Origin of the Bouarfa Manganese Ore Deposit (Eastern High Atlas, Morocco): Insights from Petrography and Geochemistry of the Mineralization

Ludovic Lafforgue, Jocelyn Barbarand, Yves Missenard, Benjamin Brigaud, Bertrand Saint-Bézar
Université Paris Sud - 11, UMR8148 GEOPS, 91405 Orsay Cedex, France

Johan Yans, Augustin Dekoninck
Département de Géologie, Université de Namur, 61 rue de Bruxelles, 5000 Namur, Belgium

Omar Saddiqi
Laboratoire Géosciences, Université Hassan II, BP 5366 Maârif, Casablanca, Morocco

Abstract. The Bouarfa ore deposit represents one of the main Manganese ore deposits of Morocco. The mineralization corresponds to a stratabound deposit in a liassic dolostone unit. Previous studies have suggested that this deposit has been formed during sedimentation at the sedimentary water interface. However, the location of the Bouarfa district along the North Atlasic Front in a fold cut by a thrust fault questions the influence of this structure on the mineralization, its origin and evolution.
The petrographic characterization of the dolostone emphasizes a late diagenetic dolomitization process prior to Mn mineralization. Moreover, petrographical, mineralogical and trace element geochemistry demonstrate that the fluids involved in the mineralization precipitated Mn tunnel-like structure oxides in a high oxidised environment. The fluids probably derived from hydrothermal systems. These elements argue for a post-sedimentary model for the mineralization.

Keywords. Manganese ore deposits, Morocco, pyrolusite, dolomitization, Bouarfa.

1 Introduction

The Bouarfa Manganese ore district is located on the northern tectonic front of the Eastern High Atlas mountain belt of Morocco (Fig. 1a). The ore deposit has been extensively mined between 1923 and 1962 and has produced 1.5 Million tons of Mn. The main mineralization is formed by a pattern of channels in Sinemurian dolostones and extends over 5 km along the belt front (Fig. 1b). The mineralization is mainly composed of tetravalent Mn oxides and Fe oxyhydroxides that are well distinct (Caillère 1938, Du Dresnay 1965, Pouit 1965).

The ore deposit has not been studied since the pioneering work of Du Dresnay (1965). This author proposed that the mineralization has formed in a syn-sedimentary context by replacement of a former early dolomite. Nevertheless, it is worth to emphasize that the singular situation of the deposit, along the North Atlasic front, cast doubts on this interpretation: Cenozoic tectonic events may have at least imprint the petrographic and geochemical properties of the deposit, if not being at the origin of the Mn concentration. In this work, petrographic, mineralogical and geochemical studies have been performed in order to constrain the timing of manganese mineralization in the Eastern High Atlas (Bouarfa). We used optical microscope, cathodoluminescence microscope and scanning electron microscopies (SEM-EDS), an electron probe (CAMECA SX-FIVE, CAMPARIS, Université Paris 7) and micro-raman spectrometry (Université de Lille 1) in order to identified the Mn-oxides minerals composing the mineralization. The paragenetic succession thus defined within the mangenese deposits of Bouarfa shows that it results from, at least two genetic events. Ionized coupled plasma mass spectrometer (ICP-MS) is used to measure the As, Cu, Mo, Pb, V, Zn, Co and Ni concentrations.

2 Geological setting and ore description

The Bouarfa Manganese ore used to be exploited in two mining sites. In the Eastern part, the main pit of Aïn Beida (Fig. 1b) is today inaccessible. In the Western part, the Hamaraouet pit (Fig. 1b) offers a good overview of the mineralization. The Hamaraouet mineralization is located in the Sinemurian dolostone. This formation is 30 m to 70 m thick in the Hamaraouet area. It disappears westward but reaches up to 180 m in Aïn Beida (Fig. 1b). At the bottom a 0,5-1 m thick dolostone layer contains various detrital phases (quartz, feldspar, micas and clays) cemented by a dolomite.

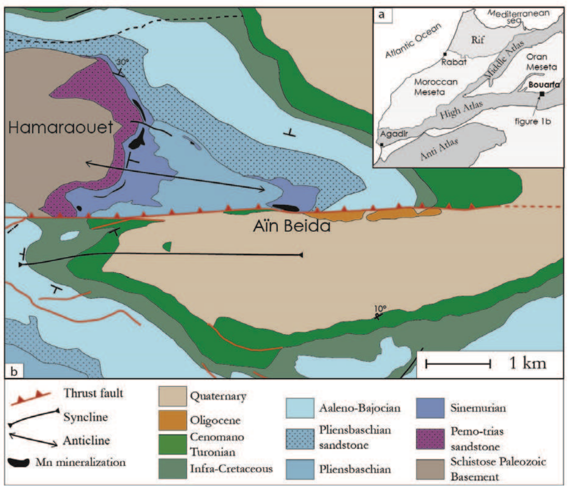

Figure 1. a. Location of the Bouarfa Mn ore district at the scale of Morocco, NW Africa. **b.** Schematic structural map of the Bouarfa area, displaying the main mining sites. The Hamaraouet and Aïn Beida areas are located in the core of a large anticline along the northern front of the Eastern High Atlas belt.

Then a pink dolostone with pisolithes, rare and birds eyes forms a 10-20 m thick layer which hosts the main massive mineralization. The Sinemurian dolostone formation overlaid a permo-triassic arkoses containing few gypsum lenses. The top of the Sinemurian dolostone Formation is overlaid by Pleinsbaschian sandstones Formation with gypsum lenses (Fig. 1b). The mineralization forms metric channels parallel to the Sinemurian dolostone strata. At the bottom of this massive dolomitic formation, dark-black lenses, coated by a reddish layer of crypto-crystalline Fe oxyhydroxide, impregnates the dolostone. Several calcite veins cut this formation. These veins are associated with Mn oxides needles or botryoidal Mn and Fe oxyhydroxides. In the southern part of Hamarouet, close to the main E-W reverse fault (Fig. 1b), the mineralization is expressed as a breccia. Dolomitic clasts are cemented by calcite with Fe oxyhydroxydes occurrences.

3 Results: Petrography and geochemistry

3.1 Primary evolution of the Sinemurian dolostone in Hamaraouet: the ore host formation

Three dolomitic phases (D1, D2, D3, Fig. 2A,B) have been characterized. These three phases follow each other, D1 being the oldest and D3 the youngest.

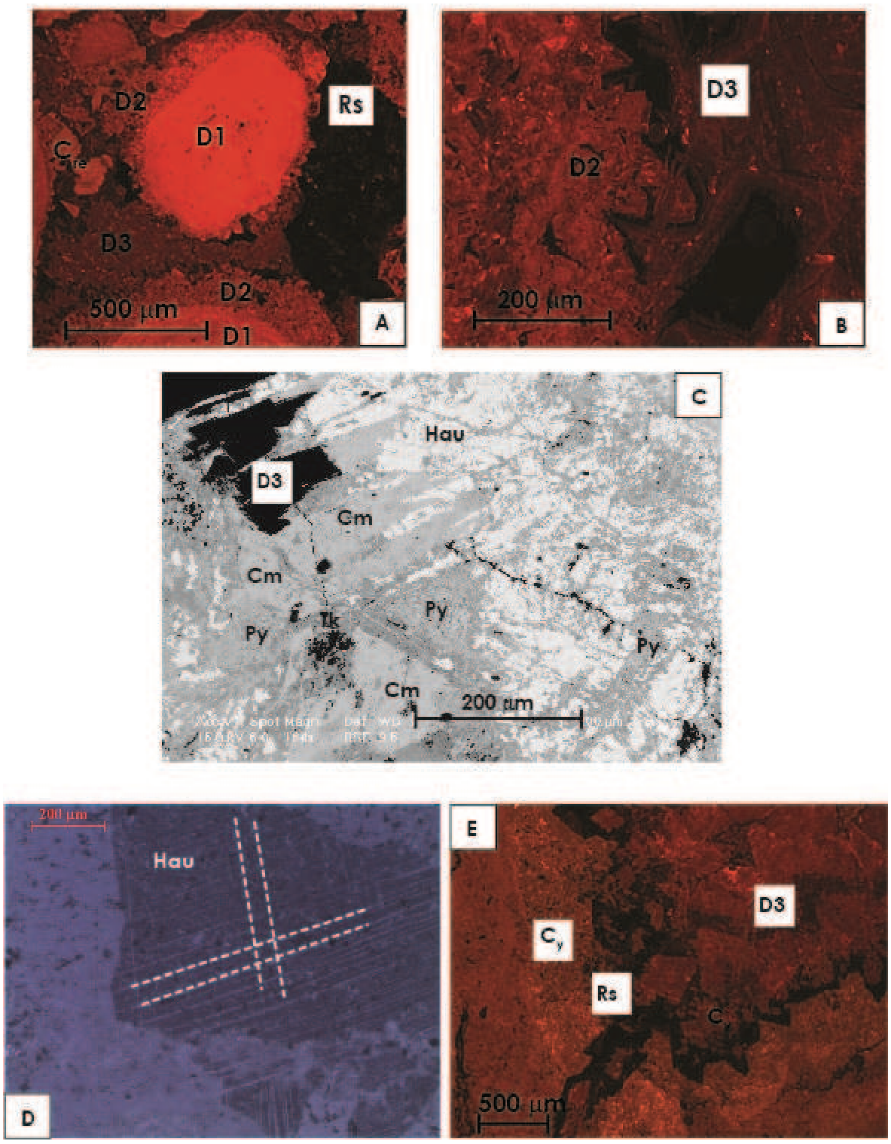

Figure 2. A. Thin section, cathodoluminescence: fisrt microsparitic and bright red dolomite D1 is coated by the bright orange dolomite D2 that is related to a remnant calcite C_{re}. The last dolomite phase D3 is reddish dull and is present as blocking cement. Ramsdellite (Rs) stage is associated to D3. B. Thin section, catholuminescence: the well zoned and dull D3 developing in vugs cuts the bright rhomb of D2. C. Thin section, SEM-backscattered: Py: Pyrolusite; Cm: Cryptomelane; Hau: Hausmannite; Tk: Todorokite. Pyolusite is in pseudomophosis of a rhomb. Cryptomelane is related to pyrolusite and even replaces it. D. Thin section, polarized analysed reflected light with optical microscope: the planar Hausmannite (Hau) (tetragonal mineral) preserves cleavages (white dashes) of a former rhomb. It must be the cleavage of a remnant trigonal carbonate phase. E. Thin section, cathodoluminescence: the late reddish dull zoned dolomite D3 is pseudomorphosed by the latter yellowish calcite C_y related to Mn oxide mineralization, here Ramsedellite (Rs). Rs forms at the interface between the two carbonate phases.

The first (D1) is a planar subhedral micro-sparitic dolomite with a bright red luminescence (Fig. 2A). The second one (D2) forms well developed rhombs and is bright-orange in cathodoluminescence (Fig. 2A,B). The last one (D3) presents zoned rhombs, reddish dull in cathodoluminescence, well-developed in vugs (Fig. 2A) or fractures (Fig. 2B). The core of the D3 rhombs often presents impurities.

From the Permo-Triasic arkoses Formation formation to the Pleinsbachian sandstones Formation, the main sedimentary facies in the Hamaraouet area correspond to a proximal depositional environment. The main mud supported fabric (mudstone to packstone texture) associated to oncoids, birds-eyes and millimetrics needles of gypsum suggest a sabkha or very restricted lagoonal environments for the Sinemurian dolostone facies. This depositional environments is common for dololomitization processes during sedimentation (Machel 2004). D1 stage may be the result of such eogenetic dolomitization s.s. in a evaporitic/sabkha environment.

D2 forms isopachous coat around pisolithe or in vugs and sometimes preserved remnant of calcite crystals. D2 is interpretated as a dolomitization s.s. stage probably during burial diagenesis.

D3 corresponds to the later stage but is more related to final dolomitization s.l. as it fills spaces and is present as a bulk. It appears in rare areas as a saddle dolomite. We interpret this D3 stage as a burial dolomite.

3.2 Bouarfa manganese ore mineralogy

The main mineral forming channels and lenses is pyrolusite. It forms disorganized clusters of micro-needles sometimes with rhomb shapes. Since pyrolusite is a tetragonal mineral, its shape testifies for the pseudomorphosis after a former carbonate (Fig. 2C). In some locations, pyrolusite is in association with several Mn tunnel-like structure oxides (Fig. 2C):

- anhedral planar micro-crystalline cryptomelane.
- anhedral planar hausmannite
- anhedral todorokite (with 6.5%wt ± 1.3% MgO)
- needlepoint hollandite s.l. (from romanechite group, with 15.0%wt ± 2.1% BaO)

Cryptomelane is often linked to pyrolusite and even seems to replace it. This shows that cryptomelane is later than pyrolusite.

Some anhedral planar Mn oxides show two cleavage families whose intersection form rhombs (Fig. 2D). These cleavages are inherited from trigonal carbonate. It shows that like for pyrolusite, carbonates are pseudomorphosed by Mn oxides.

Hollandite group mineral is always associated with a tardive calcite. This phase is the latest Mn oxide of the massive mineralization.

Other phases are barite, planar and rhombs of calcite, colloform hematite and goethite. Hematite and goethite are always close to the Mn minerals without direct textural relation.

In some fractures, ramsdellite ($(Mn_{0,95-0,99}Al_{0,5-0,1})O_2$) is present as a cluster of cleaved millimetric orthogonal disoriented prisms or as geods associated with yellowish calcite in cathodoluminesence. The texture of ramsdellite is coherent with the replacement of dolomite as well as pyrolusite (Fig. 2E). The occurrence of ramsdellite shows a direct relation to a botryoidal geodic metric massive goethite. At the bottom of this metric goethite ramsdellite got a shape of clusters of needles forming a botryoidal facies. This texture shows that Mn mineralization occurred before goethite precipitation.

The complete paragenesis is summarized in Figure 3.

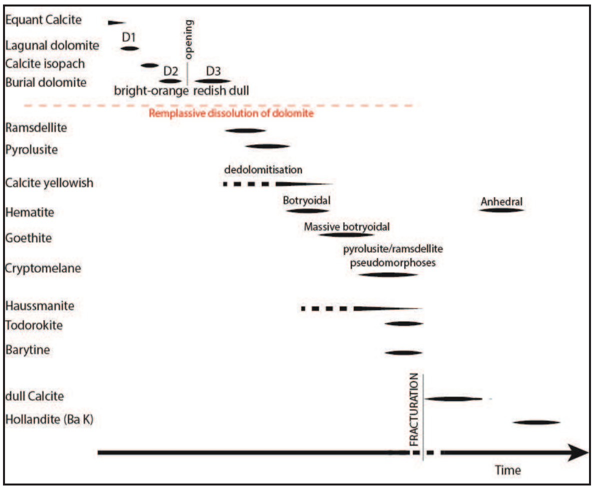

Figure 3. Paragenetic sequence of the Bouarfa Mn ore deposit.

3.3 Bouarfa geochemical studies

Manganese oxide ore deposits may take place in various environments on Earth, from supergene to hydrothermal conditions. The Mn tunnel-like structure oxides have great adsorbent proprieties because they trapped dissolved species of the mineralizing fluid. Due to the great adsorbance properties, their chemical signature is considered as representative of the depositional fluid composition (Ostwald 1992, Nicholson 1992).

Nicholson (1992) proposed a diagnostic graph to distinguish the origin of fluids in manganese ore deposit using trace elements concentration in bulk analysis. Mn deposits deriving from hydrothermal fluids are enriched in As, Cu, Mo, Pb, V, Zn compared to Co and Ni. On the other hand, a higher content in Co and Ni compared to As, Cu, Mo, Pb, V, Zn reflects a marine environment.

Despite some dispersion, all of our results plot in the hydrothermal domain of the Nicholson graph (grey crosses, Fig. 4). It suggests that the Bouarfa ore deposits did not formed during marine supergene conditions, i.e. that the deposits is probably not syn-sedimentary as usually admitted. This result is coherent with the paragenetic sequence evidenced in this study, showing that the mineralization occurred after polyphased dolomitisation episods.

4 Conclusion

Petrographical and geochemical observations show that:

- The main phase of Mn ore deposit is associated closely to the dolomite phase D3, which is interpreted as late diagenetic dolomite.
- The Mn tunnel-like structure oxides and the lack of

reduced minerals or Mn carbonate as rhodochrosite are in agreement with an oxidized environment for the formation of the ores.

- Some Mn oxides formed before a stage of massive Fe oxyhydroxides. This fact is rather surprising, given that Mn is more soluble than Fe in oxidized waters (Krauskopf 1957, Glasby 1997, Chan et al. 2000). It may indicate that Fe oxyhydroxides precipitated during a distinct, late, episode of fluid circulation.

- Even if Mn and Fe of the ore may come from dolomite pseudomorphosed and/or dedolomitization, many other elements highly concentrated in the manganese mineralization and characteristic of a hydrothermal fluid must be resulting from another source.

Finally, these new results on the large Bouarfa Manganese ore deposit show that it has been formed after many diagenetic dolomitization s.s. and s.l. processes and in a highly oxidizing environment involving hydrothermal fluids. The age of the mineralization, as well as the potential link with the Atlasic tectonic phases and structures, still remain to be investigated.

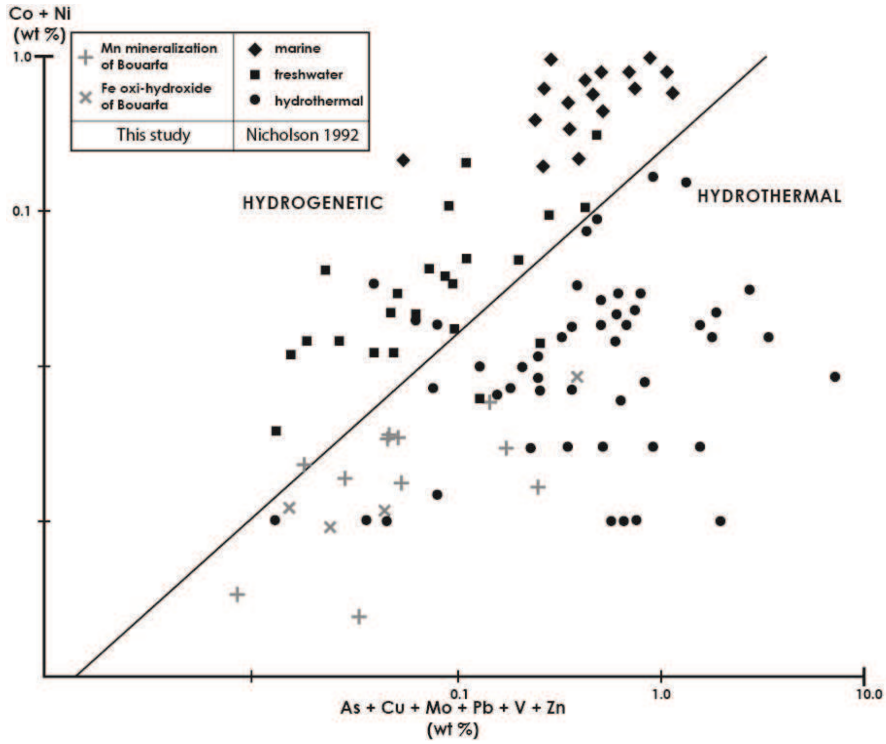

Figure 4. Contents in (Co + Ni) *vs* (As+Cu+Mo+Pb+V+Zn) in the Mn enriched phases of the Bouarfa deposit (grey crosses). Our data lie in the field of hydrothermal deposits defined by Nicholson (1992), whose data are figured with black diamonds, squares and circles.

Acknowledgements

We are greatly obliged to the city of Bouarfa for their warm welcome and the facilities access to the manganese mineralization. We also thank Gaétan Rochez of the Université de Namur for his help and the pictures of the mineralization and the whole studied field. Thank you to Valerie Godard for the thin sections she made and to Remy Pichon for his help with the SEM analysis.

References

Caillère S (1938) Quelques observations sur la composition minéralogique et la structure des minerais de manganèse de Bouarfa. (Maroc oriental). Bull Soc Sc Nancy 2:221-250

Chan MA, Parry WT, Bowman JR (2000) Diagenetic Hematite and Manganese Oxides and Fault-Related Fluid Flow in Jurassic Sandstones, Southeastern Utah. AAPG Bulletin. 84:1281-1310

Du Dresnay R (1965) Notice géologique sur la région de Bou-Arfa. Colloque sur les gites stratiformes de plomb, zinc, et manganèse du Maroc (2 mai - 14 mai 1962). Notes et mémoires du service géologique 181:107-112

Glasby GP (1997) Fractionation of manganese from iron in Archean Proterozoic sedimentary ores. From Nicholson K, Hein JE, Bühn B, Dasgupta S Manganese Mineralization: Geochemistry and Mineralogy of Terrestrial and Marine Deposits. Geological society, London, Special Publication 119:29-42

Krauskopf KB (1956) Separation of manganese from iron in sedimentary processes. Geochim Cosmochim Acta 12:61-84

Machel HG (2004) Concepts and models of dolomitization : a critical reappraisal. From Braithwaite CJR, Rizzi G, Darke G The Geometry and Petrogenesis of Dolomite Hydrocarbon Reservoirs. Geological society, London, Special Publication 235:7-63

Nicholson K (1992) Contrasting mineralogical-geochemical signatures of manganese oxides: Guides to Metallogenesis. Econ Geol 87:1253-1264

Ostawld J (1992) Genesis and Paragenesis of the tetravalent manganese oxides of the australian continent. Econ Geol 87:1237-1252

Pouit G, Jouravsky G (1965) Les minéralisations manganésifères de la région de Bou-Arfa. Colloque sur les gites stratiformes de plomb, zinc, et manganèse du Maroc (2 mai - 14 mai 1962). Notes et mémoires du service géologique 181:113-131