CARBONATE-HOSTED PB-ZN-FE (CU, F, BA) DEPOSITS OF THE NORTHERN EAST ALGERIA: METALLOGENY, STRUCTURAL AND GRAVIMETRIC/AEROMAGNETIC LINEAMENTS CONTROLS

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Abstract:
The northern east of Algeria constitutes the most important metallogenical zone for Pb-Zn-Fe (Cu, F, Ba). Mineralization is mainly in vein fillings in fractures and in epigenetic lenticular or stratabound ores that can be classified as Mississippi Valley Type “MVT” deposits. The orebodies are preferentially associated with small surface NE-SW/NW-SE and E-W-trending faults, mainly located in the margins of the subsiding basins/synclines, at the apex or along the anticline structures. The relationship between deep lineaments, surface faults and associated mineral deposits has been investigated in these regions, through the analysis of regional gravimetric/aeromagnetic surveys, metallogenic and geological data. Mineral deposits occurred along the margin of geological structures (e.g., subsiding basins) deduced from the gravimetric data. In Hodna/Setifian and Belezma Mounts, mineralization is generally lie along or near NW-SE oriented regional-scale deep lineaments. In the neighbouring regions (e.g., Batna/Aures, Tebessa Mounts and diapiric zone), mineral deposits are located along or near (or at intersections of) NE-SW/NW-SE deep lineaments. The deeper lineaments that are plausible structural controls on the mineralization in these regions play probably an important role in providing pathways for focusing mineralised fluids into the upper crust to depositional sites along surface smaller faults. It is suggested that mineral deposits appear to be regionally controlled by these structural limits, which reflect trending major deformation corridors, and can indicate a potential target in mining exploration.

Key words: Geology, metallogenical, geophysical data, ore-deposit, tectonic, exploration.

Introduction:
Many small polymetallic ore deposits of Pb-Zn-Fe- (Cu, F, Ba) have been discovered in the northern east of Algeria. The mineral deposits were mined since eighteen century for mainly Fe and Pb, Zn. These deposits are closely associated with the Jurassic and Cretaceous carbonate rocks, related to hydrothermal processes. Mineral deposits show a spatial relationship with the major faults that would have controlled the circulation of the hydrothermal fluids responsible for the emplacement of mineralization (Bouzenoune, 1993; Boutaleb, 2001; Haddouche, 2010; Haddouche et al., 2016; Sami, 2011).
This spatial relation with major faults has been successfully used as a guide in exploration for decades (e.g., National Office of Geologic and Mining Research of Algeria, ORGM). In this study we have used geological, metallogenical and geophysical data (gravimetric and aeromagnetic data) to identify structural/lineaments control on mineralization. Currently, in many other parts, several authors used similar approach in the study of ore genesis, metallogenical regularity and mineral resource prediction (e.g., Blakely and Jachens, 1991; Lü et al., 2012; Shah et al., 2013, Wang et al., 2011, Cheng, 2012; Gunn et Dentith, 1997; Chernicoff et al., 2002; Bierlein et al., 2006; Austin and Blenkinsop, 2009; Joly et al., 2012; Chen et al., 2015). For example, Austin and Blenkinsop (2009) used correlation analysis between mineralization and structures to recognize structural controls on mineralization, in the eastern Mount Isa Inlier (Australia). These studies may be combined with other techniques. Thus, Crafford and Grauch (2002) used geological, geophysical and isotopic data to suggest a fundamental link between the locations of world-class Carlin gold deposits and concealed deep crustal fault zones in north central Nevada (USA). Vos et al. (2004) employed to suggest a fundamental link between the locations of world-class Carlin gold deposits and concealed deep crustal fault zones in north central Nevada (USA). Vos et al. (2004) employed to suggest a fundamental link between the locations of world-class Carlin gold deposits and concealed deep crustal fault zones in north central Nevada (USA). Vos et al. (2004) employed to suggest a fundamental link between the locations of world-class Carlin gold deposits and concealed deep crustal fault zones in north central Nevada (USA). Vos et al. (2004) employed to suggest a fundamental link between the locations of world-class Carlin gold deposits and concealed deep crustal fault zones in north central Nevada (USA). Vos et al. (2004) employed to suggest a fundamental link between the locations of world-class Carlin gold deposits and concealed deep crustal fault zones in north central Nevada (USA). Vos et al. (2004) employed combination of structural–tectonic, geophysical and geochronological data in northeastern Queensland (Australia) to establishing linkages between orogenic gold deposits and concealed crustal breaks. The aeromagnetic data used were made by the American firm Aero Service Limited (1971-1974) whose measurement step is 150 feet, or about 46 m. The gravimetric maps have been reinterpreted, based on the gravimetric data made by Zerdazi (1990). The Bouguer data are regional, with an overall accuracy of -113.10 to 3.55 mgal, interpolated at the nodes of a regular grid of 500X500 m.

This paper reviews the geologic setting, metallogenical characteristics of these areas and the importance of major geophysical lineaments (by processed gravimetric/aeromagnetic data) and aimed at distinguishing the spatial relationship between mineral deposits, fault systems and structural/lineaments that control mineralization. A GIS of ArcView was applied for visualization of the spatial distribution of the mineral deposits and to aid interpretation. The spatial distribution of mineralization was analyzed by a plot on which each data point (e.g., mineral deposits) is marked relative to every other data (geologic, tectonic, gravimetric and aeromagnetic maps). These techniques have been successfully used by several authors and might be used as an exploration guide for this type of mineralization.

**Geological and tectonic setting**

The study area is mainly composed of Mesozoic sedimentary rocks, with locally dispersed intrusions of Triassic rocks (Fig.1).
The structural evolution of this part of North Eastern of Algeria, results from the superposition of several polyphase tectonic events. The first phase (Neo-Cimmerian phase) known in northeastern Algeria discovered at the Jurassic-Cretaceous limit and marked by discordances. This is followed by the Austrian phase, occurred in the Middle Albian, responsible for the structuring of NNW-SSE folds. On the other hand, the Lower Cretaceous period was mainly marked by the development of extensional structures with tilted blocks and grabens (Herkat, 1999). Sharp variations in thickness and facies towards the north-east indicate that basin subsidence was driven by regional tectonic movements along NE-SW, ENE-WSW and E-W- trending normal faults that placed sub basin (Herkat, 1999). The overall evolution during Cretaceous is also maintained by halokinesis of Triassic salt creating subsident rim-synclines, where organic-rich facies prevail. The post Lutetian-ante Miocene phase (Laffite, 1939; Guiraud, 1990; Vila, 1980; Marmi and Guiraud, 2006) represents the most important episode in the north-eastern Algeria, preceded by an extensional regime responsible of the large sedimentary basin subsidence and ascension of Triassic rocks. In these regions, predominantly NE-SW (N50 to N60°) folded structures were formed (Fig.2), related to a late Eocene compressive event. The Belezma anticline was starting to form at the base of Late-Eocene and thrusts developed during Miocene (intra-Tortonian, Guiraud et al., 2005).
In the eastern Saharan Atlas (e.g., Aures, Batna, Nemenchas and Tebessa Mounts), the compressive phase is responsible for the structuring of NE-SW folds. It is followed in the north of Algeria and in the Constantine Mounts (Coiffait, 1992; Aris et al., 1997) by a large compressive tectonic phase during the Miocene, which continues until the Quaternary in Southern Saharan Atlas (Adoum, 1995).

This with large extension is responsible for structuring EW to WNW-ESE folds, clearly visible on the southern edge of the Aures-Nemencha and the Timgad basin. Recent work by Aris et al., 1997, revealed a regional extension phase (N140° -150° E) during the Miocene and late Pliocene-Quaternary, followed by a compressive phase (N130° -150° E) during the quaternary and the present.

The diapiric structures are numerous and can locally influence the sedimentary and structural evolution of the sedimentary cover. In the Khencela region, diapiric movements allow the development of santonian reefs (Camoin et al, 1990; Guiraud, 1990). In the "diapiric zone", these phenomena are important, affecting Upper Cretaceous and Tertiary formations (Perthuisot, 1978-1992; Perthuisot and Rouvier, 1988; Thibieroz and Madre, 1976; Bouzenoune, 1993; Rouvier et al., 1985, Sami, 2011).

Faults that affect these regions are numerous (Fig.2a). There is a wider of orientations for NW-SE, NE-SW, E-W and rarely ENE-WSW/NS trending faults (Aissaoui, 1984; Kazi-Tani, 1986; Addoum 1995; Vila, 1980; Boutaleb, 2001; Haddouche, 2010; Sami, 2011). The NW-SE-trending faults are mainly composed by normal or strike-slip faults, intersecting locally NE-SW-trending faults.
Metallogenical aspect

Many small Pb-Zn-Fe (Cu, F, Ba) ore-deposits and showings are located in Setifian/Hodna, Batna/Aures, Tebessa, Belezma Mounts and diapiric zone (Fig.3a), majority hosted in Jurassic and lower Cretaceous (Hauterivian, Barremian, and Albo-Aptian) carbonate rocks. Mineralization occurs in veins (veinlets) fillings in fractures and in lenticular or stratabound ores, related to epigenetic hydrothermal system. Most of the orebodies (veins, lenticular and stratabounds ores) are developed mainly along the NW- SE/NE-SW and E-W-directions (Fig.3b).

**Fig.3** Simplified geological map of North Eastern Algeria, mainly showing: (a) the spatial distributions of major Pb-Zn-Fe (Cu, F, Ba) mineral deposits (b) Average rose diagrams showing orientations of major Pb-Zn-Fe (Cu, F, Ba) orebodies in north eastern Algeria.

The orebodies are dominated by banded ores (Fig.4a, b, c, d) breccias or hydraulic breccias ore (Fig.4e, f, g) and disseminated ore (Fig.4h, i), but fracture-filling (Fig.4j), veinlets (Fig.4k), massive and collomorphic textures (Fig4l) are also common in most orebodies (Boutaleb, 2001; Haddouche, 2010; Sami, 2011).
Fig. 4 Major textures of ores from some ore-deposits. (a) Banded ore from Ichmoul ore-deposit [Galena (Ga)+Barite (Ba)] affected by later deformation. (b) Banded ore from Ain Mimoun ore-deposit [Barite+ tetrahedrite (Te)]. (c) Banded ore from M’Khiriga ore-deposit [Barite+ Galena+fluorite (F)]. (d) Banded ore from Ain Kahlia ore-deposit [Barite+ Galena]. (e) Breccia ore from Hamimat ore-deposit (Morsott-diapiric zone) at contact Triassic rocks/Aptian [Barite]. (f) Hydraulic breccia ore from Boutaleb (Setifian) ore-deposit [Galena+ calcite (cal)]. (g) Breccia ore from Ichmoul ore-deposit [Barite+ calcite]. (h) Disseminated ore from Gustar ore-deposit [Sphalerite (Sph)] (i) Disseminated ore from Ouenza ore-deposit (diapiric zone) [Galena+fluorite]. (j) Fracture filling ore from Boukhdema ore-deposit [Galena+ Dolomite (Di)]. (k) veinlet ore from Boukhdema ore-deposit [Sphalerite] cutting veinlet dolomite [Dolomite]. (l) Collomorphic ore from M’khiriga ore-deposit [Galena+barite+ fluorite].

In Setifian area, the best-known ore-deposits are those of Boukhdéma, Ain Roua, Ain Sedjra, Kef Semmah, and Anini. Boukhdéma is the most important and economical ore-deposit, characterized by a mineral association with sphalerite, galena and pyrite, as a "stratabound" (Boutaleb, 2001). There is also a Cu-As-Sb-Ba mineralization related to fissure fillings and veinlets.

In Hodna region, economic carbonate-hosted Zn-Pb deposits occur at several stratigraphic horizons in carbonate rocks (dolomitic) of Jurassic, lower Cretaceous and Miocene age. As for all mineral deposits of Setifian, mineralization of Hodna is located at limited subsiding basins (Boutaleb, 2001). The lower Cretaceous (Hauterivian and Barremian) horizons contain the economically most important base metal ore-deposits. Mineral deposits are mainly as
stratabound orebodies, and in vein type filling (Boutaleb et al., 1999). The most important ore-deposits are those of Ain Kahla, Kherzet Youcef, Chabet El Hamra, Abiane, Z’Dim, Braou, Dra Sfa, and Sekkaken. Mineralization is mainly composed by galena and sphalerite, associated locally with pyrite, smithsonite, cerussite, and hydrozincite.

The Ain Kahla mineralization consists of ore bodies that are embedded in the Upper Liassic and in the Dogger dolomites. The most significant base metal concentration is emplaced within regional unconformities (Fig.5), such that of the infra-Toarcian (Boutaleb et al., 2006).

In the Belezma Mounts, there are several Pb-Zn mineral deposits. Merouana is hosted in dolomitic rocks of Upper-Aptian, related to fracture fillings with various directions (Glaçon, 1967; Boutaleb, 2001). Mineralization is reflected principally by sphalerite, pyrite and galena associated with white dolomite. During 1992 to 1998, ORGM (National Office of Geologic and Mining Research) exploration work has been concentrated in the Batna Mounts, based mainly on geophysical analysis and drilling work. As a result of this work, a new Pb-Zn ore-deposit (Ain Bougda) was discovered, hosted in limestone dolomitized of Aptian. Ore-bodies are mainly lenticular "stratabound" (Fig.6), located in the margin of the subsiding basin. Mineralization consists essentially of marcasite, pyrite, melnicovite, sphalerite, and galena, related to open spaces filling and breccia cement.
In the Aures Mountains, there are several deposits of Ba-Pb-Zn (Hg) hosted in carbonate formations of Cretaceous and Miocene. There are two principal deposits (1) Ichmoul ore-deposit essentially composed by barite and galena, in form of lenticular piles of direction E-W. These minerals are associated with disseminated red sphalerite in black shales rich in organic matter (Haddouche, 2010). (2) Ain Mimoun ore-deposit is related to NW flank of Khenchela anticline (Djebel Aidel) or provided on the edges of syncline structure (Fig.7). Mineralisation is located in veins along normal fractures (NE-SW, NW-SE and E-W), characterized by barite, galena and gray copper. It’s hosted in calcareous-dolomitic and sandstone of Albo-Aptian age.

In the diapiric zone, there are many lead, zinc and iron (siderite) ore-deposits, mostly controlled by diapiric structures according to NE-SW axis. Major ore-deposits are those of El Ouenza, Boukhadra, El Ouasta, Mesloula, M’khiriga, M’Zeita and Boudjaber. All these ore-deposits are hosted in carbonate of Aptian-Albian, related to fracture fillings or veins. Recent studies of mineralization related to Tunisian and north-east of Algeria diapirism (Perthuisot and Rouvier, 1988; Hatira, 1988; Shepard et al., 1996; Haddouche et al., 2003) show analogies with mineralization related to the “Cap rocks” of the "Gulf Coast" salt-dome,
variant of Mississippi Valley type deposits "MVT" (Kyle and Price, 1986; Posey et al., 1994; Kyle and Saunders, 1996). Concentrations type "Cap rock", related to cortical salt dome is characterized by impregnation of Pb-Zn, Fe (Ba-Sr) mineralization, near the diapir-sedimentary cover interface (e.g., Djebel Ressas, El Ouasta and Hameimat) (Fig.8). These types of concentrations whose bodies included in "Cap rock" formation or near the sedimentary cover are the subject of particular attention, due to their importance in the oil fields and mineral exploration.

Mineralization with no visible connection with diapiric systems are also numerous in the Northern East of Algeria. This is especially NW-SE and NE-SW orebodies of Es Souabah and Hdjar Merakeb (Sami, 2004). At Ouenza, polymetallic mineralization (veins) is always related to N50 and N140 fractures affecting the Aptian limestones (Bouzenoune 1993; Sami, 2011). They show a simple paragenesis with galena, pyrite, chalcopyrite, sphalerite, tetrahedrite, barite and fluorite. Mineralization is also represented by dissolution filling for fluorite, quartz and barite and by dissemination for galena and tetrahedrite. The polymetallic mineralization intersects the iron mineralization and would be of Miocene age (Sami, 2011).

**Geophysical data analysis**

Gravimetric and aeromagnetic data of the study area were used to remap the main geological units, infer the subsurface geology and to interpret the structural patterns which serve as potential mineralization zones in these regions. The Bouguer data are regional, with an overall accuracy of -113.10 to 3.55 mgal, interpolated at the nodes of a regular grid of 500X500 m. The high values of the Bouguer anomaly (-30 mgal) were located in the regions of Ouenza-Boukhdara. As for the low values (-90 mgal), they were located in the South-West of the studied region. The Gravimetric data analysis shows the presence of a large sedimentary cover. In the central part, linear structures (anticlines NE-SW) give values oscillating between -40 and -55 mgal. Linear gravity troughs directed to the NW-SE give values between -60 and -75 mgal.

The modeling software "Geosoft" was used to reverse the residual anomaly. The basement model of the study area was divided into small rectangular cells of dimensions 1000 X 1000 X 500 m (X, Y and Z). Figure 9 shows the projection of the surface density contrast distribution obtained by 3D inversion.
The interpretation of density contrast map obtained by 3D inversion, show numerous lineaments, mainly N135° to N170° and N40° to N60°. These lineaments have average lengths varying between 12 km and 120 km.

The blue anomalies of a more or less structure reflect probably the diapiric structures, or subsidence/tectonic troughs. The other density contrasts reflect linear geological structures (mainly anticlines N50°).

A large portion of the study area was covered by adjacent magnetic surveys carried out by the American firm Aero Service Limited (1971-1974). Raw aeromagnetic data were digitally-processed by "Geosoft" software. Visual inspection of the magnetic lineament map (Fig.14, 15) indicates similar linear trends (NE-SW and NW-SE-trending lineaments). Locally, the NE-SW-trending lineaments are intersected by NW-SE lineaments.

**Spatial analysis and discussion**

In this study, geological, metallogenical and geophysical analysis were employed to study the spatial pattern of known Pb-Zn (Cu, F, Ba) mineral deposits of the Setifian/Hodna and neighbouring regions (e.g., Batna/Aures, Tebessa, Belezma Mounts and diapiric zone).

The orebodies are located along small normal NE-SW/NW-SE and E-W faults cutting the lower Cretaceous carbonate rocks (Fig.10a, b, c, d). The correlation between Pb-Zn (Cu, F, Ba) mineralization density and the surface faults system show two main trends mineral occurrences (Fig.11a, b): (1) NW-SE trending at Hodna/Setifian and Belezma Mounts (2) NE-SW/NW-SE trending at Batna/Aures, Tebessa Mounts and diapiric zone.
Fig. 10: Tectonic maps (surface faults/fractures) of the Setifian, Hodna and neighbouring regions (a) Setifian/Hodna, Belezma and west of Batna/Aures Mounts (b) Batna, Aures, Tebessa Mounts and diapiric zone (c, d) Average rose diagrams showing orientations of surface faults cutting Jurassic-Cretaceous and Tertiary rocks.
Fig. 11 Correlation between Pb-Zn-Fe (Cu,F,Ba) mineralization density and surface faults trending (a) Setifian/Hodna, Belezma and west of Batna/Aures Mounts (b) Batna, Aures, Tebessa Mounts and diapiric zone

The regional-scale gravimetric lineaments show consistent spatial association with mineralization. In the Setifian/Hodna and Belezma Mounts, a large part of the mineral deposits occurs near or along deep NW-SE-trending lineaments and at margin basin, as shown by the gravimetric maps (Fig. 12a, b).

In the Southern central (Batna Mounts) and in the East (Diapiric zone and Tebessa mounts) a number of mineral deposits occur near or at the intersection of NW-SE/NE-SW trending lineaments, at margin of subsiding basins/synclines and on the apex or along the anticline structures (Fig. 13a, b). Other aspect of relevance to distribution of the mineralization, mineral deposits was deposited near or along NW-SE tectonic troughs (e.g., Morsott trough) (Fig. 11b).
Fig. 12 3D inversion contrast map interpretation of Setifian/Hodna, Belezma and west of Batna Mounts, showing the spatial relationship between Pb-Zn-Fe (Cu, F, Ba) mineral deposits and geophysical deep lineaments/structures (a, b). Small black dots indicate the locations of Pb-Zn-Fe (Cu, F, Ba) mineral deposits.
Fig. 13 3D inversion contrast map interpretation of Batna, Aures, Tebessa Mounts and diapiric zone, showing the spatial relationship between Pb-Zn-Fe (Cu, F, Ba) mineral deposits and geophysical deep lineaments/structures (a, b). Small black dots indicate the locations of Pb-Zn-Fe (Cu, F, Ba) mineral deposits.

This interpretation is supported by the spatial coincidence of some of the regional-scale of the first vertical derivative of the magnetic field (Fig. 14a, b). Analysis of this aeromagnetic map helped to delineate deep lineaments and shows essentially NE-SW and NW-SE-trending lineaments which play a pivotal role in the localization of mineralization in the studied area. Mineral deposits are mainly located along or near these deep faults.
Fig. 14 Interpretation of the first vertical derivative of the magnetic field in the North Eastern of Algeria. Small black dots indicate the locations of Pb-Zn-Fe (Cu, F, Ba) mineral deposits (a) Hodna/Setifian, Belezma and Batna Mounts (b) Batna, Tebessa Mounts and diapiric zone.

Correlation between mineral deposits and lineaments deduced from aeromagnetic map (Aero Service Limited, 1971-1974, to a scale of 1.500.000) show a broadly similar pattern (Fig. 15). In Hodna/Setifian and Belezma Mounts, mineralization is located along or near NE-SW-trending deep faults.
Fig. 15 Correlation between mineral deposits and lineaments deduced from aeromagnetic map (Aero Service Limited, 1971-1974, to a scale of 1,500.000). Small blue dots indicate the locations of major Pb-Zn (Cu, Ba) mineral deposits.

In the framework of the structural evolution outlined above, the NE-SW regional scale-gravimetric and magnetic lineaments can be interpreted as major faults (block-tilted system) that have controlled the evolution of the sedimentary basins of this region Herkat (1999). In addition, these faults may be favoured ascension of Triassic rocks from the bottom (Bouzenoune, 1993; Vila, 1980) in North Eastern part of Algeria.

NE-SW and NW-SE-trending lineaments systems have probably played a major role in the localization of mineral deposits in this area. Mineral deposits are usually either inside anticline hinge zones (example, Ichmoul and Ain Mimoum ore deposits) or on the flanks of anticline structures (example, Ain Bougda ore-deposit), related to carbonate formations of lower Cretaceous.

In the diapiric zone, the mineralized deposits are generally on the edges of the Triassic bodies, and sometimes related to NE-SW/NE-SW and E-W-trending faults (Mesloula, Es Souabaa and Hameimat ore-deposits).

These results suggest that Pb-Zn-Fe (Cu, F, Ba) are preferentially associated with smaller faults that are within close proximity of major deep lineaments. However, probably these deposits are regionally controlled by the major lineaments but locally by the combination of small faults under the influence of long deep faults. Major deep lineaments provide probably metal transport or create open spaces for fluid flow, and these fluids solution migrate or diffuse away from large deep faults to depositional sites along smaller faults. In the Setifian/Hodna and Belezma Mounts, the spatial distribution of the mineralization is along NW-SE axes, probably controlled by lineaments of the same direction at limited small subsiding-basins. In Batna/Aures Mounts and diapiric zone, mineral deposits appear to be regionally controlled by (or at intersections of) NE-SW and NW-SE-trending lineaments at limited margin of sedimentary subsiding-basins.
Conclusion

The demonstrated association between significant signatures derived from the geological, metallogenical and geophysical (gravimetric and aeromagnetic) data analysis exhibit significant spatial correlations with the locations of Pb-Zn-Fe (Cu, F, Ba) mineral deposits and confirms the spatial link between these deposits, surface faults and major deep lineaments. Orebodies are preferentially located in the margins of the subsiding basins, at the apex or along the anticline structures, mainly associated with surface NE-SW/NW-SE and E-W-trending faults system. We suggest (i) in Setifian/Hodna and Belezna Mountains; mineralization occurs near or along NW-SE deep lineaments and mineral deposits appear to be regionally controlled by structural trends (subparallel NW-SE-trending). (ii) in the Batna/Aures, Tebessa Mountains and diapiric zone, mineral deposits are located within close proximity at (or at intersections of) major NE-SW/NW-SE deep lineaments.

These deeper lineaments play probably an important role in providing pathways for focusing mineralised fluids into the upper crust to depositional sites along surface smaller faults. Thus, the axial trends (NE-SW/NW-SE) reflect probably deformation corridors that have controlled the emplacement of mineralized deposits in these areas. These results may help to predict the potential mineralization targets by integrating other geo-information such as geochemical data in future mineral exploration.

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