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THE GUELB MOGHREIN Fe-OXIDE COPPER-GOLD-COBALT DEPOSIT AND ASSOCIATED MINERAL OCCURRENCES, MAURITANIA: A GEOLOGICAL INTRODUCTION.

[1]Colin D. Strickland and [2]John E. Martyn

[1]*General Gold International SA, Perth, Australia.*
[2]*John Martyn Associates Pty Limited, Turramurra, NSW, Australia.*

Abstract – The Guelb Moghrein deposit is located within the Mauritanide Mobile Zone, north east of Nouakchott in the Islamic Republic of Mauritania, West Africa. The copper, gold and iron deposits of the Mauritanides fold/thrust belt of the Akjoujt area have many of the characteristics of the hydrothermal iron oxide copper-gold class of deposits as well as showing distinctive features of their own. Exploration by General Gold International SA since 1994 has concluded that they represent, perhaps, a carbonate-rich sub class and show considerable diversity of form and setting.

The Mauritanides in Mauritania incorporate a great diversity of rocks in multiple, thrust-bounded domains including metamorphosed siliciclastic sediments, meta-felsic volcanics, meta-basic volcanics, serpentinite, and bodies of granitoid rocks.

The Akjoujt area features a supracrustal suite of metamorphosed mafic to felsic volcanic, volcaniclastic and epiclastic rocks, with a number of banded iron formation (BIF) horizons, that have been overthrust northwards and eastwards onto the Archaean Amsaga Basement and the Taoudeni Basin edge. The supracrustal stratigraphy has recently been revised by the authors because previously published schemes were found to be inconsistent with field observations. Carbonate alteration is widespread in the supracrustal suite and the BIFs are commonly carbonate rich.

All of the Fe-oxide copper-gold mineralisation of the Akjoujt area is associated with coarse-grained Fe-Mg-Ca carbonate occurrences. These are widespread throughout the Akjoujt area and they range in size from clusters of carbonate porphyroblasts in BIF, through small pods and lenses, to large lenses, irregular sheets, and from single narrow veins to extensive stockworks and vein systems. Some form of structural control is usually apparent and emplacement has occurred at various stages in the tectonic history from early to syn-thrusting through to upright folding and doming.

The Guelb Moghrein Cu-Au-Co mineralisation within both the Occidental and Oriental bodies is hosted by a massive magnetite-sulphide bearing iron-magnesium carbonate representing a CO_2 metasomatised shear zone or 'tectonite and is characterised by prominent magnetic anomalism. A total measured and indicated resource of 23.6 Mt @ 1.88 % Cu, 1.41 g/t Au and 143 ppm Co has been calculated and currently the mineralised zone is open at depth, presenting a significant geophysical target for the discovery of additional down dip and satellite deposits.

At El Khader the carbonate vein system is interpreted to belong to a different stage in tectonic evolution than at Guelb Moghrein. There the brittle fracture event is considered to have occurred later than the ductile shear setting of Guelb Moghrein.

Given the abundance of carbonate in the country rocks, and the structurally controlled settings of the coarse grained occurrences it is likely that the carbonate bodies in the Akjoujt area evolved by remobilisation from within the system during tectonism. This would probably have involved recycling of basin fluids, however there is no evidence that magmatism played any role in this. The introduction of the metallic components is assumed to be along the same structural channels but the source of metal is unclear. The most likely origin is, like the carbonate, from within the pile, in this case from the abundant, leachable mafic volcanic rocks.

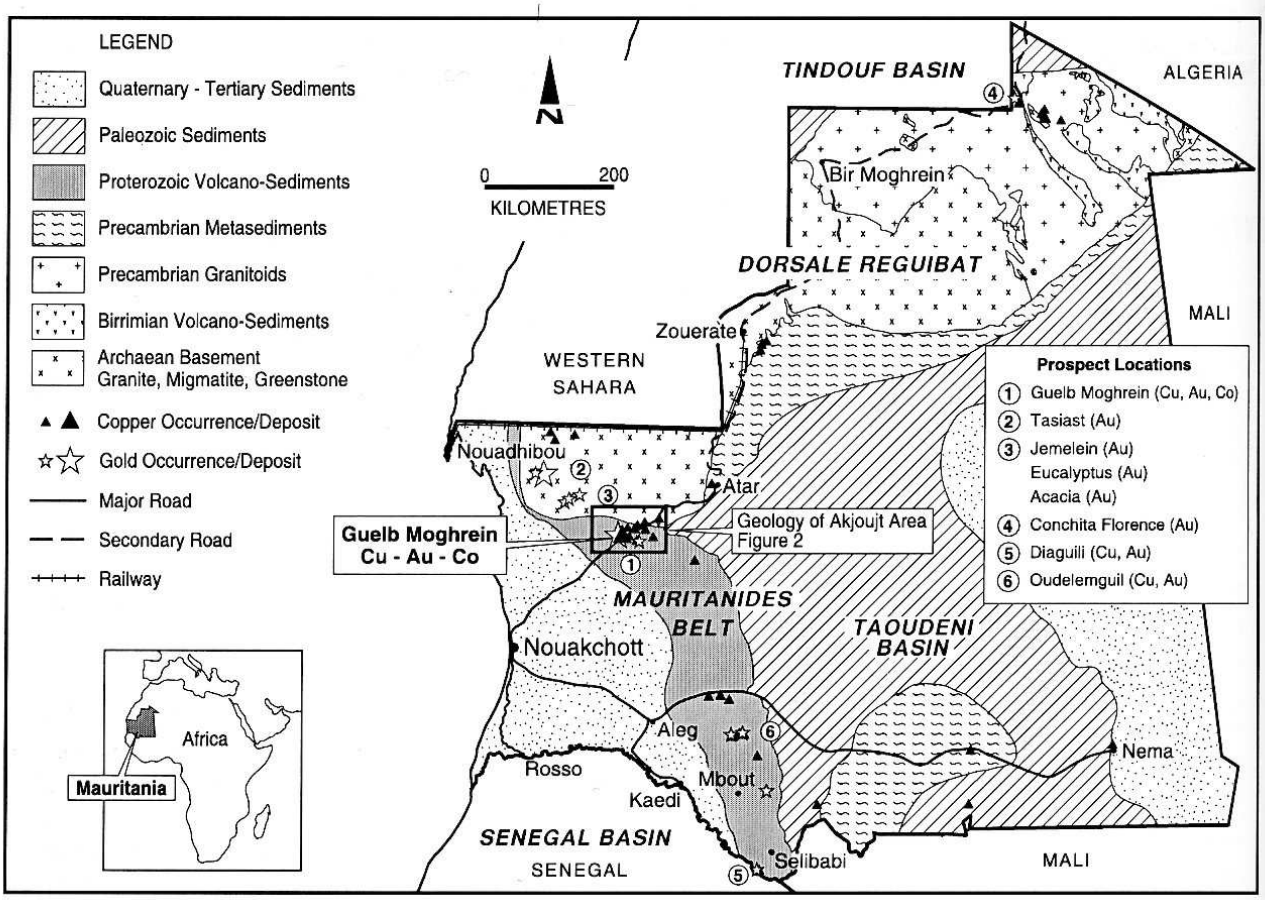


FIGURE 1: ISLAMIC REPUBLIC OF MAURITANIA GEOLOGY MAP - Showing Copper and Gold Occurrences

Introduction

The Islamic Republic of Mauritania is a sub-Saharan country occupying approximately one million square kilometres on the West Coast of North Africa, north of the Senegal River. The Akjoujt area is located 260 kilometres northeast of Nouakchott on the main national highway between the capital and the town of Atar (Figure 1). The copper, gold and iron deposits of the Mauritanides fold/thrust belt of the Akjoujt area have many of the characteristics of the hydrothermal Fe-oxide copper-gold class of deposits as well as showing distinctive features of their own. They represent, perhaps, a carbonate rich sub class and show considerable diversity of form and setting.

This paper is based on the detailed reverse circulation and diamond drilling evaluation of the Guelb Moghrein deposit together with a geological, geophysical, mineragraphic and petrographic study of the ores and host units. It also incorporates the results of a regional mapping programme based on air photographs and enhanced SPOT and TM images. The mapping was supported by an airborne magnetic and radiometric survey over the Guelb Moghrein deposit and the surrounding 300km². This survey data was examined in detail in order to identify target sources that had similarities to the magnetic expressions of the known Guelb Moghrein mineralisation (Dockery 2000).

Mining History

The principal deposit, Guelb Moghrein, was exploited for copper in Neolithic times and the ancient workings were noted in 1931 by the French military, however it was not until 1946 that A. Blanchot of the Bureau Minier systematically sampled the malachite impregnated rocks at Guelb Moghrein. (Figure 2). The *Syndicat de l'Inchiri*, an association involving the Bureau Minier, Federation of French West Africa and the Territory of Mauritania, investigated the potential of the Guelb Moghrein mineralisation for large scale mining in the late 1940's. The first modern mining venture on the deposit in the early 1950's, by the *Societe des Mines Cuivre de Mauritanie* (MICUMA) failed to develop a viable metallurgical technology and the company was disbanded in 1958.

In July 1967 *Societe Miniere de Mauritanie* (SOMIMA), commenced development of the oxide copper resource and infrastructure. Oxide reserves at the time were 7.7Mt at 2.7% Cu and 3.1g/t Au overlying open pit sulphide reserves totalling 15Mt of 1.8% Cu and 1.0g/t Au. This led in 1968 to construction of the world's largest oil fired TORCO plant (**t**reatment **o**f **r**efractory **c**opper **o**re). Design capacity of the TORCO was seldom achieved and in 1974 a combination of increasing fuel prices and a fall in the copper price placed SOMIMA in difficulty. The Mauritanian Government transferred operational responsibility to *Societe Nationale Industrielle et Miniere* (SNIM) which commenced ordering equipment for the future US$50 million dollar sulphide project on which Charter Consolidated had prepared a feasibility study. The continuing deteriorating financial situation however forced SNIM-SOMIMA to close the mine in May 1978.

In 1982 *Societe Arabe des Mines l'Inchiri* (SAMIN) commenced stripping overburden from the sulphide orebody and contracted SOFREMINES to complete an updated sulphide feasibility study. Although the latter indicated a total sulphide resource of between 34-39Mt at 1.45% Cu and 0.8g/t Au, the copper price was experiencing a 50 year low and SAMIN was forced to abandon their future mining plans. *Minproc Engineers Pty Ltd* then became involved in the resampling of the mine tailings in 1990 and established a resource of 2.4Mt at 3.08 g/t Au. *Mines d'Or d'Akjoujt* (MORAK) was incorporated in 1991 to treat the tailings using the Hunt process, but metallurgical recovery problems plagued the operation and *General Gold International SA* (GGISA) took up Minproc's equity position in 1993. Further research confirmed that the addition of oxygen was a major requirement for the successful cyanide leaching of gold in the presence of copper and ammonia. Gold recoveries of 85% were characteristic of the 50,000t per month treatment till the operation was completed in 1996. The retreated tailings produced a total 158,000 oz Au and during the project's life gold represented the third most valuable export commodity in Mauritania.

GGISA entered into a 50:50 joint venture agreement with SAMIN in 1994 and formed *Guelb Moghrein Mines d'Akjoujt SA* (GEMAK) in 1995 to conduct a feasibility study into the development of the remaining oxide and sulphide resources at Akjoujt, known as the Guelb Moghrein deposit. Following extensive RC and diamond drilling, resource estimation, metallurgical sampling and test work, flowsheet design and costing, marketing studies, provision for dust control measures for asbestiform minerals, and environmental auditing, a bankable feasibility study was commissioned and completed in April 1997 by Kilborn-SNC-Lavalin Europe.

Exploration of the El Khader mineralisation, situated 25km south-east of Akjoujt, (Figures 2 and 7) commenced in 1953. Mapping for the delineation of potential iron ore resources by A. Allon in 1956-57 resulted in the definition of a number of zones of haematite and goethite derived mainly from the weathering of a 60m thick ferruginous carbonate unit. Minor accessory malachite, chrysocolla, cuprite, and native copper locally stain the carbonate. Exploratory pits by MICUMA in 1958 resulted in a resource estimate of 18 Mt of iron ore grading 51% Fe.

The Sainte Barbe prospect, located 27km north-east of Akjoujt, (Figure 2) consists of ancient Neolithic workings that were first explored by MICUMA with trenches and adits in 1955. The mineralisation in the form of malachite, chrysocolla and azurite is associated with quartz-ankerite veining within a massive ferruginous carbonate unit up to 25m thick.

Regional Geological Setting of the Akjoujt Area

The Akjoujt area lies on a bend, or orocline, in the Mauritanides chain, a complex, generally east-verging fold/thrust belt that extends from Senegal in the south to Western Sahara in the north (Figure 1). It is bounded to the east and north by a variety of terrains including the Amsaga Basement, part of the Archaean Reguibat Shield, in the north, the vast, continental sedimentary Taoudeni Basin of Neoproterozoic to Devonian age in the centre, and the Lower Proterozoic Birrimian fold belt emerging from beneath the Taoudeni Basin in the far south. A series of overthrust basement sheets defines the western edge in the Akjoujt area, however thin marine sediments obscure the western boundary of the Mauritanides for much of its length.

The Mauritanides in Mauritania incorporate a great diversity of rocks in multiple, thrust bounded domains. These include metamorphosed siliciclastic sediments, meta-felsic volcanics, meta-basic volcanics, serpentinite, and bodies of granitoid rocks. Low to medium metamorphic grades predominate however amphibolites and eclogites occur locally, especially in the north. Stratigraphic relationships are problematic due to the intensity of deformation and thrust bounded relationships. There is very little information on the age of the various lithological units of the Mauritanides. Given the complexity of the terrain there are undoubtedly domains of diverse age dragged in by the thrusting.

Lecorche et al. (1989) summarised the thermal history of the Mauritanides from the limited data available in the southern part of the belt. These include Rb-Sr and ^{40}Ar / ^{39}Ar dates on the felsic igneous rocks of the Mbout area, 500 km to the south of Akjoujt (Figure 1) of ca. 675 to 685 Ma. This they compared to a more northerly-located U-Pb zircon age on similar rocks of 680±10. A later event of ca.620-650 Ma was also recorded representing a major tectonothermal event, the first phase of the PanAfrican orogeny. A second phase event at around 575 to 550 Ma was also distinguished, followed much later by a late Palaeozoic resetting of muscovite at ca.300 Ma.

It is probable that at least some, and possibly all of the events discriminated from further south are manifest in the Akjoujt area, however the overthrust supracrustals of Akjoujt present a suite of rocks rather unlike those to the south. They are dominated by volcanic and volcaniclastic rocks with prominent banded iron formation units (BIF). Currently we do not have any definitive data on the age of these rocks except that they are certainly pre-Hercynian. The presence of extensive BIF may be age critical. Isley and Dallas (1999) distinguished world-wide iron formation depositional peaks at around 1850, 2450, 2700 and 3000 Ma. Iron Formations also occur in the Neoproterozoic in association with glacigene sediments in Australia, Africa and South America (eg. Lottermoser & Ashley, 2000, Urban et al., 1992) and with volcanics and clastics in the Ordovician of the Tetagouche Group of New Brunswick, Canada (Saif, 1980). Based on the chronology of BIF deposition this presents a wide choice and it is wise to be circumspect until definitive dating information becomes available.

The Mauritanides of Mauritania contain a number of copper gold occurrences, mainly in two areas, the Selibabi-Mbout area in the south and the Akjoujt area (Figure 1). Occurrences in the former, such as Kadiar and Diaguili, are associated with sheared, carbonate-altered serpentinite or with faults and shears in mafic volcanics. Those of the Akjoujt area are the more substantial.

Figure 2
GEOLOGY OF AKJOUJT AREA
Distribution of stratigraphic units, main thrusts and key unconformities. Location of figures 4 & 7

Geology of the Akjoujt Area

Stratigraphy

The Akjoujt area features a supracrustal suite of metamorphosed volcanic, volcaniclastic and epiclastic rocks that has been overthrust northwards and eastwards onto the Archaean Amsaga Basement and the Taoudeni Basin edge (Figure 2). The Amsaga Basement consists of gneisses and granulites with embryonic greenstones, while the Taoudeni Basin sediments are of continental, shallow water character and consist of red and grey conglomerate, sandstone, siltstone and carbonate. To the southwest the supracrustals have been overthrust by their own basement rocks that consist of gneisses, granitoids and older, more metamorphosed supracrustals.

The supracrustal stratigraphy has recently been revised by the authors as previously published schemes (eg Giraudon, 1964, Michaud, 1963) were found to be inconsistent with field observations. The proposed new scheme has yet to be published separately. The sequence is presently believed to consist of two suites separated by an unconformity (Figure 3). The lower assemblage, for which the name Eizzene Group is proposed, consists of altered basalt flows, the Raoui Metabasalts, overlain by fine grained clastics and quartz-magnetite BIF, the Khmeiyat Formation. These are intruded by small plagiogranite plutons.

The Eizzene Group is overlain unconformably by a volcanic and clastic succession for which the name Oumachoueima Group has been proposed. This begins with a basal quartzite, the Atilis Quartzite, followed by fine grained meta-greywacke and siltstone, the Irarchene el Hamra Formation. This is overlain by fine grained intermediate to mafic volcaniclastics with BIF units up to tens of metres thick, the Atomai Formation. A massive BIF at the top of the Atomai Fm is followed by increasingly felsic lavas and volcaniclastics of andesite to rhyodacite composition, the Sainte Barbe Volcanics. These are capped by a widespread BIF/chert marker, the Lembeitih Formation, which is overlain by thick and extensive basalt flows with dolerite intrusives, the Akjoujt Metabasalts.

The BIF units of the Oumachoueima Group are variable but commonly rich in Fe carbonate as well as magnetite. Carbonate is also pervasive throughout the volcanics and volcaniclastics as an alteration phase. Carbonate is locally concentrated in schistose, sheet like zones associated with layer parallel ductile thrusts and these had been previously interpreted as carbonate sediments (eg. Pouclet et al., 1987).

The Oumachoueima Group has not suffered any intrusive activity other than synvolcanic dolerites. The only granitic intrusives to have affected it are where the basal quartzitic units are preserved attached to overthrust basement and multiple leucogranite sheets are intruded.

Structure and tectonic history

The overthrust and allochthonous nature of the supracrustals, with respect to the basement to the north and east, was first recognised by Giraudon & Sougy (1963). Preliminary work by the authors has suggested that principal thrusting took place on multiple planes during two main periods, the first from a south southwest direction, followed by a second event from the west southwest. These events also brought the basement to the supracrustals over the top. Subsequent open to tight, upright-folding contorted the thrust sheets and this operated above a sole thrust on which the entire supracrustal mass was carried onto the Archaean Amsaga Basement and Taoudeni Basin. The later folding down-folded the overthrust basement which is preserved in synformal remnants and embayments (Figure 2).

Metamorphic grade varies from lower to upper greenschist or low amphibolite and rises upwards towards the overthrust basement which is generally amphibolite grade. This suggests that the sequence was first metamorphosed and then partially inverted during subsequent thrusting. Retrogression and carbonate alteration is widespread.

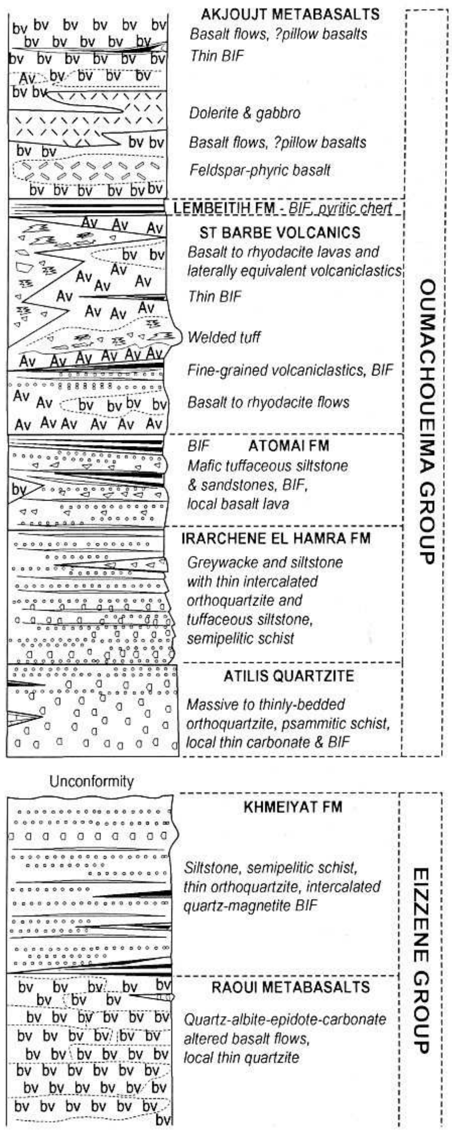


Figure 3
Proposed stratigraphy for the supracrustals of the Akjoujt area

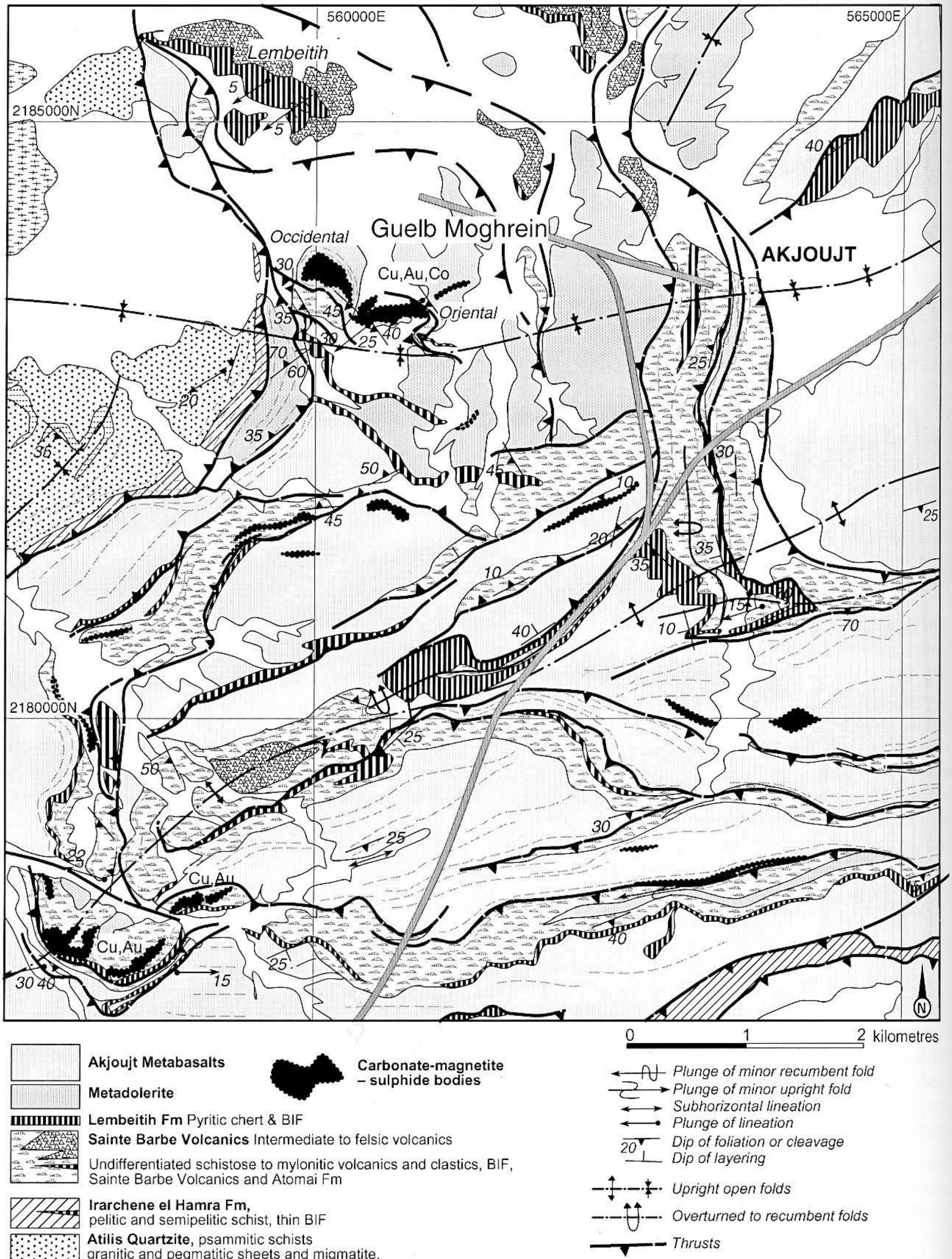


Figure 4 GEOLOGICAL SETTING OF GUELB MOGHREIN based on field traverses and air photo interpretation showing multiple thrust repititions, refolding of thrusts and carbonate-magnetite bodies.

General Character of the Iron Oxide Copper Gold Occurrences

All of the Fe oxide copper gold mineralisation of the Akjoujt area is associated with coarse-grained Fe-Mg-Ca carbonate occurrences. These are widespread throughout the Akjoujt area and they range in size from clusters of carbonate porphyroblasts in BIF, through small pods and lenses, to large lenses, irregular sheets, and from single narrow veins to extensive stockworks and vein systems. Some form of structural control is usually apparent and emplacement has been at various stages in the tectonic history from early-to syn-thrusting through to upright folding and doming. The carbonate may be accompanied by Mg rich silicates such as cummingtonite, tremolite or anthophyllite or by quartz or magnetite. Porphyroblasts of garnet, cummingtonite and biotite are locally present in schistose rocks enveloping some of the lenses in the Guelb Moghrein vicinity.

Most coarse grained carbonate occurrences do not contain significant Fe oxide or Cu sulphides but there are a number of exceptions, the main ones being the mineral occurrences shown on Figure 2. The two principal deposits, or systems, described below, are Guelb Moghrein and El Khader. They have some features in common with one another but in other respects are contrasting in style, setting and timing in relation to tectonic events.

Guelb Moghrein

Guelb Moghrein outcrops in a zone linking two abrupt hills rising from the low undulating desert terrain on the western outskirts of Akjoujt townsite. (Plate 1). Structurally the deposit is situated just north of the axis of a gentle east-west synform which folds an assemblage of multiple thrust sheets in which elements of the upper part of the Oumachoueima Group, mainly the Akjoujt Metabasalts, Lembeitih Formation and Sainte Barbe Volcanics, are repeated several times. (Figure 2). Immediately west of the deposit lies the eroded eastern edge of a major, downward facing, gently west-dipping overthrust sheet. Within this overthrust structure the basement granitic gneisses and intrusive granites grade downwards into granite sheets interlayered with quartzites, psammitic schists and thin carbonates correlated with the Atilis Quartzite. They rest in turn on pelitic schists of the Irarchene el Hamra Formation in a completely overturned sequence. Throughout the Guelb Moghrein area thrusts are accompanied by zones of strong ductile deformation expressed as intense schistosity and mylonitic fabrics. (Figure 4).

The country rocks in the immediate vicinity of the Guelb Moghrein mine are dominated by amphibolite or meta-dolerite but also include narrow shear bounded sheets or lenses of strongly deformed felsic metavolcanic rocks and BIF. The meta-dolerite is believed to be part of the Akjoujt Metabasalts while the other units belong to the Sainte Barbe Volcanics and Lembeitih Formation.

Mineralisation

The Guelb Moghrein ore system (Figure 5) consists of two lensoid bodies of carbonate known as Occidental and Oriental, linked by an attenuated zone of carbonate in mafic schists. (Plate 2). The Oriental body is a massive, thick pod about 250 m long and at least 150 m thick, largely preserved in the oxide zone and lacking a major down-dip extension. Occidental however is a broader, flatter and more extensive lensoid body about 500 m across and up to 150 m thick, apparently tapering down-dip, but open at depth.

X-ray diffraction analysis of the Guelb Moghrein carbonate shows it to be a magnesian siderite with the main peak at 2.77Å (compared to 2.80Å for siderite and 2.74Å for magnesite) (Henley 1995). This ferromagnesian carbonate falls within the range of pistomesite and is characterised

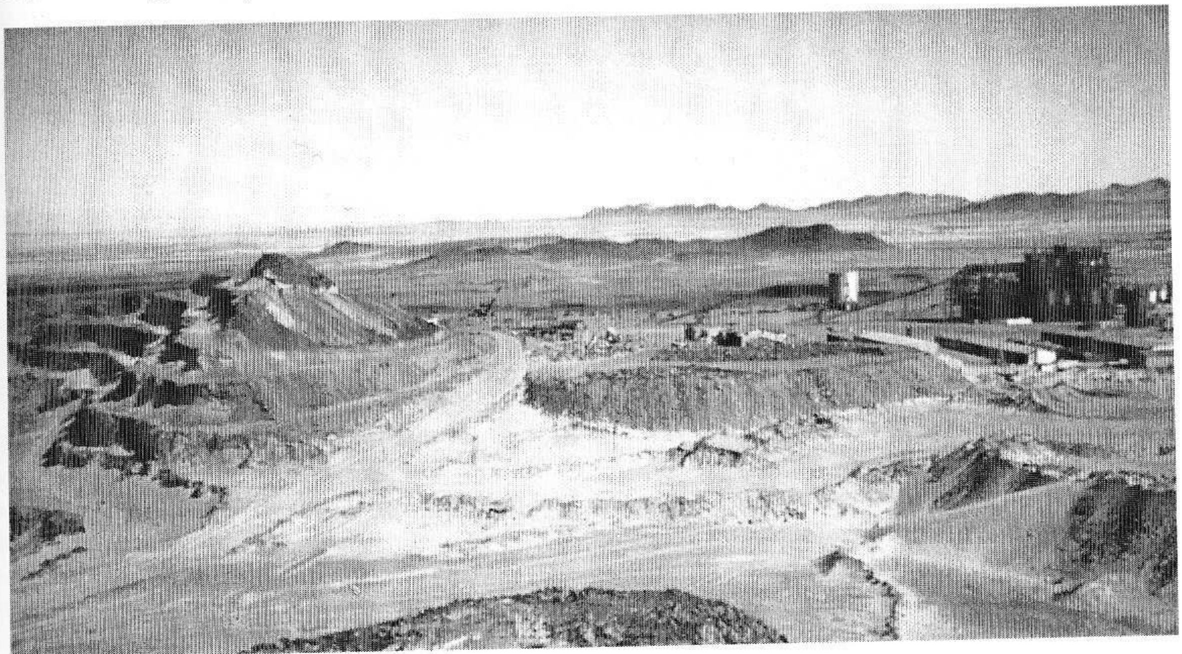


Plate 1 Guelb Moghrein Deposit
View from the crest of the Oriental mineralisation showing the footwall mafics within the existing Occidental open cut and the TORCO plant.

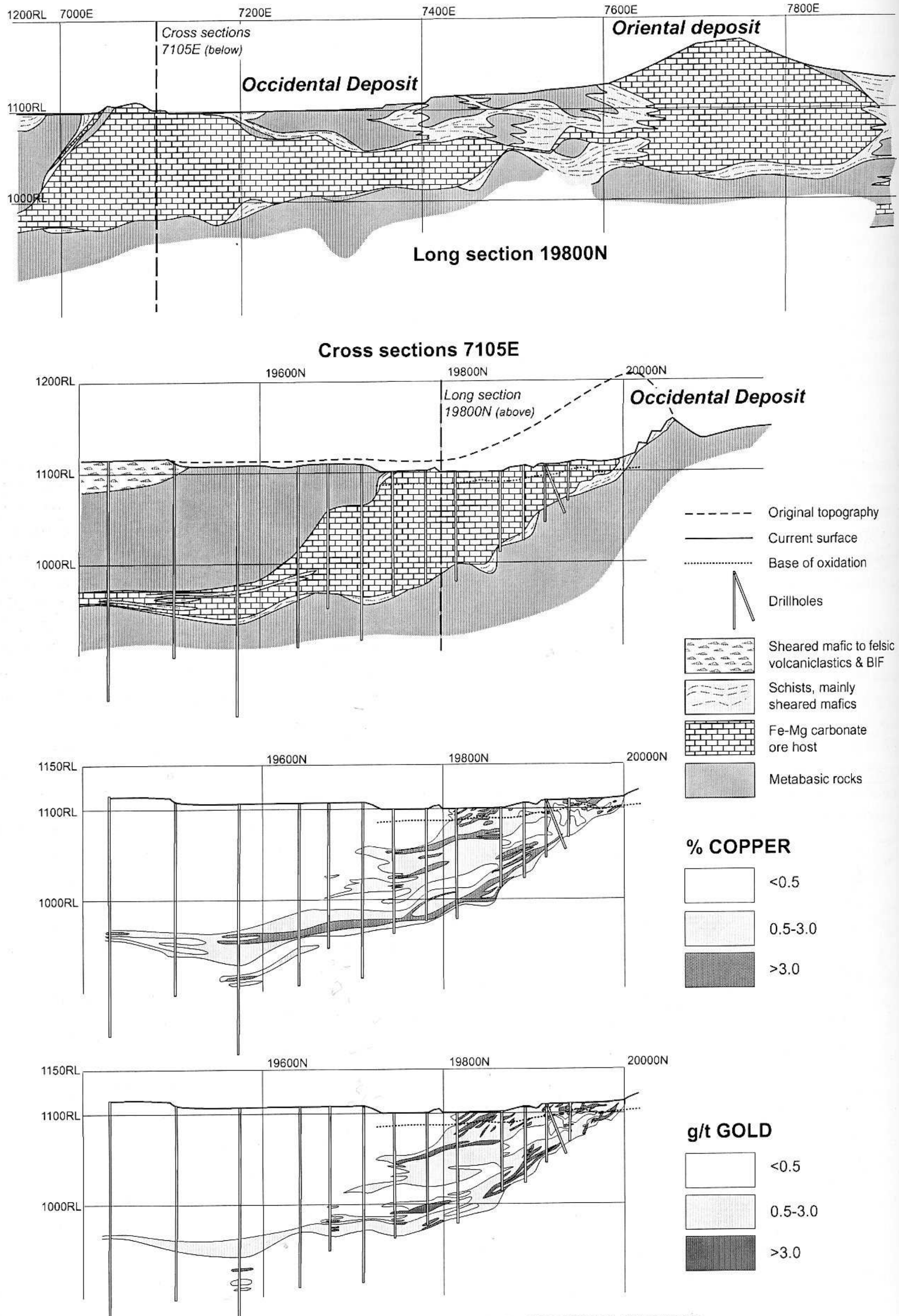


Figure 5 GEOLOGICAL AND GEOCHEMICAL SECTIONS THROUGH GUELB MOGHREIN OREBODY

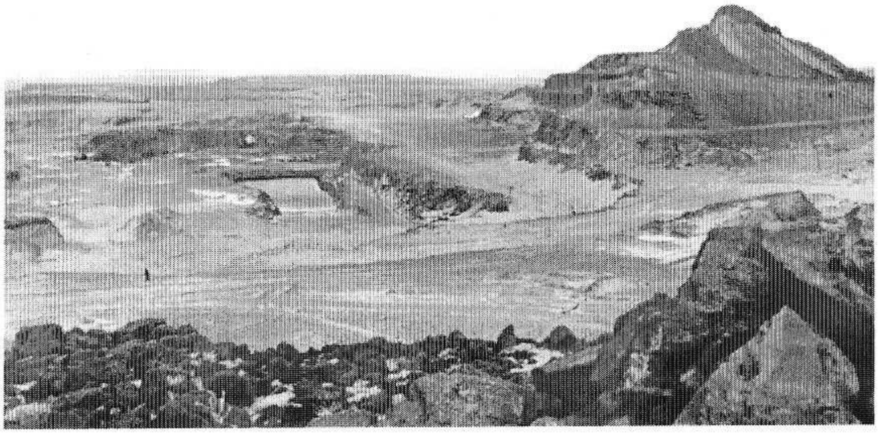


Plate 2 Guelb Moghrein Deposit
View west from Oriental showing exploratory development of the sulphide mineralisation within the Occidental oxide open cut.

by an intergrowth of massive brown or grey irregular crystals up to several millimetres in size. The carbonate body at Guelb Moghrein has been subdivided into oxide, transition and sulphide zones on the basis of colour, texture and mineralogy.

Copper and gold rich zones are interpreted from drilling to occur as multiple, coalescing lenses that are broadly elongate in the direction of the elongation of the carbonate envelope (Figure 5). There is a concentration of lenses in the upper, thicker part of the body, and at the base.

Within the sulphide zones the carbonate is grey to dark grey in colour, coarsely crystalline with intergrowths of chalcopyrite, pyrrhotite, cubanite, arsenopyrite and cobaltite. Magnetite is dominant, accounting for up to 35% of the mineralisation. The magnetite commonly occurs as irregular to euhedral grains up to several millimetres in size and granular masses intergrown with both the carbonate and the sulphides, it is also observed to occur as narrow cross-cutting veins. Euhedral grains of magnetite in places contain inclusions of chalcopyrite. Both the chalcopyrite and cubanite form anhedral grains, which typically are associated with the magnetite or occur as individual anhedral aggregates up to a few millimetres in diameter. Lamellar intergrowths of chalcopyrite and cubanite are occasionally observed, although they commonly form marginal intergrowths or interstitial intergrowths between the magnetite crystals.

Electron microprobe analyses determined that the cobalt in the sulphide zone occurred as cobaltite, whereas in the oxidised ore samples the cobalt was associated with goethite and malachite. An examination of the native gold particles from the reverse circulation drill cuttings indicated irregular shaped grains with a hackly character and either a very bright surface with no coating or a dull reddish brown appearance due to an iron-oxide coating.

There is approximately 2% by volume of fibrous amphibole minerals. Asbestiform minerals including actinolite, tremolite and anthophyllite occur as discrete fibrous aggregates, along fractures or attached to the carbonate. Rarer mineral species include pentlandite, graphite, valleriite and sylvanite. Simultaneous deposition of magnetite, chalcopyrite, pyrrhotite and arsenopyrite is evident, with exsolution of pentlandite, cubanite, cobaltite and valleriite. The epigenetic sulphides were emplaced in the pre-existing ferromagnesian carbonate body. The sulphide ore zones are characterised by high iron and magnesium with relatively low levels of sulphur. During late folding events the sulphides were probably locally remobilised within the major fold axes and fractures. Physical characteristics of the sulphide mineralisation relevant to future mining are the hard yet unabrasive nature of the ore and it's significant density of 3.7 t/m^3.

The transition zone, containing iron and copper oxides, native copper and trace sulfides occupies a thin irregular blanket between the oxide and sulphide zones. This ore consists of siderite with lesser amounts of magnetite, haematite, goethite and anthophyllite, with trace amounts of graphite, quartz, native copper, malachite and chalcocite. The transition mineralisation is characterised by siderite, with lesser amounts of magnetite, quartz, chalcopyrite, pyrrhotite, anthophyllite, cubanite and arsenopyrite. Trace amounts of pentlanditite, graphite, molybdenite and sylvanite were also observed. Native gold, electrum and melonite ($NiTe_2$) were observed associated with arsenopyrite (Ramdohr et al, 1956).

The oxide zone at Occidental was originally capped by a siliceous iron gossan, depleted in copper and up to 15m thick, few remnants of the mineralised outcrop now remain. This oxide mineralisation at the Oriental deposit currently is present as an undisturbed silicified cap. Haematite, goethite and residual magnetite are the dominant iron minerals present. Goethite coats and partially replaces the carbonate forming a carbonate gossan and haematite commonly coats the magnetite. X-ray diffraction and ore microscopy of thin and polished sections show that the

TABLE 1
GUELB MOGHREIN OCCIDENTAL
ANALYSES OF METALLURGICAL SAMPLES.

Species	Oxide Ore	Sulphide Ore	Species	Oxide Ore	Sulphide Ore
Cu %	1.47	1.76	Al ppm	105	1800
Cu (sol) H_2SO_4 %	1.05	0.016	As ppm	730	101
Cu (sol) Cyanide %	0.89	0.033	Ba ppm	6.4	9.5
Co %	0.02	0.018	Be ppm	<1	<1
Fe %	45.0	38.2	Ca ppm	11700	8520
S %	0.09	2.77	Cd ppm	45	41
S= %	<0.01	2.49	Co ppm	215	186
Au g/t	1.7	2.0	Cr ppm	24	20
Ag g/t	-	-	Cu ppm	14900	19000
CO_3 %	17.8	29.7	Fe ppm	547000	467000
CO_2 %	13.1	21.8	K ppm	689	538
SiO_2 %	5.3	4.7	La ppm	<100	<100
Al_2O_3 %	0.09	0.31	Mg ppm	63100	89000
Fe_2O_3 %	65.5	57.3	Mn ppm	9450	8450
MgO %	8.4	11.8	Mo ppm	<10	<10
CaO %	1.72	1.19	Na ppm	392	870
Na_2O %	<0.05	<0.05	Ni ppm	148	163
K_2O %	0.02	0.03	P ppm	200	303
TiO_2 %	0.03	0.04	Pb ppm	48	36
P_2O_5 %	0.04	0.09	Sb ppm	<10	<10
MnO %	1.28	1.11	Se ppm	<50	<50
Cr_2O_3 %	0.05	0.03	Sn ppm	<20	<20
V_2O_5 %	0.02	<0.01	Te ppm	<50	<50
Loss On Ignition	16.3	21.0	Zn ppm	43	39

TABLE 2.
GUELB MOGHREIN OCCIDENTAL
GEOPHYSICAL PROPERTY MEASUREMENTS

Sample Description	Density g/cm^3	IP Effect mrad	Conductivity S/m	Resistivity ohm.m	Susceptibility cgs x 10^{-6}	Remanence Q factor
Stringer sulphides	4.12	630	1130	0.000780	81700	8.1
Low grade ore	3.70	697	113	0.038000	49100	2.5
High grade ore	3.77	603	472	0.001900	13300	3.2
Massive sulphides	4.29	564	3122	0.000170	28900	0.3
Massive sulphides	4.23	420	5836	0.000032	31700	0.5
Dissem. sulphides	3.88	585	89	2.000000	68300	0.4

oxide ore beneath the siliceous cap is characterised by goethite, siderite, haematite and magnetite with lesser amounts of anthophyllite, graphite, malachite, chalcopyrite and covellite. Carbonate and oxide copper minerals dominate the remainder of this zone including malachite, azurite, cuprite, native copper and chrysocolla. Native gold is commonly attached to goethite and haematite and minute telluride inclusions were observed in the magnetite, chalcopyrite and arsenopyrite.

The spatial distribution of both the carbonate and the economic copper, gold and cobalt mineralisation appears to be a function of total fluid movement throughout the shear structure. Well-defined thin, tabular shoots are typically present, complicated by sulphide enrichment on late fractures, representing a remobilisation overprint. (Figure 5).

A detailed analysis of two composite metallurgical samples, representing oxide and sulphide ore types is presented in Table 1.

Hangingwall and Footwall Lithologies

Petrographic examination of the hangingwall and footwall amphibolites has indicated that the primary textures have been obliterated by upper greenschist to lower amphibolite facies metamorphism. The hangingwall amphibolite is composed of intergrowths of amphibole and quartz, with minor feldspar, biotite, ilmenite and trace amounts of chlorite, carbonate, sphene and pyrite. Chlorite is intergrown with hornblende and biotite, and porphyroblasts of plagioclase feldspar are common. Discordant streaks and lenses of hornblende-biotite and quartz-carbonate-chlorite intergrowths probably representing shears, disrupt the amphibolites.

The highly sheared footwall examples, although mineralogically similar to the host amphibolites, contain a pronounced fine-grained, lenticular-banded structure and increased fine-grained phyllosilicates and carbonate. The texture is commonly porphyroblastic with quartz and amphibole in a fine grained groundmass of phyllosilicates. Feldspars are sericitised and silicified, and tremolite is developed along the cleavage. The footwall is cut by numerous shear zones, often with a pinched or boudinaged core of carbonate and lenses of fine-grained quartz.

Sulphide mineralisation and tremolite are observed within the highly sheared, carbonated footwall and hangingwall 'schists'. These narrow ore zones occur as irregular selvages to the main body and appear to rapidly decrease in frequency and thickness outwards from the body (Figure 5).

Geophysical Characteristics

The Guelb Moghrein Cu-Au-Co mineralisation within both the Occidental and Oriental deposits is characterised by prominent magnetic anomalism and has the following geophysical properties (Emerson 1998).

- All samples are generally dense with the massive sulphide examples averaging over 4.2 g/cc.
- IP measurements show the samples to be highly polarisable with little difference between strongly or weakly mineralised samples.
- Inductive electromagnetic measurements show all the samples to be conductive, ranging from a low of 89 siemens/m for disseminated sulphides, up to extremely high values of up to 5836 siemens/m for the massive sulphides.
- Galvanic resistivity results show all samples to have low resistivity, with the massive sulphides having extremely low resistivity.
- Magnetic susceptibility values for all samples are very high and equate to between 1% and 27% magnetite equivalent.
- Significant remnant magnetisation was indicated in all samples. Precise measurement of the direction of the remnant magnetism is required prior to any detailed quantitative interpretation of magnetic surveys.

A summary of the measured parameters and results is presented in Table 2.

The Guelb Moghrein mineralisation forms an ideal target for a large variety of geophysical survey methods. For reasons of cost and efficiency a magnetic survey is considered as a first pass method, with the transient electromagnetic (TEM) method the preferred follow up technique, as it allows both deep detection of mineralisation and quantitative interpretation. Figure 6 presents an image of the surface source enhanced total magnetic intensity data and a 3D model of the results viewed from the southeast. The data clearly highlights the Guelb Moghrein mineralisation at Occidental and Oriental and has identified additional magnetic anomalies in the mine environs for future exploration.

Mineral Resources

A 105 hole exploratory drilling programme by GGISA in 1994-95 together with the results from previous drilling campaigns has resulted in a comprehensive database of over 220 diamond drill and reverse circulation holes. Computer studies have involved solid modeling, statistical and geostatistical analysis, and the interpolation of the copper, gold and cobalt grades according to copper cut-off grade and bench elevation.

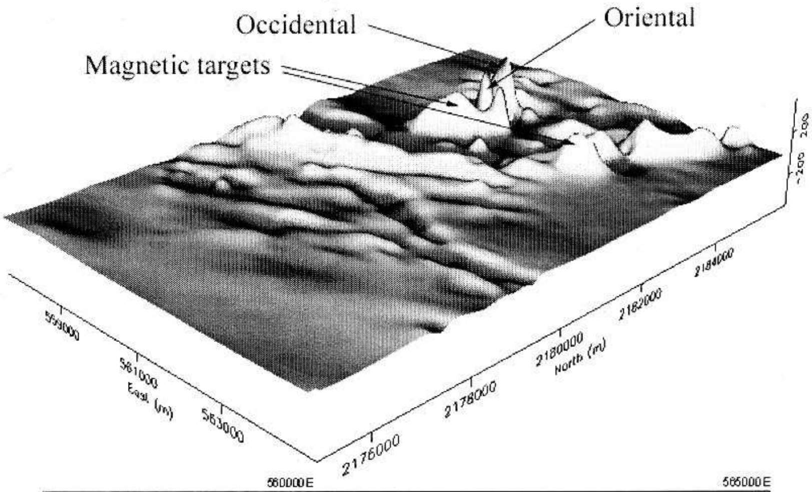
Using a 1% Cu cutoff the Total Resource (including Measured and Indicated) for the Guelb Moghrein Deposit has been independently calculated as 23.6 Mt @ 1.88 % Cu, 1.41 g/t Au and 143 ppm Co. (Kilborn SNC-Lavalin Europe. 1997).

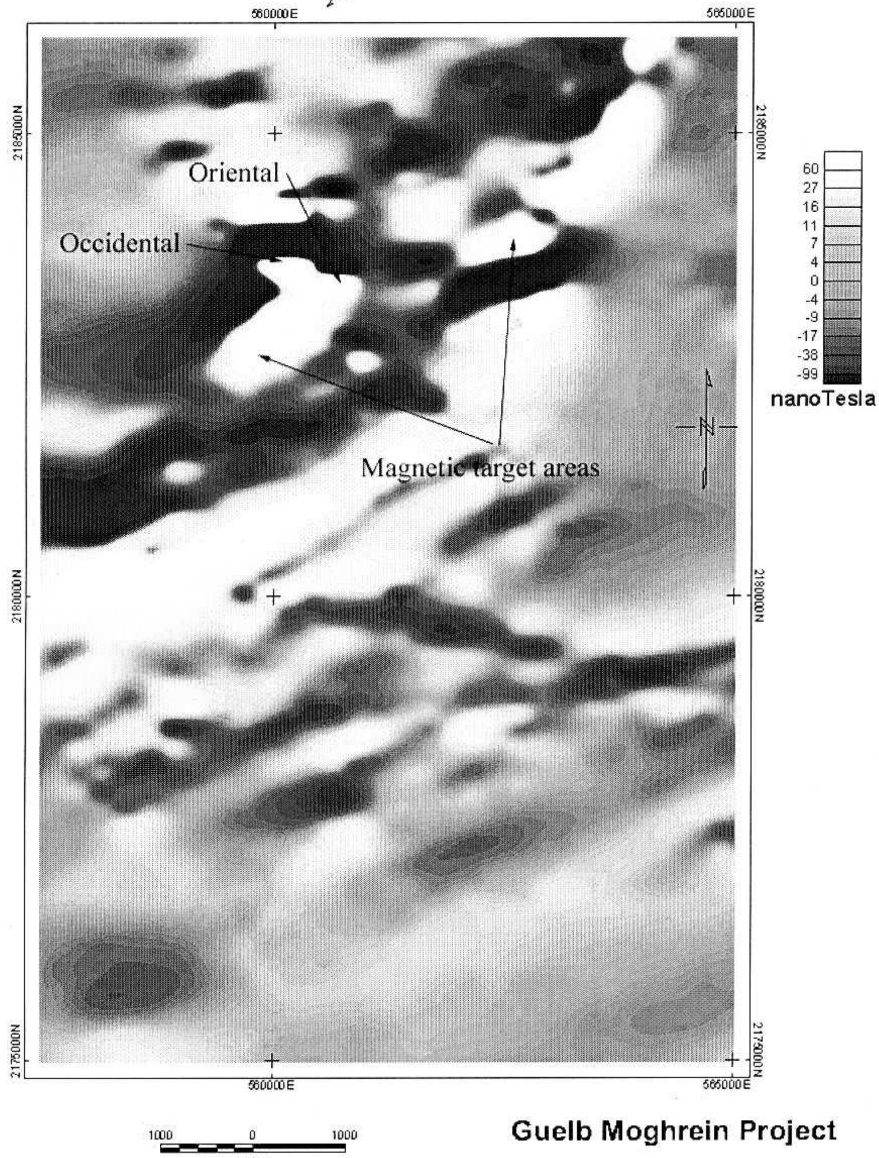
A polygonal resource estimate by GGISA in 1999 using a 0.5 % Cu cutoff and incorporating the existing oxide stockpiles and the Guelb Moghrein Oriental mineralisation, resulted in a Total Resource (including Measured and Indicated) of 32.3 Mt @ 1.61 % Cu, and 1.36 g/t Au.

El Khader

The El Khader prospect (Figure 7) is situated in a hilly dissected area known as Legleitat el Khader. The domal structural setting is formed by the intersection of a moderate, slightly north-verging, arcuate, northeast-southwest asymmetric antiform with a gentle north-northwest trending antiform. The doming is a part of the later folding that warps an extremely complex system of early, stacked thrust sheets.

The southern side of the dome consists of quartz-muscovite-chlorite schists representing meta-siltstone and meta-greywackes of the Irarchene el Hamra Formation. Overlying BIFs and tuffaceous siltstone of the Atomai Formation form a north dipping range on the northern side. The core of the dome is complex and outcrop is partially obscured by supergene ironstone rubble. Meta-dolerite is the most common rock type exposed in the deeper gullies on the south side, but the eastern side of the core is formed from quartz-sericite altered felsic volcaniclastic rocks, interpreted as part of the Sainte Barbe Volcanics. Similar rocks occur as infolds and enclaves within the meta-dolerite. Reverse circulation drilling to shallow depth at various points on the dome encountered interlayered felsic volcaniclastics and 'amphibolites'. A thrust plane is interpreted to separate the core of the dome from the rim in order to explain the disordered stratigraphic succession.





Guelb Moghrein Project

Surface Source Enhanced TMI

Figure 6

The El Khader vein system has not been studied in detail as a coherent system. Mapping has been carried out as part of regional programme and a few selected examples of country rock and hydrothermal alteration have been examined petrographically. Exploration to evaluate the iron ore resource in the supergene cap was carried out by MICUMA in 1958 and resulted in the delineation of a resource of 18 Mt of iron ore grading 51% Fe.

Essentially El Khader consists of an extensive Fe-Mg-Ca carbonate vein system or stockwork, up to 2 km across at the surface, in which the veins of coarsely crystalline brown Fe-rich carbonate thicken and coalesce towards the top. This top is generally represented by a massive supergene goethite cap in which the rock type definition is blurred. Gullies on the southeast side of the vein system cut into its roots where the carbonate veins narrow downwards and become widely spaced in altered meta-dolerite country rock. Reconnaissance petrography has revealed a complex suite of alteration phases in this part of the system. Meta-dolerites are commonly rich in alteration plagioclase ranging from almost pure andesine rock with interstitial magnetite close to the carbonate vein margins to more disseminated albitic plagioclase further away. Plagioclase also occurs as quartz-albite veinlets. These plagioclase-altered rocks were previously interpreted as 'oligoclasite' or 'albitophyre' intrusives (eg. Marcelin, 1968). Other samples reveal strong sericite and chlorite alteration and there is evidence of a sericite event that post-dated the plagioclase. Meta-felsic volcaniclastic rocks, to the northeast, and in enclaves within the dolerite, are generally quartz-sericite altered and there are localised zones of strong silicification and quartz veining (Figure 7). The top of the carbonate vein system corresponds approximately to the interpreted thrust though it appears to slightly transgress, and therefore post date this structure.

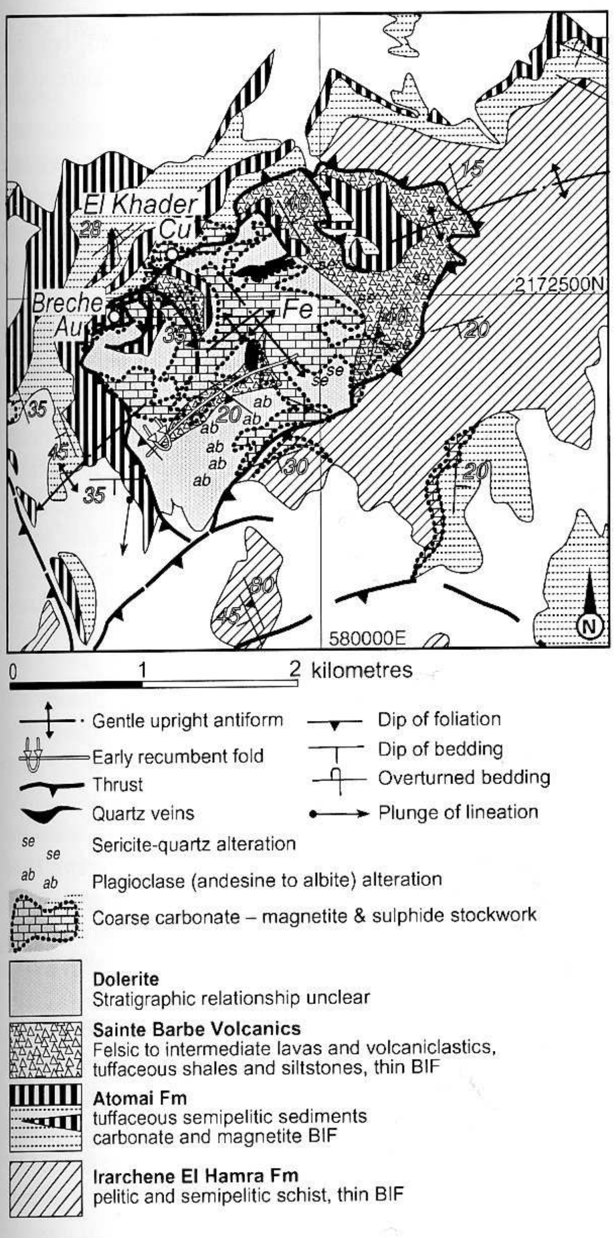


Figure 7 GEOLOGICAL OUTCROP MAP OF EL KHADER based on field traverses and air photo interpretation

The El Khader supergene copper occurrence is in the oxidised capping to the upper part of the carbonate vein system and consists of malachite staining in the weathered, veined country rocks and goethitic cap. Minor gold has been recorded at the Breche prospect, a quartz-rich breccia developed as a late, cross-cutting phase towards the northwest of El Khader. Drilling of the El Khader prospect has encountered only patchy, low grade supergene copper values in the 0.1-0.3% range, accompanied by anomalous barium and arsenic. More recently the gold and copper potential of the upper, northern rim of the system was investigated by Normandy La Source with a programme of reverse circulation drilling, however no primary mineralisation was encountered. The results of the drilling suggest that, despite the impressive scale of this vein and alteration system, there is little potential for the discovery of a significant Cu, Au resource in close proximity to the surface.

The carbonate vein system at El Khader is interpreted as belonging to a later stage in the tectonic evolution than at Guelb Moghrein. El Khader's brittle fracture event is considered a later event than the ductile shear setting of Guelb Moghrein. Localisation of the veining in a dome structure, and the upward intensification of the veining, suggest that the principal control may be extension across the crest of the dome. No evidence of contemporaneous igneous intrusion has been encountered and the meta-dolerites are believed to belong to an earlier, pre-thrusting event.

Other Deposits

There are a number of smaller occurrences of copper mineralisation in the Akjoujt area with or without iron oxide or gold. The Masse and El Joul groups of deposits close to Akjoujt (Figure 2) are similar to Guelb Moghrein, consisting of numerous pods of coarse-grained ferromagnesian carbonate with magnetite, and copper sulphides. They are crudely concordant to, and hosted by, intensely sheared metavolcanic and metasedimentary rocks showing multiple thrust repetition, and the larger occurrences in the two groups are localised on antiformal refold structures.

The historic Sainte Barbe workings 25 km northeast of Akjoujt (Figure 2) are of oxide copper hosted by quartz-ankerite stockworks in discordant carbonate bodies hosted by chloritised mafic and felsic flows and volcaniclastics of the Sainte Barbe Volcanics. The mineralisation is located 100-200 metres above the regional sole thrust which rests on Archaean basement and thin cover sediments.

At Tabrinkout, 30 km east of Akjoujt (Figure 2), schistose mafic to felsic volcanics are the hosts to an extensive zone of complex carbonate stockworks, which is broadly controlled by a strong, late-stage north-south fracture. The irregularly distributed lenses of coarse-grained ferromagnesian carbonate are intercalated with narrow quartz veins and contain tungsten mineralisation in the form of wolfram, scheelite and tungstite. Secondary copper in the form of malachite, chalcocite and covellite accompany the tungsten within the quartz veins. Minor bismuthinite and native gold are found at the quartz-carbonate contacts.

Discussion

All of the iron, copper and gold occurrences at Akjoujt and within the broader Inchiri area, feature coarse-grained carbonate as a host. Carbonate is also a pervasive mineral phase in the country rocks as iron carbonate in BIF and as alteration carbonate in a wide variety of rock types. A detailed study of the carbonate has so far been limited to petrographic and mineragraphic work. No oxygen, carbon or indeed sulphur isotope studies have been conducted on the hosts or ores and therefore this discussion lacks the critical analysis such data could provide. Mapping has revealed very little bedded carbonate sediment in the supracrustal sequence, other than iron carbonate in BIF. It is deduced that the carbonate either entered the system at the volcanic-hydrothermal or sea floor alteration stage during the deposition of the BIF, or during tectonism, or perhaps in both periods. Given the abundance of carbonate, and the structurally-controlled settings of the coarse grained occurrences it is likely that the carbonate bodies evolved from within the system during tectonism.

Previously the Guelb Moghrein deposits were thought to be stratiform within a sedimentary carbonate sequence and confined to the nose of southerly plunging syncline (Pouclet et al., 1987). An alternative genetic model as a VHMS style deposit had earlier been proposed by Ba Gatta, (1982). The features of the deposit do not however match any known deposits of these types, and the folded carbonate sediment model of Pouclet et al. is not supported by drilling data (Figure 5). The host rocks are predominantly metabasic igneous rocks, which have been strongly altered along low angle, 10-30 degree thrusts or shears. It is postulated that extensive carbonate alteration has occurred along these zones of structural weakness, and the carbonate has acted as the favourable host for later mineralising fluids. The mineralisation is open at depth and presents a significant target for the discovery of satellite deposits of the Guelb Moghrein type.

There is no evidence of an igneous intrusive event that could have brought about the introduction of the mineralised carbonate bodies. However there is sporadic evidence of a thermal peak that post-dated early thrusting from the garnet, cummingtonite and biotite porphyroblasts that are scattered through the schistose margins of many of the smaller carbonate-magnetite bodies to the southwest of Guelb Moghrein. These porphyroblasts in turn have suffered subsequent partial retrogression to phases such as chlorite, so the thermal history is complex and as yet poorly understood. The domal setting and strong plagioclase and sericite alteration in the deeper exposures at El Khader is suggestive of an intrusive body at depth, but apart from the altered host meta-dolerite, no intrusive rocks have been identified.

The alteration style of the country rocks to the various bodies is quite variable. At Guelb Moghrein the presence of tremolite and biotite in the schistose envelope rocks points to minor magnesium and potassium metasomatism but the effect does not appear to extend very far into the amphibolite country rocks. In contrast, El Khader features strong albite to andesine alteration of the rocks in the roots of the carbonate vein system, and widespread but patchy sericite and chlorite. The sodium, calcium and potassium alteration at El Khader is more typical of the iron-oxide, copper gold class described in (Porter, 2000) but that alteration style is by no means a universal feature of the deposits described therein.

The variation in style of the carbonate bodies of the Akjoujt area is consistent with their development at different times during the tectonic history. The character of the Guelb Moghrein mineralisation is compatible with emplacement during an early thrusting. The asymmetry of the obliquely-bevelled western edge featured in Figure 5 may be interpreted as a response to a second period of thrusting from the west. In contrast the style of El Khader is extensional and related to a late-stage doming event rather than to early compression. It is interpreted that the doming took place as an interference effect in the folding, above the decollement of the sole thrust. El Khader thus would have evolved when the supracrustals were in an allochthonous position above a 'cold', underthrust basement.

The occurrence and origin of the metallic phases and magnetite in the Akjoujt area is more problematic since their distribution is much more localised. Evidence from Guelb Moghrein suggests an introduction of at least the sulphides and gold at a later period than the host carbonate. The very weak copper and gold at El Khader seems to be concentrated at the top of the system, and is therefore related to the evolution of the system, but its very localised distribution suggests that it was also a late stage event.

Although the Akjoujt supracrustal sequence evolved in a rifted continental setting and features strong compression and shortening, it lacks the other two key elements of Hitzman's model (Hitzman, 2000), the evaporites and later magmatism. The formation of the carbonate bodies by remobilisation or concentration of carbonate during tectonic processes seems to be the essential preparation process, and this would have involved recycling of basin fluids, although there is no evidence that magmatism played any direct role in this. The introduction of the metallic components is assumed to be along the same structural channels that controlled the localisation of the carbonate but the source of the metals is unclear. The most likely origin is, like the carbonate, from within the pile, in this case from the abundant, leachable mafic volcanic rocks.

Literature research has yet to unearth any analogues to the Akjoujt deposits although a number of districts worldwide show some comparative features or processes. Regional metamorphism of sedimentary intervals of BIF, chert and marble has been invoked to explain the so-called 'skarn iron ores' of the Pajala District of northeast Sweden (Carlon, 2000). These consist of lenses rich in magnetite, with carbonate, actinolite, diopside, hornblende, chlorite and biotite. Some of them contain minor pyrite, pyrrhotite and chalcopyrite. Many iron-rich carbonate lenses in the Akjoujt area are within the BIF-rich part of the sequence, and porphyroblasts and segregations of coarse carbonate are common in some of the BIFs.

Carbonate is the principal host of the 1500 Mt Bayan Obo Fe-REE-Nb deposit in northern China (Smith & Chengyu, 2000). Here the setting is a major subduction boundary involving northwest to southeast thrusting of Proterozoic sequences during Caledonian and Hercynian times, a setting and timing comparable to the Mauritanides. The host carbonates show sedimentary features, while the O and C isotopic signatures are comparable to carbonatite, leading those authors to conclude that they were carbonate sediments modified by magmatic fluids. As at Akjoujt, no igneous intrusives were located in the vicinity of the Bayan Obo mineralisation.

Also comparable in overall orogenic setting and timing are the Bou Azzer deposits in the Anti Atlas of Morocco (Leblanc & Billaud, 1982). These consist of bodies of epigenetic cobalt arsenide mineralisation in quartz-carbonate gangue, with accessory nickel, copper and molybdenum. They are located in the tectonised contacts of Neoproterozoic ophiolitic serpentinite and its unconformable cover, in a complex orogenic belt of PanAfrican to Hercynian age like the Mauritanides, and possibly an extension of them. The difference in ore mineralogy to Guelb Moghrein may be more a function of host rocks than style or genesis, the copper and iron of the latter being related to the mafic host in contrast to the cobalt and nickel of the country rocks at Bou Azzer. The carbonate hosted, shear related, copper occurrences of the Selibabi-Mbout region such as at Kadiar, further south in the Mauritanides of Mauritania (Figure 1), may also have comparable paragenesis to those of the Akjoujt area.

A significant feature of the collection of papers in the AMF monograph (Porter, 2000) is the diversity of style and setting of the deposits in the hydrothermal Fe oxide, copper gold class. When an apparently unifying theme is discerned, conspicuous exceptions seem to emerge. For example the Olympic Dam (Reynolds, 2000) and Tennant Creek deposits (Skirrow, 2000) provide a major exception to the characteristic sodium and calcium alteration of the country rocks as seen in most other districts. In the Akjoujt area the El Khader system features moderately strong sodium, calcium and potassium alteration but the Guelb Moghrein system shows only moderate magnesium enrichment of the host envelope.

Descriptions of iron, copper gold mineral provinces like Tennant Creek, or the Curnamona and Cloncurry districts (Williams & Skirrow, 2000) reveal a diversity of style, setting and mineralogy even within one province. Hitzman (2000) discusses a variety of tectonic settings ranging from anorogenic magmatism to orogenic basin collapse. In the latter case, a rifted continental basin is subjected to compression and under plating, leading to a high heat flow and the formation of hydrothermal cells of basin fluids. Examples that were cited include the Cloncurry District of Australia and the Lufilian Orogen of Southern Africa. Key features of the model are the presence of evaporitic continental sediments as a source for brines, and also extensive magmatism driving the cells. Although the Akjoujt supracrustal sequence evolved in a rifted continental setting and features strong compression and shortening, it lacks the other two key elements.

In conclusion, the essential preparation process for the occurrence of the mineralised carbonate bodies in the Akjoujt region has been the remobilisation or concentration of carbonate during tectonism and involving the recycling of basin fluids. However there is no evidence that magmatism played any direct role in this process. The later introduction of the metallic components is assumed to have been along the same structural channels that controlled the localisation of carbonate but the source of the metal is unclear. The most likely origin of the metallic species is, like the carbonate, from within the pile, in this case from the abundant, leachable mafic volcanic rocks.

Further exploration and geological research is necessary at the Guelb Moghrein deposit and associated mineral occurrences to assist in the definition of this style of mineralisation as a carbonate rich sub class of the hydrothermal Fe-oxide copper-gold class of deposit. The ability to effectively target both the magnetic and conductive characteristics of the Guelb Moghrein mineralisation has encouraged the future exploration for extensions to the existing ore resources and satellite deposits. Research during this programme should help address the age, origin and occurrence of both the carbonate, magnetite and the metallic phases of this style of mineralisation.

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