Developing the lithotectonic framework and model for sulphide mineralization in the Jebilet massif, Morocco: implications for regional exploration

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Abstract. The central Jebilet massif, part of the North African Variscan Belt, hosts significant polymetallic sulphide mineralization. It is generally considered syngenetic and has many features of volcanogenic massive sulphide (VMS) mineralization. However, some characteristics are not compatible with a classic VMS model and two alternative scenarios for formation have been proposed. Our preliminary research favours a complex, multi-stage development of the sulphide deposits. Uncertainty as to the critical processes controlling the mineralization and lack of agreement on a genetic model inhibit regional exploration. We identify the key knowledge gaps regarding sulphide mineralization in the central Jebilet and outline a research program to address these, with the ultimate aim of improving regional mineral exploration targeting and unlocking the economic potential of this relatively undeveloped district.

Keywords. Morocco, Variscan, Jebilet, VMS, exploration.

1 Introduction

The central Jebilet massif, in the Marrakech region of western Morocco, comprises a block of Carboniferous sedimentary rocks that were extensively deformed and metamorphosed during the Variscan orogeny (Moreno et al. 2008) (Fig. 1). This block, and its extension to the south of Marrakech (Guemassa massif), are characterized by bimodal intrusive magmatism and significant massive sulphide mineralization (Essaifi and Hibti 2008), e.g., the Draa Sfar deposit: 10 Mt grading 5.3% Zn, 2% Pb, 0.3% Cu (Belkabir et al. 2008). Mining is taking place at the Draa Sfar and Hajjar mines. Previously worked deposits at Kettara, Roc Blanc, and Koudiat Aicha have extensive reserves, and prospects such as Lachach and Ben Slimane are being explored (Fig. 1B) (Essaifi and Hibti 2008).

The massive, polymetallic sulphide mineralization has generally been classified as volcanogenic (Bernard et al. 1988; Belkabir et al. 2008; Marcoux et al. 2008). However, whilst displaying some features characteristic of syngenetic volcanogenic massive sulphide (VMS) mineralization (e.g., sulphide mineralogy dominated by pyrrhotite; generally stratabound; hosted by a marine volcano-sedimentary succession; chlorite-sericite alteration; Bernard et al. 1988; Marcoux et al. 2008; Moreno et al. 2008), some features of the deposits and controls on their distribution remain enigmatic.

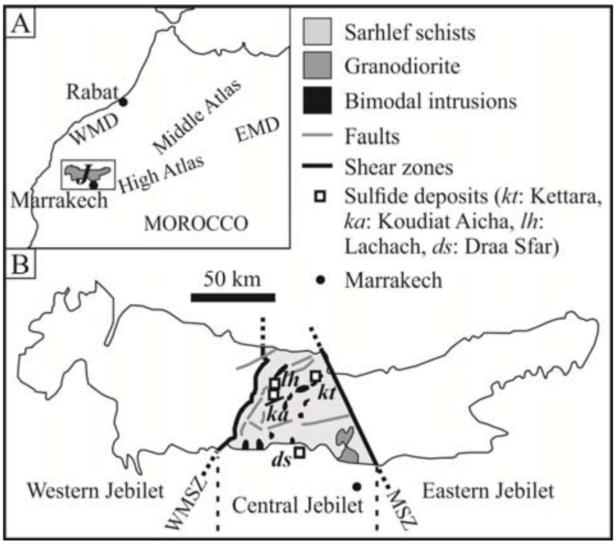

Figure 1. (A) Location of the Jebilet massif (J) in Morocco, WMD: Western Meseta Domain; EMD: Eastern Meseta Domain; WMSZ: West Moroccan Shear Zone; MSZ: Marrakech Shear Zone. (B) Structural domains of the Jebilet massif and selected sulphide deposits of the central Jebilet. Adapted from Essaifi and Hibti (2008).

It has also been suggested that some of the deposits may be epigenetic, associated with Variscan tectonics and magmatism (Essaifi and Hibti, 2008). Interpretation of the mineralization is complicated by the Variscan deformation and metamorphism resulting in a lack of sedimentary or diagenetic textures (Moreno et al. 2008). Whilst some deposits are well characterised at the mine-scale, with good understanding of local structural controls, geometry, host rock geochemistry, ore mineralogy and hydrothermal alteration (e.g. Belkabir et al. 2008; Moreno et al. 2008), the overall structure and stratigraphy of the central Jebilet are poorly known and thus regional controls on the distribution of mineralization are not well established.

Below we outline a collaborative research programme between the British Geological Survey and Cadi Ayyad University, with support from the Managem Group (the principal company operating in the region), which aims to develop a detailed stratigraphy for the central Jebilet and a regionally-applicable mineral deposit model. This will be used as the basis for an exploration targeting system and support future GIS-based prospectivity analysis to identify the next generation of exploration targets.

2 Geological Setting

The Jebilet massif, 7 km north of Marrakech in north central Morocco, forms a component of the Western Meseta, part of the North African Variscan Belt (Fig. 1A). The massif, 170 km long and 40 km wide, is dominated by a succession of sedimentary rocks, deposited in the shallow marine environment of a Devonian-Carboniferous, continental margin, transtensional rift basin (Huvelin 1977; Aarab and Beauchamp 1987; Beauchamp and Izart 1987; Moreno et al. 2008). Extension was rapidly followed by compression and basin closure during the Variscan Orogeny, resulting in low-grade metamorphism and deformation of the region (Essaifi et al. 2014). Three tectono-stratigraphic domains, separated by major shear zones, have been defined (Huvelin 1977): i) the western Jebilet, comprising unmetamorphosed Cambro-Ordovician sedimentary rocks (Huvelin 1977); ii) the central Jebilet, a block of low-grade metamorphosed, schistose, marine Visean shales (Sarhlef schists) deposited in an anoxic environment (Beauchamp 1984; Essaifi and Hibti 2008); and iii) the eastern Jebilet, composed of unmetamorphosed Visean rocks (Huvelin 1977) (Fig. 1B).

The central Jebilet hosts the polymetallic sulphide mineralization and is also characterized by the presence of minor rhyolitic and rhyodacitic extrusives, reported by Belkabir et al. (2008) at Draa Sfar to have FIIIb (see Hart et al. 2004) tholeiitic compositions. The rocks of the central Jebilet have been folded and sheared and low-grade metamorphism has resulted in a schistose fabric (Essaifi and Hibti, 2008). Syn-tectonic magmatism comprising an ultramafic to granitoid bimodal association (>65% mafic−ultramafic, the remainder felsic) is widespread, associated with peraluminous granodiorites emplaced at ca. 330 Ma, intruded by younger (300 Ma) leucogranites (Fig. 1B). The bimodal plutonism principally occurs in three linear zones parallel to shear zones (Essaifi et al. 2014).

3 Mineralization

The characteristics of the central Jebilet sulphide mineralization are described in detail by Essaifi and Hibti (2008) and references herein, and those features relevant to the subsequent discussion are summarised below and in Table 1. The host sequence, dominated by siliciclastic rocks deposited in a continental margin basin, is consistent with the 'siliciclastic' class of VMS deposits defined by Franklin et al. (2005). The massive sulphide deposits occur at different stratigraphic levels of the Sarhlef metasedimentary rocks and do not appear to be confined to a specific lithological package. The mineralization is typically focused in shear zones, which have a consistent spatial relationship with the bimodal intrusions. Regional deformation means the sulphide deposits are sub-vertical, and comprise long and narrow ellipsoidal lenses in three dimensions (Essaifi and Hibti 2008). Small sulphide veins are locally present below the massive sulphide ore and interpreted to represent stockwork or stringer zones. However, their occurrence is sporadic and in some instances they have very limited vertical extent (Moreno et al. 2008).

Siliciclastic-hosted VMS	Jebilet
Marginal basin setting	✓
Extensional tectonic regime	✓
Continental basement	✓
Siliciclastic sediments ~80%; volcaniclastic rocks and extrusives	✓
Bimodal magmatism	✓
Felsic rocks with FIII signatures	?
Thick, complex volcanic stratigraphy	×
Exhalites (chemical sediments)	?
Favourable stratigraphic intervals	?
Stratabound sulphide lenses	?
Discordant stockwork zones	?
Pyrite-pyrrhotite-chalcopyrite-sphalerite-galena ore mineralogy	✓
Chlorite-quartz-sulphide- or sericite-quartz-pyrite ± aluminosilicate alteration	✓
Evidence for metal zonation	✓
Syngenetic, genetically related to volcanism	?
Deep-water marine environment	×

Table 1. Comparison of the characteristics and lithotectonic setting of the central Jebilet mineralization with those of siliciclastic-type VMS deposits. Features are based on those described by Allen and Weihed (2002), Franklin et al. (2005), and Gibson et al. (2007).

The mineralization has variable base metal concentrations, with some deposits being distinctly Pb-Zn-rich, e.g., Draa Sfar. Pyrrhotite forms up to 90% of the sulphides, with variable quantities of sphalerite, galena, chalcopyrite, pyrite, and arsenopyrite (Essaifi and Hibti, 2008) (Fig. 2B,C). The abundance of pyrrhotite contrasts with deposits of the Iberian Pyrite Belt, which has the same lithotectonic setting (Franklin et al. 2005). The regional metamorphism results in a range of recrystallization and deformation textures in the ores with primary depositional textures largely absent (Moreno et al. 2008) (Fig. 2B).

Well-developed supergene mineralized zones, indicated by surface gossans (10–100 m in width), are a characteristic feature of the deposits (Belkabir et al. 2008; Essaifi and Hibti 2008; Marcoux et al. 2008) (Fig. 2A).

Two models for the formation of the central Jebilet sulphide deposits have been proposed: (i) syngenetic, representing either classic VMS or SEDEX mineralization (Marcoux et al. 2008; Moreno et al. 2008); or (ii) epigenetic, formed during the waning stages of Variscan orogenesis and associated with the abundant bimodal intrusive magmatism (Essaifi and

Hibti 2008; Lotfi et al. 2010).

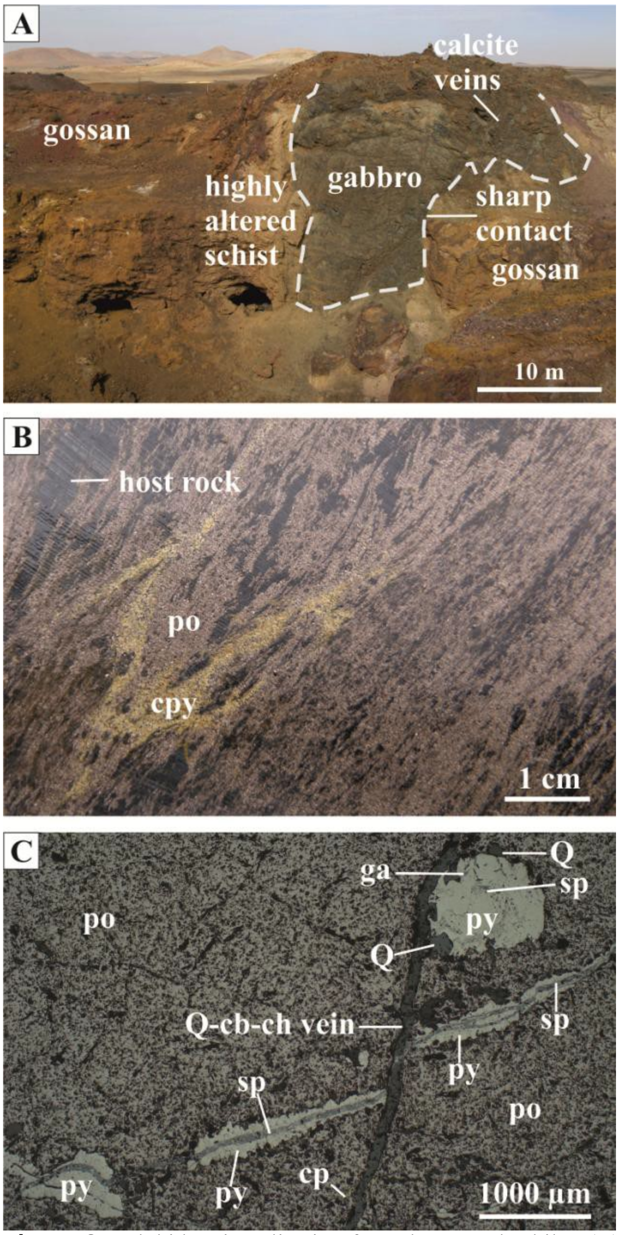

Figure 2. Sulphide mineralization from the central Jebilet. (A) Gossan developed over the massive sulphide at Kettara. (B) Core from Draa Sfar South containing pyrrhotite (po) stringers and later chalcopyrite (cp). (C) Photomicrograph (XPL) of a sample from Draa Sfar North showing a late, undeformed pyrite (py) vein with a sphalerite (sp) core, hosted in massive pyrrhotite. The pyrite vein is offset by a quartz (Q)-carbonate (cb)-chlorite (ch) vein. The large, subhedral pyrite crystal contains minor, 50 µm size, anhedral inclusions of sphalerite and galena (ga).

3.1 Sulphide paragenesis

Preliminary study of drill core from several of the main deposits demonstrates that the earliest stage of mineralization is represented by pyrrhotite ± chalcopyrite, sphalerite, galena, typically associated with quartz + chlorite (Fig. 2B). The massive pyrrhotite bodies typically show evidence of shear deformation, and are clearly pre- to syn-tectonic. Some deposits also contain a later pyrite-carbonate paragenesis, with pyrite veins replacing earlier pyrrhotite (e.g., Kettara, Draa Sfar North, Fig. 2C) or forming the main stage of mineralization (e.g., Lachach). Textural evidence indicates that the pyrite veins are post-tectonic, overgrowing the main schistosity (Fig. 2C). This is evidence for a multi-stage evolution of the Jebilet sulphide deposits.

4 Knowledge Gaps and Future Research

Despite possessing some features typical of syngenetic VMS mineralization (Table 1) many aspects of the central Jebilet hydrothermal system and the geology of the district remain enigmatic, leading us to question continued application of a simple VMS mineral deposit model. The uncertain geological relationships, principally resulting from deformation and metamorphism, the unclear genetic controls on mineralization, the absence of a robust baseline regional stratigraphy, coupled with our preliminary field observations and sulphur isotope work identify the following research areas and questions to address:

i) At a district scale VMS deposits are typically concentrated at one or two stratigraphic intervals (Gibson et al. 2007). This is not apparent in the central Jebilet, due to the lack of detailed mapping and stratigraphy across the block. Does any stratigraphic control exist at the district-scale, and if so can favourable stratigraphic positions (ore-bearing horizons) be identified in the regional stratigraphy, distal from known deposits? A good quality regional stratigraphy based upon detailed (i.e. ~1:50 000 scale) mapping is fundamental to assessing this.

ii) VMS deposits have a 'spatial, temporal, and genetic association' with bimodal volcanism (Allen and Weihed 2002; Franklin et al. 2005). Whilst the Jebilet mineralization is generally classified as volcanogenic, volcanic rocks are uncommon across much of the region, and a genetic relationship between mineralization and volcanism is unconfirmed (Essaifi and Hibti, 2008; Moreno et al. 2008).

iii) There is significant uncertainty about the source of metals and sulphur in VMS systems (Franklin et al. 2005; Gibson et al. 2007). Whilst the composition of intrusions proximal to the Jebilet deposits may explain their variable base metal composition, isotope evidence for the origin of the ore-forming fluids is inconclusive (Lotfiet al. 2010), and the importance of the sedimentary sequence as a source of metals remains unclear (Essaifi and Hibti 2008). VMS ores frequently contain a diverse suite of trace metals (e.g. Co, Sn, Cd, Bi, Te, Se, Ga) (Galley et al. 2007). Trace element data for sulphides from the Jebilet mineralization is limited (e.g. Marcoux et al. 2008), variation between deposits has not been documented, and the processes controlling the preferential enrichment of some metals (e.g. Se at Draa Sfar) are not understood.

iv) Understanding the detailed parageneses of the mineralization is essential for determining the chronology of mineralizing events and associated ore-forming processes.

v) Whilst the sheet-like sulphide ore bodies are interpreted as upturned lenses (Belkabir et al. 2008), and zones thought to represent stockwork vein mineralization are described from some deposits, the origin of the veins and their pre-deformational relationships to the stratiform ore are dubious. Although stockwork zones are not always well developed in VMS deposits (Franklin et al. 2005), reconstructing their pre-deformation architecture in the Jebilet would be valuable for guiding exploration at the mine-scale.

vi) Whilst many sulphide deposits in the Jebilet are associated with gossans (Marcoux et al. 2008) detailed studies of these zones and their relationships to the sulphide ores are lacking. From an exploration perspective it is vital to be able to discriminate between gossans overlying sulphide mineralization and those produced by other processes such as the pedological concentration of iron. Detailed mapping and textural and geochemical characterization studies are required to determine if the gossans can be used as a reliable indicator of buried sulphide mineralization.

vii) Refining the genetic model for the Jebilet mineralization represents the first stage in developing an effective exploration targeting system for the region. Preliminary observations indicating multi-phase evolution of the deposits suggests elements of both existing models may be valid. However, given the uncertainty about the 'critical processes' controlling the formation and location of these deposits and timing relationships we propose a 'mineral systems' approach as described by McCuaig and Hronsky (2014).

5 Conclusion

The sulphide deposits are evidence for a significant hydrothermal system existing in the central Jebilet, which has many hallmarks of an important, albeit relatively undeveloped, VMS district. However, fundamental questions remain unanswered regarding the broad-scale controls on mineralization, deposit size, morphology and composition, and, from a genetic perspective, on heat sources, deposit growth mechanisms and fluid, sulphur and metal sources. Integrated mapping and research studies (including a comprehensive stable and radiogenic isotope programme), focused on stratigraphy and structure, as advocated by Allen and Weihed (2002), are a prerequisite for making meaningful interpretations of the sulphide deposits and their local environments of formation. The research is vital for understanding the essential elements of the mineral system of the central Jebilet, which can be translated into an exploration model and strategy aimed at identifying mineralization distal from known deposits.

Acknowledgements

PL and KG publish with the permission of the Executive Director, British Geological Survey (NERC). G. Gunn and J. Slack are thanked for their reviews and comments. M. Zouhair and M. Outhounjite from Managem Group are gratefully thanked for their assistance in fieldwork in Morocco and for making samples available for study.

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