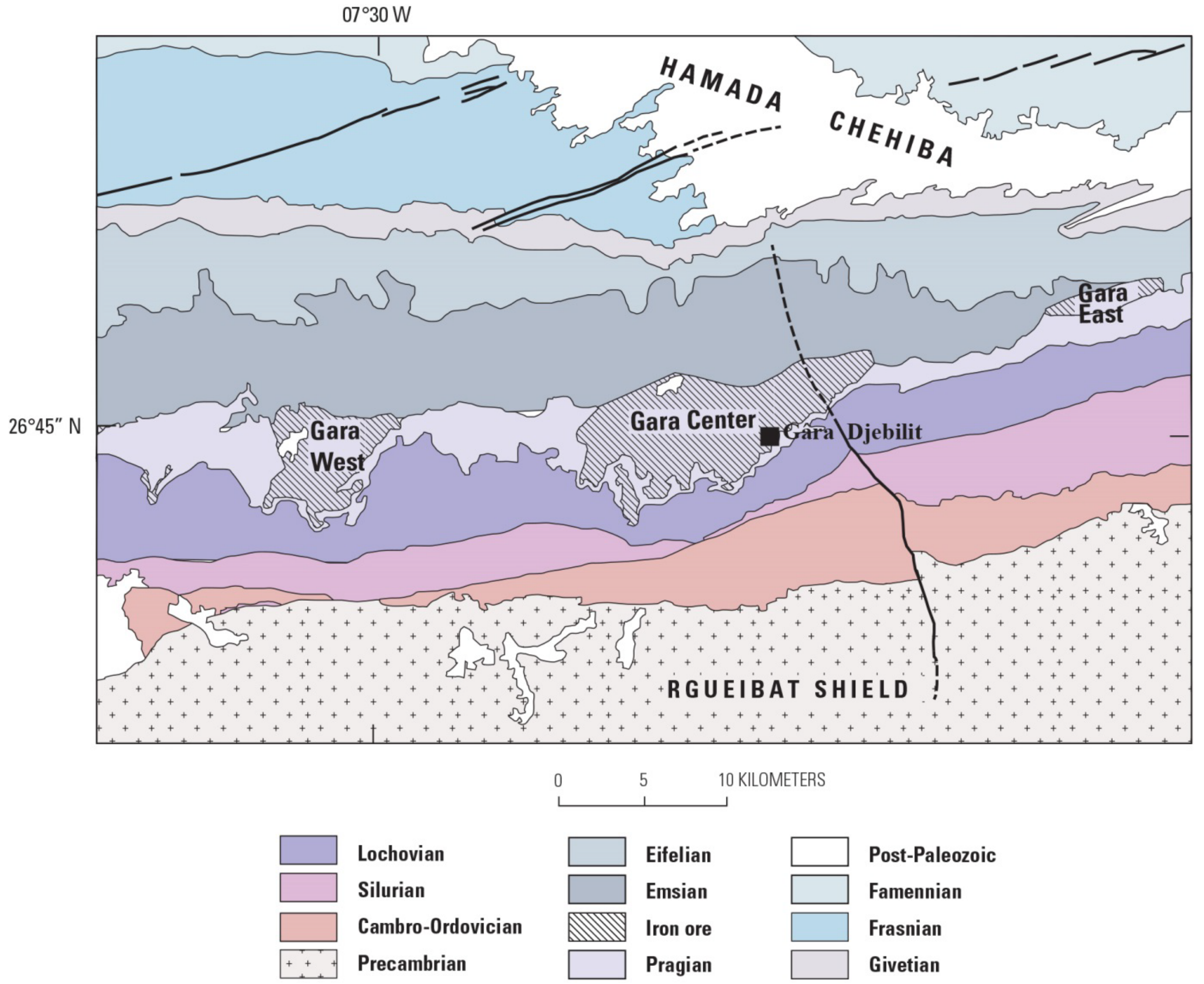

Figure 67. Geological map of the Gara Djebilet field of southern Algeria and northern Mauritania. The Gara Djebilet West deposit straddles the border between Algeria and Mauritania (modified from Guerrak, 1988).

The Gara Djebilet Formation consists of three coarsening upwards cycles of argillaceous to sandy sedimentary rocks in between fining upwards sequences consisting of shales of the upper Silurian Sebkha Mabbes Formation at the base and conglomerates, sandstones, and siltstones of the lower Devonian Oued Talha Formation at the top (Guerrak, 1988; fig. 66). Oolitic ironstones of the Gara Djebilet field occur as lenses at the top of the uppermost cycle interbedded with chloritic to ferruginous quartz arenites. Guerrak (1988) interprets each coarsening upwards cycle as representing a barrier island depositional sequence, with facies variations within each cycle representing different portions of a barrier island. Shoreface sedimentary rocks along the seaward side of islands consist of laminated ferruginous sandstones with low shell content. Overlying sandy foreshore beach sandstones contain tabular planar cross-beds of medium scale. Large scale (1–1.5 m thick sets) tabular-planar cross-bedding characterizes an aeolian dune facies rich in fossil vegetation. Such aeolian dune facies are a widespread feature of the Gara Djebilet field. The last cycle overlying the dune facies starts with parallel laminated argillaceous sandstones representing an inner foreshore environment grading upwards into oolitic ironstone. The ironstone has an upward decreasing quartz content and is interpreted as indicative of a depositional setting in a lagoon or embayment. Within the ironstone lenses, quartzitic ironstone facies are present closest to the barrier whereas the non-detrital ironstone facies occur above or landward (Guerrak, 1988).

Mineralogy of the oolitic ironstone lenses is characterized by magnetite, hematite, goethite, maghemite, chamosite, siderite, apatite, and quartz. Three principal ore types are distinguished and are vertically distributed within each lens. They consist of a lower non-magnetic ore facies, a magnetic facies, and an upper non-magnetic facies. Petrographically, the ores are distinguished into three types consisting of cemented, detrital, and non-detrital ore types. Averages of geochemical data for the entire field show differences in iron content between the three main ore types. The lower non-magnetic, magnetic, and upper non-magnetic facies contain 54.6, 57.8, and 53.0 percent Fe, respectively. The magnetic ore represents a potentially economic resource and contains 4.9 percent SiO_2, 4.2 percent Al_2O_3, 61.4 percent Fe_2O_3, 19.2 percent FeO, and 1.8 percent P_2O_5. At a 57 percent Fe cutoff, a resource of 985 million tonnes at 57.8 percent Fe has been reported (Guerrack, 1988).

Correlation of the Gara Djebilat Formation (of Algeria) across the border into Mauritania is somewhat problematic due to sparse descriptive data in regard to oolitic ironstones in Mauritania. However, descriptions of sedimentary rock units of upper Silurian and lower Devonian age in the Black Zenmour and North Yetti sub-basins by the BRGM (Lahondère and others, 2003) record the presence of shallow water regressive cycles containing phosphatic rocks, oolites, and ferruginous sandstones that are similar to rocks of similar age described by Guerrak (1988; 1989) in the Gara Djebilet field of Algeria.

Specifically, the fining upward sequence of upper Silurian shales underlying the Gara Djebilet Formation in Algeria is probably correlatable with the Gara Bouya Ali Group of the Tindouf Basin in Mauritania. The Gara Bouya Ali Group is described as conformably overlying the glaciogenic sedimentary rocks and tillites of the end-Ordovician Garat el Hamoueid Group and is marked by an abrupt transition to black, graptolite-bearing argillaceous shale interlayered with fetid, fossiliferous limestone that grade upwards into a massive, blue-black, fossiliferous limestone. The entire unit is uniformly 80–90 meters thick and is thought to represent a distal (outer shelf) platform sedimentary environment (Lahondère and others, 2003).

The Gara Bouya Ali Group is conformably overlain by the Devonian marine regressive cycles of the Zemmour Group. This unit consists of ~1,100 meters of sandstones, argillites, and limestones that are divided into three sub-groups, each representing a regressive cycle. Sub-group 1 of the Zemmour Group, assumed here to correlate with the Gara Djebilet Formation, is described as having a basal section of non-fossiliferous clays (approximately150 m thick) succeeded by interbedded marly-limestones and coquina horizons rich in diversified fauna (trilobites, brachiopods, orthoceres, lamellibranches, crinoids, and so forth). This is overlain by a non-fossiliferous argillaceous sandstone (25 m) and a shell-rich limestone with phosphatic nodules (10 m). Upwards the sub-group becomes argillaceous with several 100 m thick horizons of shelly limestone containing brachiopods. The sequence then grades into more terrigenous, coarser sandstones intercalated with thinner shelly limestone horizons. The top of the unit has been removed by erosion and is indicated by the presence of a fine grained conglomerate with phosphatic clasts that marks the beginning of the next sub-group. This marine sequence is thought to have been initiated in the latest Silurian and is interpreted as a regressive cycle characterized by the development of benthic faunas and a coarsening upwards sequence of argillaceous to sandstone facies. The unconformity at the top of the sub-group is thought to be related to end-Caledonian tectonics (Sougy, 1964; Hollard, 1967; Lahondère and others, 2003). Although not emphasized in their descriptions, Lahondère and others (2003) state that the development of the coarser terrigenous sandstones toward the top of the sub-group is sometimes accompanied by ferruginous quartzites.

In general, the stratigraphy of lower Paleozoic units along the southern margin of the Tindouf Basin in Mauritania is similar and correlatable between the Black Zemmour and North Yetti sub-basins. All units thin somewhat from west to east along the margin (Lahondère and others, 2003).

Inspection of the current mapping in the Silurian-Devonian rocks of the North Yetti sub-basin (Lahondère and others, 2003) and known occurrences of iron in the Mauritanian National Mineral Deposits Database (Marsh and Anderson, 2015) shows that two occurrences are present and are located in rocks of the Gara Bouya Ali Group (fig. 68). The Gara Djebilet West occurrence is briefly described as an iron mineralized layer containing lenses of iron-rich oolites and sandy limestones with brachiopods (*Spirifer*) indicating a lower Devonian (Emsian) age. The occurrence is interpreted as the western continuation of the Gara Djebilet West deposit in Algeria and consists of a layer rich in hematite, magnetite, maghemite, and phosphate minerals. The extension of the deposit in Mauritania continues for approximately 13 km at a thickness of about 10 meters. Iron content is reported as lower (46–47 percent Fe) than the deposit in Algeria and of poorer quality and less continuous in extent. No formal evaluation has been performed, however, the occurrence may contain several hundred million tonnes of ironstone (Marsh and Anderson, 2015).

A second occurrence is also located in the Gara Bouya Ali Group in the North Yetti sub-basin near the border with Western Sahara (fig. 68). The Oued el Hamra occurrence is briefly described as a continuous layer of ironstone approximately 1–2 m thick and 20–25 km long at the base of a bioclastic limestone cliff on the north side of the Oued el Hamra. The presence of orthoceres fauna establishes the age of the host rocks as lower Devonian (lower Seigonien; Marsh and Anderson, 2015). No other information is available for this occurrence.

Additional occurrences of Phanerozoic oolitic ironstone are known in the Black Zemmour sub-basin of the Tindouf Basin in Mauritania. From south to north they are the Bir Aidiate, Tighirt, Oumat el Ham, and Khang Leghouat occurrences (fig. 69). The Bir Aidiate, Tighirt, and Khang Leghouat occurrences are all hosted in rocks of the Zemmour Group, sub-group 1 based on current mapping (Lahondère and others, 2003). The Oumat el Ham occurrence is mapped in exposure of the Zemmour Group, sub-group 2, approximately 7 km to the west-northwest of the Tighirt occurrence. A fifth occurrence of iron is located in rocks of the Ordovician Oumat el Ham Group approximately 18.5 km east of the Khang Leghouat occurrence, named the Gara Bouya Ali occurrence. Little is known about these occurrences beyond what is briefly reported in the Mauritanian National Mineral Deposits Database (Marsh and Anderson, 2015). The Bir Aidiate occurrence is described as an oolitic limestone containing a meter thick layer characterized by the presence of phosphate, goethite, and chamosite. Geochemical analysis indicates the layer contains 42 percent Fe and 1.2 percent P_2O_5. The Tighirt and Khang Leghouat occurrences are described as horizons of unknown size containing hematite and goethite in Paleozoic detrital sedimentary rocks. The Oumat el Ham occurrence is described as a clay horizon in Silurian (Gothlandian) sedimentary rocks containing pyrite-bearing ochers, gypsum, and alunite. Finally, the Gara Bouya Ali occurrence is described as a basal layer of the Oumat el Ham Group lying directly on the Precambrian unconformity and consisting of sandstones and pelites containing quartz, iron oxides, glauconite, phosphate, and illitic clays. The description is vague and suggests that the horizon may be fairly thick and could contain significant tonnages of this material (Marsh and Anderson, 2015).

In summary, both the Black Zemmour and North Yetti sub-basins contain known occurrences of Phanerozoic oolitic ironstone in upper Silurian and lower Devonian rocks of the Gara Bouya Ali Group and the Zemmour Group, sub-group 1. These host rocks are thought to be correlative with similar rocks in Algeria and are therefore suggested to form part of the North

African Paleozoic oolitic ironstone belt (Guerrak, 1988; 1989). However, the occurrences in Mauritania appear to be of lower iron grade and of limited extent, and in some cases uncertainty exists in regard to their age or deposit type. For the purposes of this report, the Gara Bouya Ali Group and the Zemmour Group, sub-group 1 are both regarded as having potential for the discovery of additional resources of Phanerozoic oolitic ironstone. However, the potential for the discovery of economic deposits of this type is regarded as low.

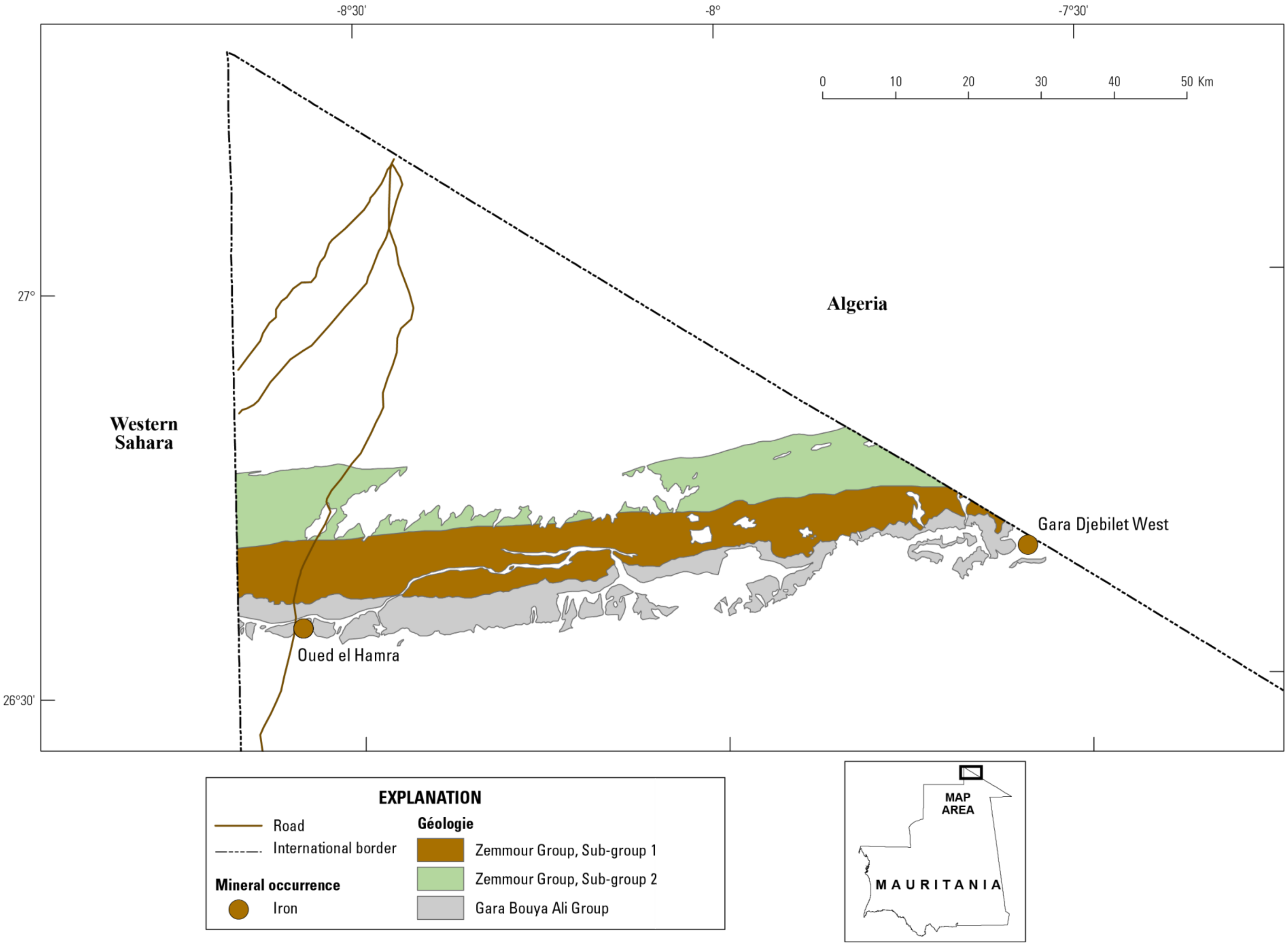

Figure 68. Geology and locations of Phanerozoic oolitic ironstone occurrences in the North Yetti sub-basin of the Tindouf Basin, Mauritania.

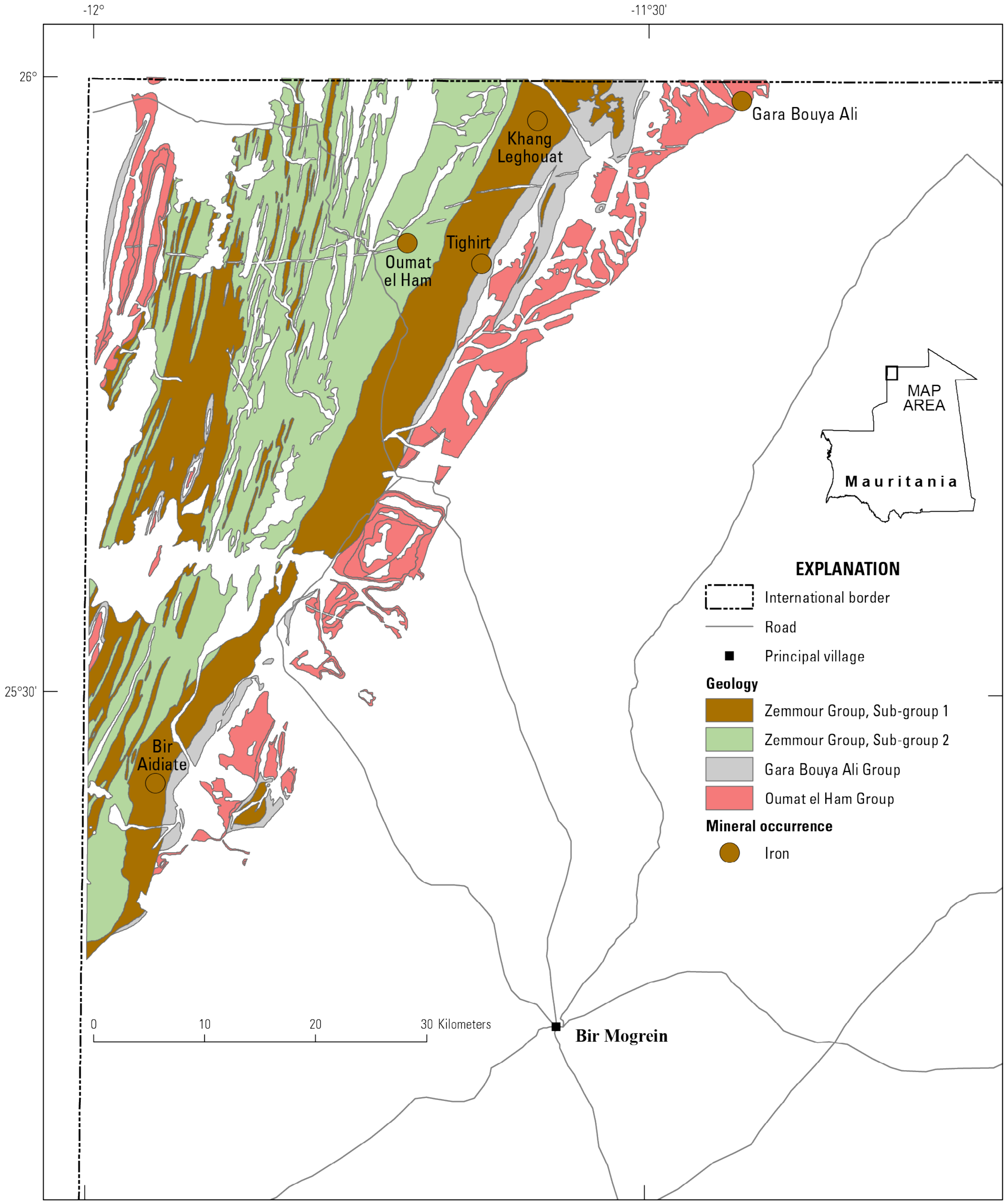

Figure 69. Geology and locations of Phanerozoic oolitic ironstone occurrences in the Black Zemmour sub-basin of the Tindouf Basin, Mauritania.

5.3.2 Oolitic Ironstones of the Taoudeni Basin

There are only a few known occurrences of iron in Paleozoic sedimentary rocks of the Taoudeni Basin and descriptive information on them is extremely limited. The Chegga occurrence is located in the extreme northeastern portion of the Taoudeni Basin in Mauritania approximately 35 km south-southeast of the village of the same name. The occurrence is described as ironstone of unknown type or mineralogy located at the contact between a layer of limestone overlain by sandstone of Cambrian age (Marsh and Anderson, 2015). Ironstone lenses are 100 meters long, 50 meters wide and of unknown thickness. The occurrence is thought to have insignificant potential for future iron resources of Mauritania (Marsh and Anderson, 2015).

Current geologic mapping identifies the host rocks at the Chegga occurrence as coarse grained sandstones and pelites of sub-group 1 of the Neoproterozoic Cheikhia Group. Lahondère and others (2003) describe the Cheikhia Group as a transgressive sequence of shoreface to fluviatile siliciclastic rocks consisting of sandstones, siltstones, and claystones, where each lithological unit is approximately 100 meters thick. An age of approximately 610 Ma is assigned to the group based on the presence of Ediacara-like fauna (medusoids). Along the northern margin of the Taoudeni Basin the Cheikhia Group is laterally correlated with the Bir Amran sandstones as well as the siliciclastic Assabet el Hassiane Group. Neither ferruginous sandstone nor ferruginous oolitic facies are described in any of these rocks. Based on the insignificance of the Chegga occurrence and the lack of described ironstone in other Neoproterozoic units along the margin of the Taoudeni Basin, these units are not regarded as permissive of oolitic ironstone deposits and are not discussed further.

The only other sediment-hosted iron occurrence in the Taoudeni Basin that is listed in the Mauritanian National Mineral Deposits Database (Marsh and Anderson, 2015) is the Lac Goussas occurrence in southern Mauritania located approximately 13 km to the west-southwest of the village of Bouly. Sparse descriptive data suggest that the occurrence is a ferruginous schist in fine grained sandstones or dolomites. Current mapping (Lahondère and others, 2005) places the occurrence in the Tichilit et Beida sub-group of the Neoproterozoic-Cambrian Teniagouri Group. Iron content of the ferruginous schist is approximately 20 percent. Similar to rocks of the same age described at the Chegga occurrence, the Neoproterozoic-Cambrian sequence in the southern Taoudeni Basin are regarded as equally non-permissive of oolitic iron formation and will not be considered further. Marot and others (2003) mention the presence of the Oum Akka Denach sediment-hosted iron occurrence on the northern margin of the Taoudeni Basin and state that it is an oolitic ironstone type of occurrence hosted in upper Ordovician sedimentary rocks. However, this occurrence does not appear in the Mauritanian National Mineral Deposits Database (Marsh and Anderson, 2015) and no information regarding the location or setting of the occurrence is known to the current authors.

Recent work by the BRGM in the central western part of the Taoudeni Basin suggests that there is potential for Phanerozoic oolitic ironstone in latest Ordovician, upper Silurian, and lower Devonian rocks in an area to the east of the Inchiri district. Ferruginous layers are described in the Khneg Ten Titane Formation of the end Ordovician Tichit Group, which represents the last of a series of Ordovician glacial units deposited during retreat of Ordovician glaciers.The Khneg Ten Titane Formation establishes a transition between the glacial facies of the underlying formations and the pelitic facies of the Oued Chig Group. It is characterized by bioturbation and the first fossils. This transition is expressed in two distinct ways: a quartzitic littoral facies, or an argillaceous sandy succession that is partly glaciomarine. In the Adrar and northern Tagant region the formation is a quartzitic unit 1 to 20 m thick that systematically caps the outcrops of the Tichit Group. The contact of the Khneg Ten Titane Formation with the Oued Chig Group is locally marked by a conformable ferruginous facies that is interpreted to be a chemical precipitate

(Lahondère and others, 2008). This horizon is generally 0.2 to 4 meters thick and contains variable amounts of detrital quartz and bioturbated iron oxide horizons 2 to 10 centimeters thick, phosphatic nodules as well as pseudo-oolites (chamosite cores with ferrugino-phosphatic cortexes).This interval is interpreted as a condensed facies that indicates increasing water depth during the final end-Ordovician to Silurian transgression. Maximum flood stage is represented by mudstones and graptolites of the overlying Oued Chig Group (Lahondère and others, 2008).

The Oued Chig Group is transgressive onto the glacial sandstones of the Tichit Group and represents a condensed series 50 to 100 meters thick of variably sandy mudstones with graptolites whose faunas represent various stages of the Silurian (Lahondère and others, 2008). In the Far' aoun and El Moinan 1:200,000 geological maps, the BRGM has divided the Oued Chig Group into a basal unit (Og1), corresponding to the heterolithic interval resting on the Tichit Group and an upper unit (Og2) for the argillaceous interval with graptolites and sandy intercalations. Locally present sand bars occur between the two units ($Og1^1$). The basal unit (Og1) forms a several-meter-high cuesta overlain by thick sand bars consisting of poorly sorted quartzitic sandstone and conglomerate, ($Og1^2$) that form morphological projections. On the Far' aoun 1:200,000 geological map, these heterolithic pelitic sandstones locally show ferruginous (hematitic) oolitic deposits (unit $Og1^1$) that locally form thick lenses (5 to 8 m in the sector of Akadnech; Nagel, 2008: Lahondère and others, 2008).

At the time of this writing, the BRGM report by Nagel (2008) was not available to the authors and USGS fieldworkers in October-November 2007 did not visit this area of the Taoudeni Basin. The Mauritanian co-authors of this paper provided oral communications (June, 2012) stating that two oolitic ironstone occurrences have been located and defined in this area, named Far'aoun and Akadnech. No occurrences of these names are present in the Mauritanian National Mineral Deposits Database (Marsh and Anderson, 2015) and no further details on the exact coordinates, size, or tenor of these occurrences were provided. It is notable that the Akadnech occurrence spelling is close to that of the Oum Akka Denach occurrence mentioned by Marot and others (2003). As no location and little detail was provided for the Oum Akka Denach occurrence, it is suggested here that it is the Akadnech occurrence described here and presumably in Nagel (2008).

The Oued Chig Group is paraconformably overlain by the lower Devonian Tenemouj Group. The Tenemouj Group is divided into three formations: sandstones of the Aouïnet Zbel Formation (80 m), limestones of the Dhlaïet el Ateuch Formation (100 m), and sandstones of the El Ahguid Formation (locally up to 400 m). The Aouïnet Zbel Formation consists of coarse, sandy, ferruginous, sandstone containing brachiopods and is of lower Devonian age (Coblencian: well dated Siegenian and poorly dated Emsian; Lahondère and others, 2008). This unit is also regarded as permissive of Phanerozoic oolitic ironstone deposits.

In the southernmost Adrar region in the southwestern portion of the Far' aoun 1:200,000 geological map the Tenemouj Group is approximately 50 m thick. The Aouïnet Zbel Formation is present as large slabs, frequently covered with aeolian sand, capping the Silurian mudstones of the Oued Chig Group. In the Far' aoun 1:200,000 geological map sheet the formation forms a continuous cuesta consisting of approximately 10 meters of sandstone at the base locally overlain by a ferruginous oolitic horizon. To the west-southwest the upper portion of the formation consists of a greenish micaceous mudstone facies with bioclastic sandy lenses. In this sector, the Aouïnet Zbel Formation is characterized by white to yellowish, coarse, sandy, ferruginous, quartzitic sandstones interlayered with meter-scale ferruginous oolite horizons. No iron occurrences have been defined within the Aouïnet Zbel Formation, however, the lower Devonian age and presence of oolitic ironstone suggests similarity with other units included within the North African oolitic ironstone belt. The Aouïnet Zbel Formation is therefore included within the tract permissive of Phanerozoic oolitic ironstones on the western margin of the Taoudeni Basin (fig. 70).

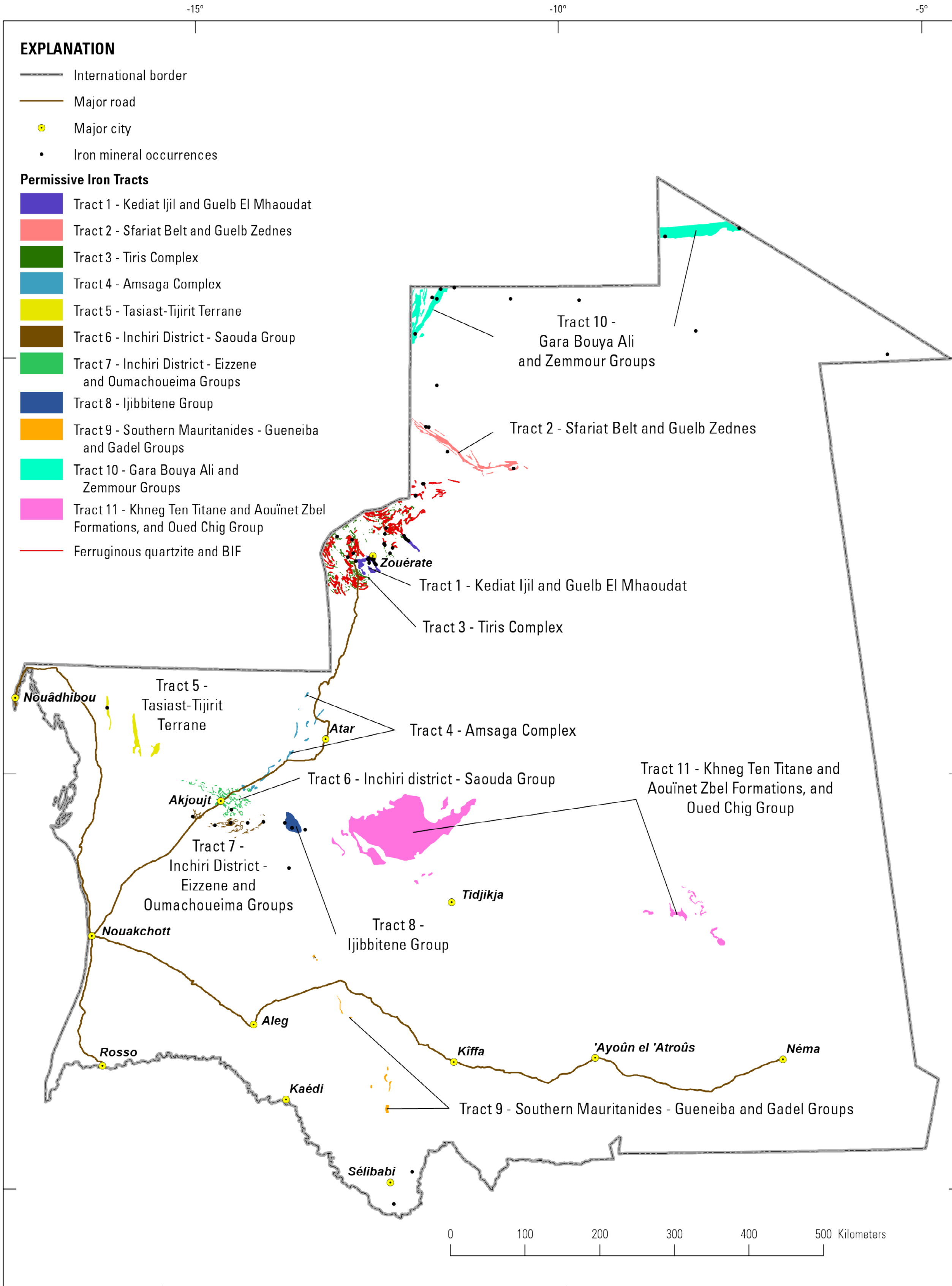

Figure 70. Permissive tracts for deposits classified as Algoma- and Superior-type iron formation and Phanerozoic oolitic ironstone deposits in Mauritania.

6 Permissive Tracts for Algoma-, Superior-, and Oolitic-Type Iron Deposits in Mauritania

Based on the USGS synthesis of PRISM data for the iron potential of Mauritania, tracts considered permissive for deposits classified as Algoma- and Superior-type iron formation and Phanerozoic oolitic ironstone deposits are shown on figure 70. Criteria for the delineation of these tracts are based upon permissive geology as described in BGS (Gunn and others, 2004; Pitfield and others, 2004; O'Connor and others, 2005) and BRGM (Lahondère and others, 2003; Marot and others, 2003; Lahondère and others, 2005; Lahondère and others, 2008) reports and the tracts are broken out primarily at the group level and at the sub-group or formation level where possible. A second major criterion for selection of tracts is the distribution of known occurrences of iron where they are hosted within permissive host rocks. Currently producing mines and known deposits and occurrences of iron in Mauritania are listed in the Mauritanian National Mineral Deposits Database (Marsh and Anderson, 2015).

Eleven tracts are defined as follows:

1. In allochthonous to parautochthonous Paleoproterozoic rocks overlying or imbricated with the northeastern margin of the Mesoarchean Rgueïbat Shield, a tract is drawn that is permissive for Superior-type iron deposits within the supracrustal sequences of the Kediat Ijil and Guelb El Mhaoudat. More specifically, the Tazadit Formation and the correlative El Mhaoudat Formation encompass all of the currently known Superior-type BIF protore and all currently producing mines and known deposits of high grade hematite iron formation. This tract is extended under cover of the Taoudeni Basin using the regional aeromagnetic map (see Finn and Anderson, 2015). The southeastern boundary of the tract was drawn where linear magnetic anomalies related to Superior-type BIF deposits could no longer be recognized, and where the depth of cover over Mesoarchean basement is less than 1,000 m.
2. A second Superior-type BIF tract is drawn on BIF units of the Sfariat Belt and Guelb Zednes that includes four known occurrences of Paleoproterozoic magnetite and hematite bearing BIF. Host units that define the tract are primarily in the Rich Anajim Complex and include the Guelb Zednes Formation and ferruginous quartzites designated as RAqz.
3. A tract is drawn on Mesoarchean Algoma-type BIF of the Tiris Complex that includes the producing mine at Guelb el Rhein, the deposit at Guelb El Aouj, and an additional 11 prospects and occurrences. Numerous outcrops of Algoma-type BIF (designated TRfe) are shown and are extended under cover using aeromagnetic data.
4. A second tract of Mesoarchean Algoma-type BIF is drawn on outcropping exposures of BIF (designated AMfe) within the Amsaga Complex and is extended under cover based on aeromagnetic data. There are currently no known iron occurrences in the Amsaga Complex.
5. A third tract of Mesoarchean Algoma-type BIF is drawn on outcropping exposures of BIF hosted within the Lebzenia Group in the greenstone belts of the Tasiast Tijirit terrane. Specifically, the tract is drawn upon mapped occurrences of BIF in the Sebhket Nich and Aouéoua Formations and is extended under cover based on aeromagnetic data.
6. A fourth tract of Mesoarchean Algoma-type BIF is drawn on outcropping exposures of BIF hosted within the Saouda Group in the Inchiri district. There are six known occurrences hosted in BIF of the Saouda Group.
7. A tract is drawn on Neoproterozoic Algoma-type BIF of the Eizzene and Oumachouiema Groups within the Chouiema nappe of the Akjoujt nappe pile of the Inchiri district. Specifically, BIF at the base of the Eizzene Group, Khmeiyat Formation and BIF units in

the Oumachoueima Group, Atomai and Lembeitih Formations. Thin BIF units in the Oumachouiema Group, Sainte Barbe and Akjoujt Formations are not regarded as extensive enough to be considered permissive of iron deposits. There are no known iron occurrences associated with the Algoma-type BIF of the Eizzene and Oumachouiema Groups. However, an unusual iron oxide-silica cap to the Cu-Au occurrence at El Khader represents an unusual goethite-hematite deposit.

8. A second tract of Neoproterozoic Algoma-type BIF is drawn on outcrop of the Ijibbitene Group within the Ijibbitene nappe. Specifically, two units, the El Mbehteh and Bou Demje Formations are composed of or contain significant amounts of BIF. However, the locations and descriptive information available for three iron occurrences in the area are vague, resulting in the entire Ijibbitene Group being considered as permissive of Neoproterozoic Algoma-type iron occurrences. Reports of an occurrence in undifferentiated sedimentary rocks of the Teniagouri and Jbeliat Groups may indicate potential for iron occurrences of an unknown type.
9. Neoproterozoic Algoma-type BIF is also present in thin horizons within the Gueneiba and Gadel Groups of the Gorgol Noir Complex of the southern Mauritanides. However, because BIF units within these rock Groups are not mapped as separate geologic units, aeromagnetic data was used to draw tracts on Gueneiba and Gadel Group rocks interpreted to host greater thicknesses of BIF. These tracts are regarded as somewhat speculative and are thought to have low potential for the discovery of economic Algoma-type iron deposits.
10. Both the Black Zenmour and North Yetti sub-basins of the Tindouf Basin contain oolitic ironstones within Silurian and Devonian platform sedimentary rock sequences of the Gara Bouya Ali and Zemmour Groups. Tracts in both sub-basins are drawn on these rock groups. Four separate occurrences are located within the tract in the Black Zenmour sub-basin and two occurrences are within the North Yetti sub-basin.
11. Finally, a large tract is drawn on the Khneg Ten Titane Formation of the end Ordovician Tichit Group, the overlying Oued Chig Group, and the Aouïnet Zbel Formation of the lower Devonian Tenemouj Group on the western margin of the Taoudeni Basin north of Tidjikja and in the center of the basin east of Tidjikja.

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