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ORIGINAL PAPER

Mineral deposits of northeastern Algeria (southern Medjerda mounts and diapiric zone): regional-scale structural controls, spatial distribution, and importance of geophysical lineaments

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Abstract
The Southern of Medjerda mounts and the diapiric zone in the northeast of Algeria host a significant hydrothermal Pb-Zn-Fe-Ba (±Cu, ±F, ±Sr, ±Au, ±Ag) ore deposits and showings. The integration of geophysical data (ground gravity and aeromagnetic datasets) was undertaken in order to clarify and define the litho-structural control of the mineralization. These geophysical surveys allowed the identification of several prominent geophysical features. Some of these features correspond to lithological contacts; others reflect tectonic trough zones, Triassic salt diapirs, sedimentary basins, anticlines, and faults. The preferential (primary) trend of structural features within the study area is NE–SW and NW–SE. Integrated interpretation of geological and regional geophysical data helped the identification of the main factors *controlling* the *distribution o*f mineral deposits within the study area. Most of the mineral deposits are likely to be found along or near major NE–SW/NW–SE deep lineaments. These major deeper lineaments have probably controlled the kinematic evolution of geological structures, sedimentary basins, and the ascension of the Triassic rocks during the lower Cretaceous. They seem to play a significant role providing favorable pathways for the migration and ascent of mineralized fluids to depositional sites along smaller faults into the sedimentary cover or at contact between Triassic salt outcrops and lower Cretaceous carbonate rocks.

Keywords Geology · Metallogeny · Gravimetric · Aeromagnetic · Ore deposit · Tectonic

Introduction

Southern Medjerda mounts and the diapiric zone contain significant numbers of small hydrothermal Pb-Zn-Fe-Ba ore deposits (Fig. 1), locally associated with copper, fluorite, silver, and gold. The mineralization occurs at the surface along the NE–SW/NW–SE and E–W trending faults or along the contact between Triassic salt outcrops and Albian-Aptian/Campanian units (Bouzenoune 1993; Boutaleb 2001; Haddouche 2010; Sami 2011). In the study area, many ore deposits were mined since the eighteenth century for mainly Fe, Pb, and Zn. Mineral deposits are mainly found as veins or fracture filling and as epigenetic (lenticular or strata-bound) ores classified as Mississippi Valley Type "MVT" deposits (Boutaleb 2001; Haddouche 2010; Sami 2011).

A combination of indirect sensing techniques (gravimetric and aeromagnetic) and geological information has been used to map the geological structures and tectonic lineaments. Currently, there are a variety of geophysical methods that may aid mineral and geological environment investigations, but these can have their own advantages and disadvantages. Gravity and magnetic methods have been described by many authors (Van Blaricom 1980; Mwenifumbo 1993; Reynolds et al. 1990; Hanna 1969; Criss and Champion 1984; Zhou 1998; Hui et al. 2015; Grant 1985a, b) as an essential part of mineral exploration. These geophysical tools effectively used in deciphering the physical contrast (density and magnetic susceptibility contrasts) either between the anomalous mineral concentration and the host rock or between the different geological units. Gravity method is used to identify geological

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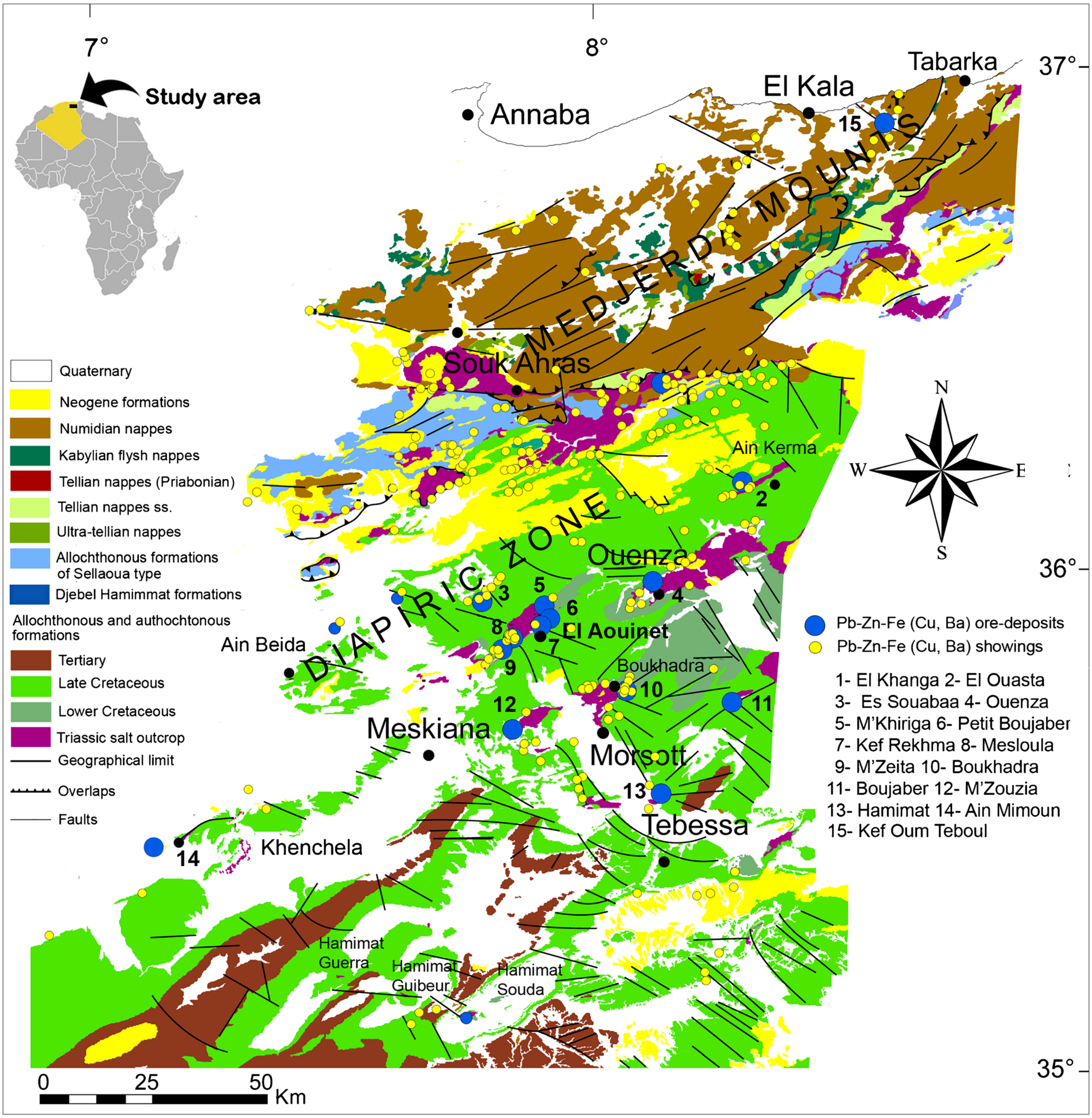

Fig. 1 Geological map of the Northern East Algeria (modified after Vila 1980; Haddouche et al. 2014). The small dots indicate the location of major Pb-Zn-Fe-Ba (±Cu, ±F, ±Sr, ±Au, ±Ag) ore deposits (blue dots) and showings (yellow dots)

structures, the top, and bottom interfaces of bedrock, studying the spatial distribution of fault structure and delineating faults and intrusions (Zhou 1998). The applications of the gravity method in the context of mineral deposits include identification of lithologies, tectonic structures, and orebodies themselves (Wright 1981). However, small anomalous bodies are not easily detected by gravity surveys unless they are at shallow depth. Some mineral deposits show high-density (e.g., hematite and barite) yield gravity highs, whereas other mineral deposits show low-density (e.g., halite, which is abundant in salt domes of the study area). Magnetic data are generally used to draw the geological structures together with gravity and seismic surveys, study the faults, and determine the alteration zone and the fracture zone, as well as classify the distribution of sedimentary, intrusive, extrusive, and metamorphic rocks (Grant 1985a, b). Magnetic exploration may directly detect some iron ore deposits. The magnetic method detects variations in magnetic mineralogy (essentially, magnetic iron, and iron-titanium oxide minerals). The data only images one physical property (i.e., induced magnetization in magnetic data—i.e., it is only really imaging the distribution of magnetite). Magnetic anomalies may be related to primary igneous or sedimentary processes that establish the magnetic mineralogy, or they may be related to secondary alteration that either introduces or removes (this production is highly sensitive to redox state or oxygen fugacity of the system) magnetic minerals.

Several authors used a similar approach in the study of structural controls and mineral resource prediction (Betts and Lister 2002; Austin and Blenkinsop 2008, 2009; Chernicoff et al. 2002; Anand and Rajaram 2003, 2007; Airo and Mertanen 2008; Boadi et al. 2013, Haddouche et al. 2016; Wilkinson et al. 2005; O'Reilly et al. 1999; Neudert and McGeough 1996, Mohebi et al. 2015). Gravity and aeromagnetic data have been performed in well-established Pb-Zn provinces from a more generic point of exploration and targeting (e.g., North Australia Craton, Canadian Cordillera, Mississippi Valley, Irish type systems) to understand the structural and broader tectonic context and the alteration styles associated with the Pb-Zn systems.

Generally, geophysical studies show major crustal structures/faults (with the reactivation of older basement fractures, strike continuity, width, and vertical extent of the deformation). The intensity of the alteration and the predominance of breccias suggest that these major crustal faults acted as a fluid pathway for alteration and base metal mineralization (Andrews, 1998; Betts et al. 2003; Austin and Blenkinsop 2008; Broadbent and Waltho, 1998; Hobbs et al. 2000; Betts and Lister, 2002; O'Reilly et al. 1999; Wilkinson et al. 2005; Neudert and McGeough, 1996; Allingham, 1966; Cordell, 1979; Cordell and Knepper, 1987). For example, gravity and magnetic exploration have been used in Mount Isa Inlier (North Australia Craton) which contains several economic and sub-economic Pb-Zn-Ag and Cu-Ag deposits, including Mount Isa, HYC, Century, Hilton, George Fisher, Lady Loretta, Walford Creek, Cannington, and Ernest Henry. The ore deposits sit near or along the major lineaments (e.g., Cloncurry gravity and magnetic worm) and are located in proximity to the intersections of faults active throughout the basin history (Betts and Lister, 2002; Neudert and McGeough, 1996). In Pb-Zn Irish type systems (Central Ireland, Wilkinson et al. 2005; O'Reilly et al. 1999) geophysical studies demonstrate that the Pb-Zn deposits are spatially related to the local magnitude. The lineaments correlate with mapped faults, indicate strong Caledonian basement control on Variscan tectonic development, and related episodes of base metal mineralization (O'Reilly et al. 1999). Airborne magnetic surveys have been used in Southeast Missouri to define buried Precambrian topography (paleorelief), and an important control on the localization of some ore. *The* most *common magnetic minerals* found in these deposits are *pyrrhotite* (Symons et al. 2010)*; airborne magnetic surveys are successfully used to locate them.*

At a regional scale, the metallogenic context of the study area remains relatively unknown. The mineral deposits have been the subject of several metallogenic and structural studies, but the data and interpretations are mainly valid at the local scale. Generally, mineralizations show a spatial relationship with the major surface tectonic elements that controlled the circulation of hydrothermal fluids responsible for mineralization (Bouzenoune 1993; Boutaleb 2001; Haddouche 2010; Sami 2011).

In this paper, geological, metallogenic, and geophysical data were combined in order to clarify and understand the spatial distribution and structural control on mineral deposits. Gravity data were acquired from 1986 to 1989 by the Algerian National Mining Research Company (SONAREM), currently ORGM. The collected data were reduced to the sea-level datum by standard reductions (drift, tidal, latitude, free air, Bouguer and terrain corrections) by Zerdazi (1990). The aeromagnetic data was completed by Aeroservices Limited in 1974 on behalf of the SONAREM. These data were acquired with a nominal terrain clearance of 150 m to provide information about the near-surface geology, using a higher solution (0.02 nT) optically pumped cesium vapor magnetometer. Conventional data processing procedures, such as tie-line leveling, International Geomagnetic Reference Field (IGRF) calculation, and removal, lag effect correction and microleveling, were carefully achieved to obtain good quality data. The geophysical data were analyzed to explore at large scale various concealed geological structures such as faults/contact systems and geological structures possibly controlling regional distribution on mineral deposits. The ArcView GIS and Oasis Montaj Geosoft software packages were used for visualization purposes of the spatial distribution of the mineral deposits and to aid interpretation.

Geology of the study area

The study area is composed of Mesozoic sedimentary rocks that mainly consist of various types of carbonate rocks. Triassic outcrops (diapiric structures) are numerous, piercing Cretaceous and Tertiary strata (Fig. 1). Triassic rocks are mainly composed of chaotic breccias dominantly formed by gypsum, associated with shale, sandstone, detrital rocks, minerals of neoformation (quartz and dolomite), and magmatic rocks (Triassic tholeiitic dolerites "Ophites"), widely represented in the Pyrenean domains (Lago San José et al. 2000; Curnelle 1983; Lucas 1985) and North Africa (Kurtz 1983; Sami 2011).

The main Orogenic events of the study area occurred during two distinct times, Middle-Late Eocene-Oligocene and Late Miocene-Pliocene, respectively (Vila 1980;

Frizon de Lamotte et al. 2000). Geodynamic evolution of this part of Algeria is related to western Mediterranean extension that began 32–30 Ma and that was mainly controlled by the subduction rollback and closure of Tethys Ocean under the European Plate (Frizon de Lamotte et al. 2000). A major structural NE-trending boundary longitudinally divides northerneast Algeria, separating the diapic zone that is part of Eastern Saharan Atlas in the south from the Medjerda mounts to the north which is part of the Tellian (Maghrebides) thrust belt. The thrust belt represents the southernmost segment of the Alpine Orogeny, characterized by Miocene south-directed tangential tectonism of Tellian and Numidian nappes (Vila 1980; Durand Delga and Fontobé 1980; Frizon de Lamotte et al. 2000). Halokinesis of Triassic salt is due to the overall geodynamic evolution and an extensional tectonic regime during lower Cretaceous, which is related to the opening of the Tethys, and was driven by regional tectonic movements along NE–SW-trending normal faults (Vila 1980; Herkat 1999). These NE–SW-trending normal faults have favored the ascent of Triassic salt domes from the upper Aptian and created subsiding rim-synclines and large sedimentary basin subsidence. Thickness and lithological variations of the post-Triassic strata (lower and middle Cretaceous) over and around the Triassic salt domes have been interpreted to be associated with diapiric activity (Perthuisot 1978). In addition, the diapiric movements can locally influence the sedimentary and structural evolution of the sedimentary cover (particularly pronounced in upper Cretaceous and Tertiary strata). The diapiric activity favored the development of reefal accumulations around sub-basins, characterized by organic-rich facies (Aoudjehane et al. 1992; Herkat 1999; Vila 1980; Bouzenoune 1993; Perthuisot 1978, 1992; Perthuisot and Rouvier 1988; Thibieroz and Madre 1976; Rouvier et al. 1985; Sami 2011).

The late Eocene event (major NW–SE shortening direction) corresponds to the development of predominantly NE–SW folded structures (Fig. 2a) separated by synclines or minor subsident basins (Vila 1980; Aissaoui 1984; Addoum 1995; Haddouche et al. 2014). At a regional scale, small E–W trending folds are associated with a regional Miocene to Quaternary compression episode (Aissaoui 1984; Addoum 1995; Haddouche et al. 2014). This latest N–S-directed shortening event deformed some of the NE–SW-trending anticline structures at their extremities (e.g., Hamimat Guerra, Hamimat Guibeur and Hamimat Souda, Vila 1980; Aissaoui 1984; Addoum 1995; Haddouche et al. 2014). Faults that affect these regions are oriented NE–SW/NW–SE, E–W, and rarely N–S (Fig. 2b). The NW–SE-trending faults mainly show strike-slip displacements or normal displacements (Vila 1980; Boutaleb 2001; Haddouche 2010; Sami 2011).

Metallogenic overview

Several small Pb-Zn-Fe-Ba (±Cu, ±Sr, ±F, ±Au, ±Ag) ore deposits and showings have been identified in the southern Medjerda mounts and diapiric zone (Fig. 1). These ore deposits are hosted mainly in lower and middle Cretaceous (Albian-Aptian and Campanian) formations. Lead, zinc, iron, and barite are the primary commodities of these ore deposits. Fluorite, copper, gold, and silver are occasionally present in some deposits.

The orebodies display vein fillings associated with NE–SW/NW–SE and E–W-trending faults. They also show epigenetic lenticular or strata-bound and brecciated zones located at the contact between the diapiric structures and Cretaceous formations (peridiapiric concentrations). Sulfide and sulfate mineralization are mostly related to open-space filling of breccias and/or as replacement of the host dolostone and fractures. Veinlets, bands, disseminations, vugs, massive sulfide, and sulfate textures are also observed (Boutaleb 2001; Haddouche 2010; Sami 2011). The absolute age of mineralization is not known for these deposits, but the majority has been attributed to epigenetic deposits that can be classified as Mississippi Valley Type "MVT" (Anderson and Macqueen 1982; Sangster 1983, 1990, 1996, Sverjensky 1986; Leach and Sangster 1993; Leach et al. 2001; Bradley and Leach 2003; Paradis et al. 2007). At a large scale, the available fluid inclusion and isotopic studies (Boutaleb et al. 1999; Haddouche et al. 2014; Laouar et al. 2016) suggest that the formation of "MVT" deposits of northeastern Algeria is related to basinal brines that migrated during the Atlasic Orogeny (and probably also during Miocene tectonic movements) (Boutaleb 2001). Zn–Pb deposits are formed close in margin of sedimentary basins by hydrothermal fluids convecting through subsiding basins (Boutaleb 2001; Haddouche 2010; Sami 2011).

In the diapiric zone, the best-known ore deposits are those of El Ouasta, Ouenza, Mesloula, Boujaber, and M'Khiriga. Recent studies (Hatira 1988; Orgeval et al. 1986; Bouhlel 1993; Haddouche et al. 2004) showed that African diapirs are similar to the salt diapirs in the Gulf Coast (Kyle and Price 1986; Posey et al. 1994; Kyle and Saunders 1996). These authors reported high concentrations of Fe, Zn, Pb, Mn, Ba, and Sr minerals in cap rocks at the Hockley Dome in south-central Texas. Since then, sulfides and barite have been explored from many domes in the Gulf Coast (Kyle and Price 1986). These domes host principally zinc-lead deposits, mainly within the cap rock sequences (in both calcite and anhydrite cap rocks levels). In the diapiric zone (Tunisia), geological surface and drilling data reveal a mineralized brecciated carbonate zone (Bou Grine and Fedj El Adoum ore deposits), considered as a transition zone that represents the equivalent of detrital formation of calcitic "Cap rocks" (Hatira 1988; Sheppard et al. 1996). In the El Ouasta area,

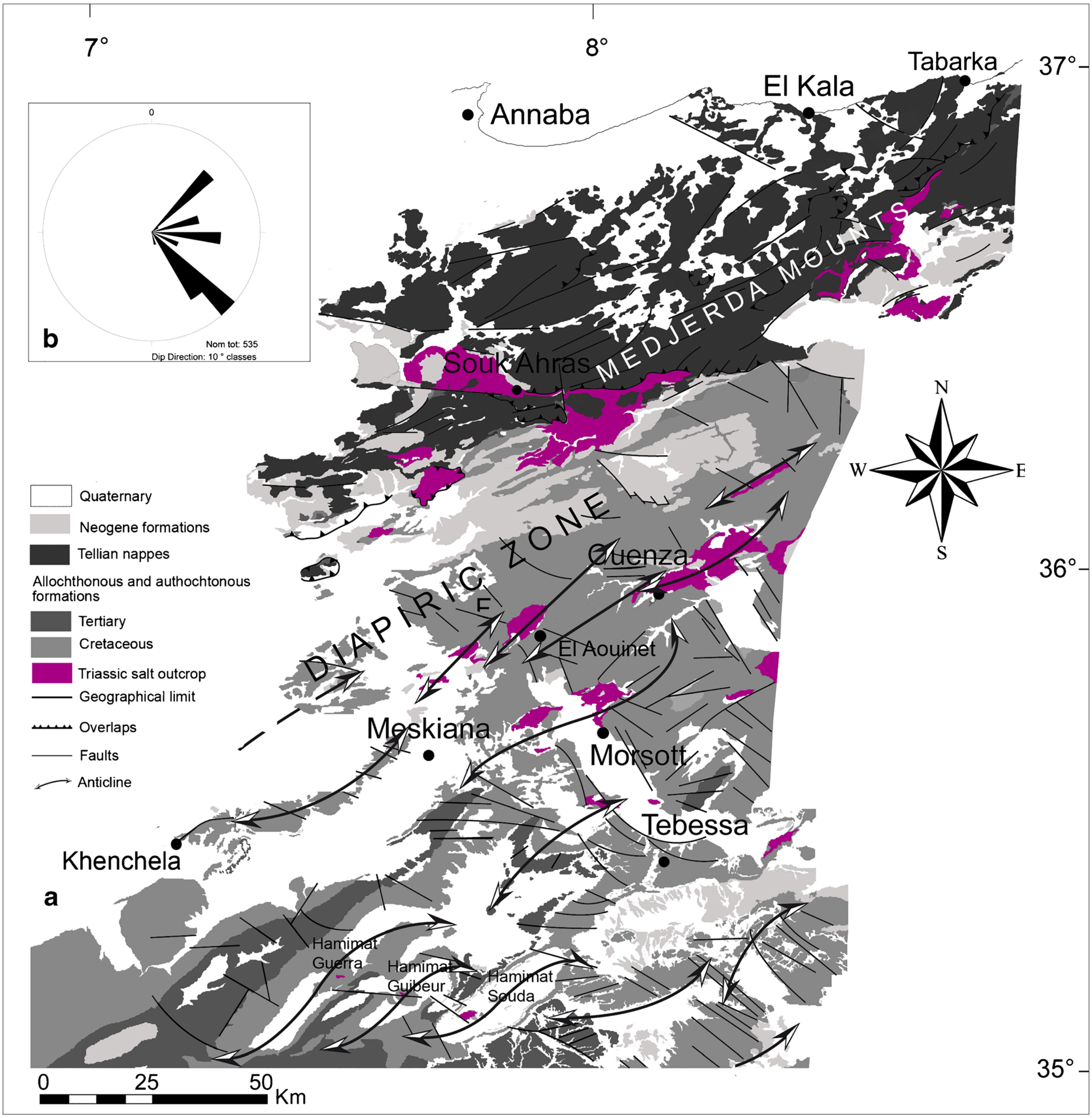

Fig. 2 Regional geological sketch map of North Eastern Algeria (**a**) showing the locations of regional-scale folds, and the extent of Cretaceous and Tertiary rocks (**b**) Average rose diagrams showing orientations of 535 faults in the study area

this brecciated zone is 3- to 20 m thick, with principally Ba (Sr) mineralization (Haddouche et al. 2004).

Several polymetallic vein orebodies occur mainly away from diapiric structures (e.g., Es Souabaa and Ouenza ore deposits) and are related to NE–SW, NW–SE, and E–W-trending faults cutting the Aptian limestones (Bouzenoune 1993; Sami 2011). The mineralization has mineral assemblages that consist of galena, pyrite, chalcopyrite, sphalerite, tetrahedrite, barite, fluorite, dolomite, calcite, and quartz.

The carbonate-hosted, Ba-Fe (±Cu, ±F)-rich showings of southern Medjerda mounts occur in Campanian/or on contact with Triassic salt outcrops, where numerous small orebodies occur principally in east–west-trending veins and breccia-filling. At El Khanga deposit, two types of mineral deposits are observed: (i) a ferro-barytic zone mineralized on Cu, Ag, Ba, and Au and (ii) brecciated orebodies mineralized on Fe (±Cu).

The mineralization age of these regions is still uncertain. At Ain Mimoun ore deposit, the presence of barite mineralization hosted in Miocene conglomerates indicates a post-Miocene emplacement for the mineralization (Haddouche 2010).

Geophysical data analysis

Data used in this study include ground gravity and airborne magnetic data gathered at a regional scale for geological mapping (lithological discrimination and structural mapping) purposes.

Gravity data

Gravity data were acquired from 1986 to 1989 by the Algerian National Mining Research Company (SONAREM), currently ORGM. Originally, The gravity survey was focused on the area between longitudes 5° 30′ W and 8° 20′ W and latitudes 35° 17′ N and 36° 09″ N. Gravity measurements were made at 7896 stations in an area of about 29 500 km^2 (approximately one station per 4 km^2). Collected data were reduced to the sea-level datum by standard reductions (drift, tidal, latitude, free air, Bouguer and terrain corrections) by Zerdazi (1990). The results of the gravity processing were compiled as complete Bouguer, regional and residual anomalies at scales 1:200,000 and 1:500,000, calculated using three Bouguer densities: 2.40, 2.67, and 2.75 g/cm^3, and a contour interval of 2 mGal for the Bouguer maps.

We have integrated only the eastern part of the gravity survey, located between longitudes 7° 00′ W and 8° 20′ W and latitudes 35° 17′ N and 36° 09′ N. A standard Bouguer reduction density of 2.67 g/cm^3 is used in this study. This density is considered appropriate since the correlation between the Bouguer anomaly and topography is minimum, apart from some areas.

Our interpretation is mainly based on the residual Bouguer anomaly, obtained by subtracting the regional component estimated by upward continuation of the Bouguer field up to an altitude of 30 km. As shown in Figs. 3 and 4, the resulting residual anomaly over the study area ranged from − 23.0 to + 37.5 mGal with an average of 0.5 mGal.

To further characterize the delineated features, the first vertical derivative (1VD) of the Bouguer anomaly was calculated (Fig. 5). This method is routinely used as a supplement to geological mapping in the identification of lithological contacts by emphasizing shallow geological sources (enhance detail and enhance the edges of anomalies) while masking the response of deep sources.

The next step in gravity data interpretation is the generation of a 3D density contrast model for the study area. The resulting 3D density model will provide the sub-surface architecture that should assist in the identification of favorable zones for Pb-Zn-Fe-Ba mineralization, which will better guide exploration programs. An unconstrained 3D gravity inversion was performed on the residual gravity data, using VOXI GRAV3D Earth Modeling software of Geosoft.

The modeled mesh block was divided by 264 × 172 × 33 rectangular cells of 500 m in easting (X) and northing (Y), and 250 m in depth (downward). Margin elements (5 cell paddings) were added to the sides of the model to move the effects due to model edges away from the bordering data points. Once the mesh is defined, the topography is discretized onto it. The 1,944,852 cells (with the padding) below this surface define the density model for the study area, and the inverse problem is therefore formalized by inverting 33,266 data contaminated with the Gaussian noise whose standard deviation is equal to 1.5% to recover the density contrasts in those cells.

After setting up the data and the 3D mesh block, two numerical inversions were used to optimize the density contrast of the model elements in such a way that the synthetic (predicted) response will fit the measured (residual) data. At first, the VOXI 3D inversion generates a smooth solution. Subsequently, an Iterative Reweighting Inversion Focusing (IRIF) takes the obtained smooth model and uses it as a reweighting constraint to finally provide more refined and realistic structures.

The final inversion result is illustrated in Fig. 6a, b, as combined horizontal and vertical sections of the density contrast distribution. The unconstrained 3D gravity inversion reveals the underground geometry of the major structures of the study area.

Aeromagnetic data

The aeromagnetic survey over the study area (northeastern Algeria) is part of the national airborne magnetic and radiometric coverage of Algeria. The survey was completed by Aeroservices Limited in 1974 on behalf of the SONAREM (Algerian mining and geological researches company). The data were acquired with a nominal terrain clearance of 150 m to provide information about the near-surface geology, using a higher solution (0.02 nT) optically pumped cesium vapor magnetometer. Flying lines were oriented N160° (NNW–SSE), with a spacing of 2 km. Tie lines (control lines) were oriented perpendicular to traverse lines with a spacing of 10 km. Readings were taken at 1-s intervals, yielding at an average aircraft speed of 165 km/h, a magnetic measurement about every 46 m along.

Several data processing procedures, such as De-spiking, lag correction, leveling (tie-line leveling), International Geomagnetic Reference Field (IGRF) calculation and removal, and microleveling, were carefully achieved to obtain good quality data. The resulting magnetic anomaly field is displayed as color-shaded map (Fig. 7). The interpretation which consists of determining the geological structure of the area is defined by zones that are more or less magnetic, corresponding to different geological formations or faults.

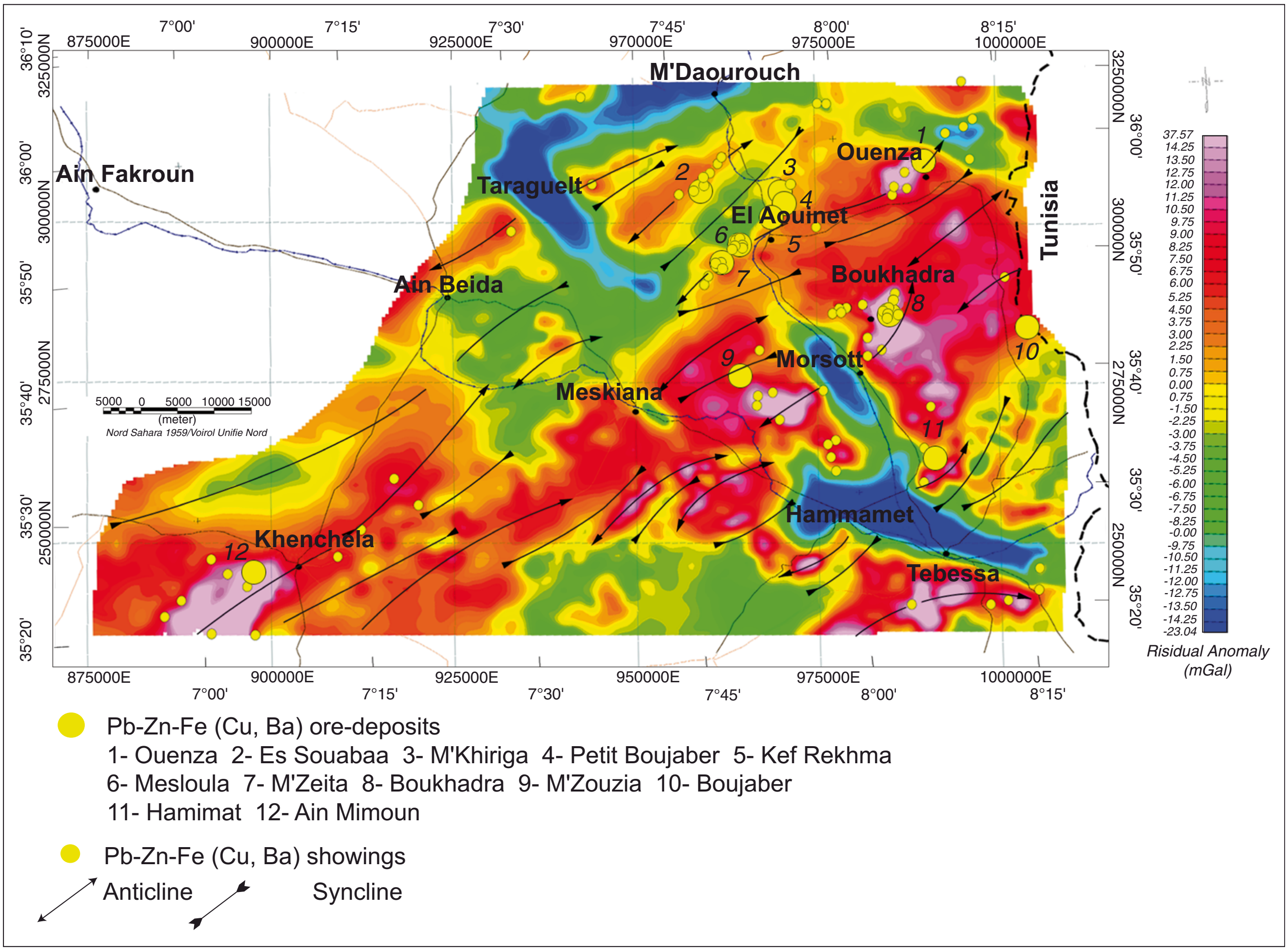

Fig. 3 Residual gravity anomaly map. The yellow dots indicate the location of major Pb-Zn-Fe-Ba (±Cu, ±F, ±Sr, ±Au, ±Ag) ore deposits and showings

Data analysis and discussion

In this study, geological, metallogenic, and geophysical analyses were employed to study the spatial pattern of known mineral deposits of the southern Medjerda mounts and diapiric zone. The different maps obtained from geological/metallogenic and geophysical data show preferential linear-trends of mineralization, coincident to the directions of the regional structures (anticlines, diapiric structures, tectonic troughs, and faults). Gravity and aeromagnetic data revealed lithological contacts and tectonic features (lineaments) which coincide with some notable mining sites. The most distinctive features on the residual gravity map are:

- High-gravity anomalies exceeding + 10 mGal in amplitude, highlighted in the center, NE, SE, and SW of the study area. Some of these gravity features appear associated with the iron deposits (Ouenza and Boukhadra ore deposits) (Fig. 3). The rest of the anomalies coincide with massive limestone/dolostone sedimentary rocks of the lower and middle Cretaceous (Fig. 4).
- Pronounced NW–SE negative gravity lineaments (< − 13 mGal amplitude), outlined in the north of Tebessa, west of Morsott, and NE of Ain Beida. According to the geological map, these negative gravity axes correspond to collapse trough structures known as troughs of Tebessa, Morsott, and Tarraguelt (NE of Ain Beida).
- Large zones striking NE–SW alternating positive and negative anomalies of moderate amplitudes ranging from about 3 to 6 mGal. These gravity signatures are associated with anticline and syncline structures (subsiding basins), respectively. These structures are indicated by arrow axis on the residual gravity map (Fig. 3).
- Irregular to elliptical-shaped low-gravity anomalies of moderate size mostly trending NE–SW. These gravity features exhibit large range amplitudes varying from − 2 to + 2 mGal. These gravity depressions correlate with Triassic evaporates known as diapir zones.

As shown in Fig. 3, the residual gravity map has well characterized the contours of the diapir of Mesloula, diapir of Oued-Melah (located south of Mesloula), diapir of mount Meridef (located NE of Ouenza), and diapir of Argoub Zeimbai (located SW of Boukhadra).

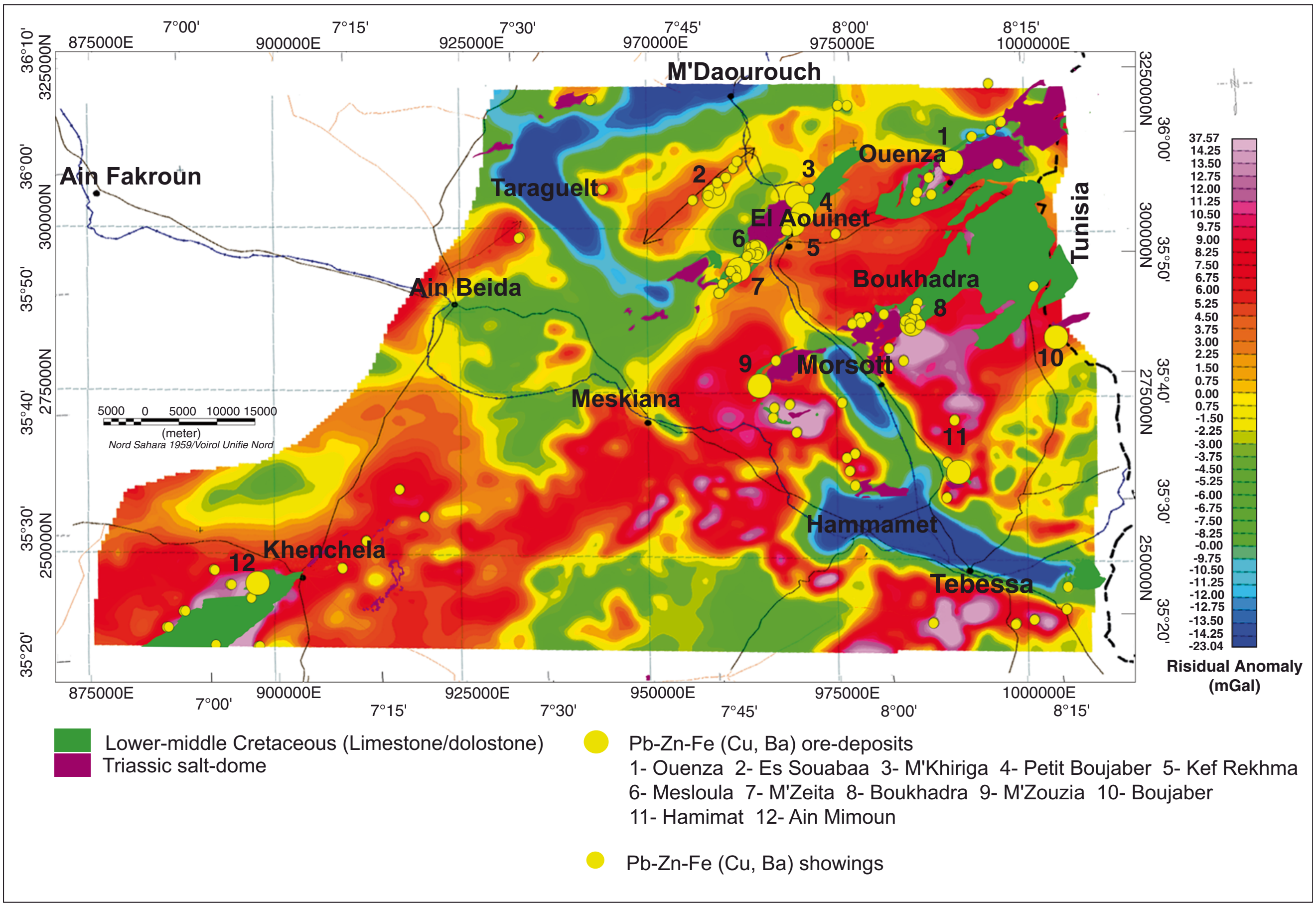

Fig. 4 Residual gravity anomaly map combined with lower-middle Cretaceous and Triassic salt domes formations. The yellow dots indicate the location of major Pb-Zn-Fe-Ba (±Cu, ±F, ±Sr, ±Au, ±Ag) ore deposits and showings

Enhanced first vertical derivative (1VD) of the Bouguer anomaly successfully highlighted the zones where the dense materials are concentrated (hematite iron deposits and massive limestone/dolostone formations), as well as the zones of deficit masses reflecting the collapsed troughs and diapiric zones (Fig. 5). Several major faults (NE–SW/NW–SE) were also delineated from the residual and 1VD gravity maps. The disrupted character of the high-gravity anomalies and the presence of collapsed troughs indicate that intense tectonic activity has affected the study area.

The density model obtained from the unconstrained 3D gravity inversion shows density contrast values ranging from − 0.45 to + 0.60 g/cm^3. The trough zones and the Triassic salt structures (diapirs) are characterized by negative density contrast values ranging from − 0.45 to − 0.12 g/cm^3. The calculated density model shows that the depth extension of Tebessa and Morsott trough zones exceeds 11 km, while the bottom of the Taraguelt trough zone (northeast of Ain Beida) is estimated to be about 7–8 km. As for Triassic evaporate structures, the gravity inversion shows that the diapir of Mesloula is dipping towards the north and its depth extension is estimated about 4–6 km while the diapir of mount of Meridef (located NE of Ouenza) appears more steeply dipping (almost subvertical) and its bottom is approximately at 8–9 km deep.

The outlined dense sources correspond mostly to hematite iron formations and to carbonate limestones/dolomites rocks. The gravity inversion has characterized these geological units by density contrast values ranging from + 0.15 to + 0.55 g/cm^3. Apparently, the densest interpreted structures exceeding 0.20 g/cm^3 correspond with Ouenza and Boukhdra iron deposits and with the mount of Belkfif (located SW of Morsott), the mount of Bou Roumane (located SE of Tebessa), and NE–SW anticline structure of Khenchela. Many Pb-Zn-Fe ore occurrences are associated with these geological structures (Fig. 5).

Prominent deficit masses of moderate size, associated with diapir structures, have been clearly characterized in the 3D gravity inversion. Emplacement of these diapirs is important because the Pb-Zn mineralization often wraps these structures or occurs in the cap rock breccias of these diapirs. This type of mineral deposits is known as peridiapiric Pb-Zn deposits (Bouzenoune 1993; Boutaleb 2001; Haddouche; 2010; Sami 2011).

The interpretation of the ground gravity survey has improved the understanding of the sub-surface density contrast

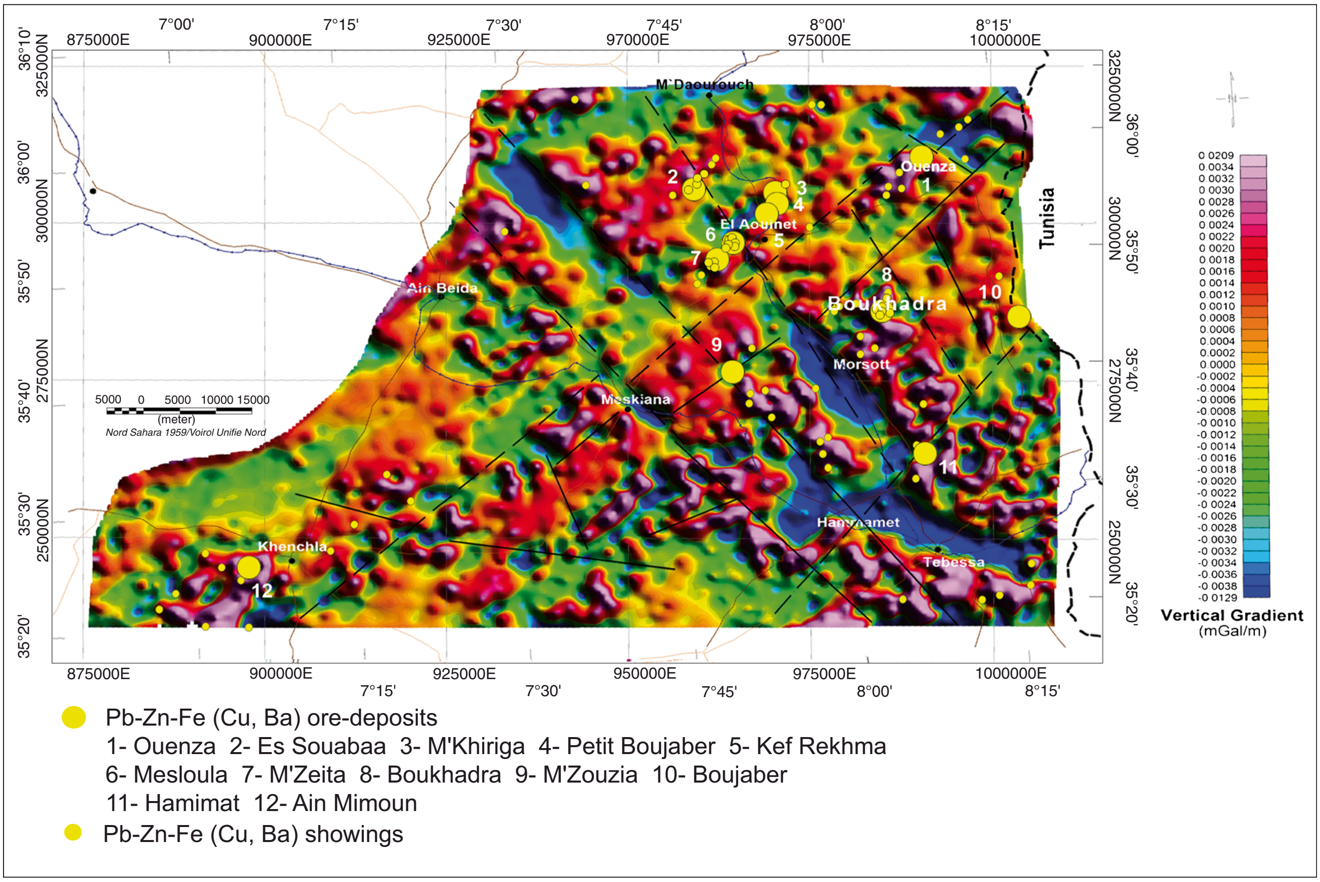

Fig. 5 First vertical derivative map (1VD) of the Bouguer anomaly. Small yellow dots indicate the location of major Pb-Zn-Fe-Ba (±Cu, ±F, ±Sr, ±Au, ±Ag) ore deposits and showings

and its relationship to the geological setting to the South of Medjerda mounts and diapir zones. Dense areas probably associated with limestone/dolostone rocks of lower-middle Cretaceous, favorable for hosting Pb-Zn mineralization and iron deposits, were successfully identified (Fig. 4). Several mineral deposits are located near or along Triassic structure border (peridiapiric concentrations), related to NE–SW/NW–SE-trending faults (e.g., El Khanga, Ouenza, Mesloula, M'Khiriga, Petit Boudjaber, and Kef Rekhma deposits).

The aeromagnetic survey was limited to the definition of long wavelength features mainly reflecting sedimentary basins by broad and low magnetic signatures, limestone/dolostone anticlines by broad weak to moderate positive signatures, and tectonic features by linear gradient signatures and breaks and inflexions in the contours of the magnetic anomalies. The distribution of the residual magnetic field is well presented in Fig. 7 with the inferred tectonic features as well as the distribution of known ore occurrences. Amplitudes of the residual magnetic features appear weak varying from about − 70 to + 70 nT. A bipolar magnetic lineament trending approximately NNW is highlighted near the longitude 8° 00′. This magnetic trend seems to follow the road linking Tebessa-Morsott to the town of Souk Ahras. The outlined bipolar magnetic signature is not the results of remanent magnetization, as the study area is completely devoid from igneous rocks, except a few dolerites "Ophites" rocks associated with the salt diapirs.

Regional ground gravity and aeromagnetic maps (Figs. 5 and 7) show major sub-parallel NE–SW-trending lineaments that correspond to mineralized axis, intersected locally by dextral NW–SE-trending lineaments. Mineralization occurs along or near these deep-seated faults, which delimited locally the sedimentary sub-basins.

Other Pb-Zn-Fe (Ba) mineral deposits seem to be located along geological structures delimited by NW–SE-trending trough zones. In Morsott region, Pb-Zn mineral deposits (e.g., Hamimat ore deposit) are located along these deep fracture type, clearly marked by gravimetric and aeromagnetic data. Some Pb-Zn mineral deposits occur along or near major NW–SE-trending faults (e.g., Es Souabaa deposit) and within geological contacts, usually either inside anticline hinges zones/on the flanks of anticline structures. On the surface, NW–SE-trending faults are represented by strike-slip/normal faults, which locally cross-cut NE–SW-trending faults. These faults may control tectonic troughs of Morsott region as suggested by Sami (2011).

NE–SW-trending lineaments constitute regional sub-parallel faults (Figs. 6a and 7). At a regional scale, the

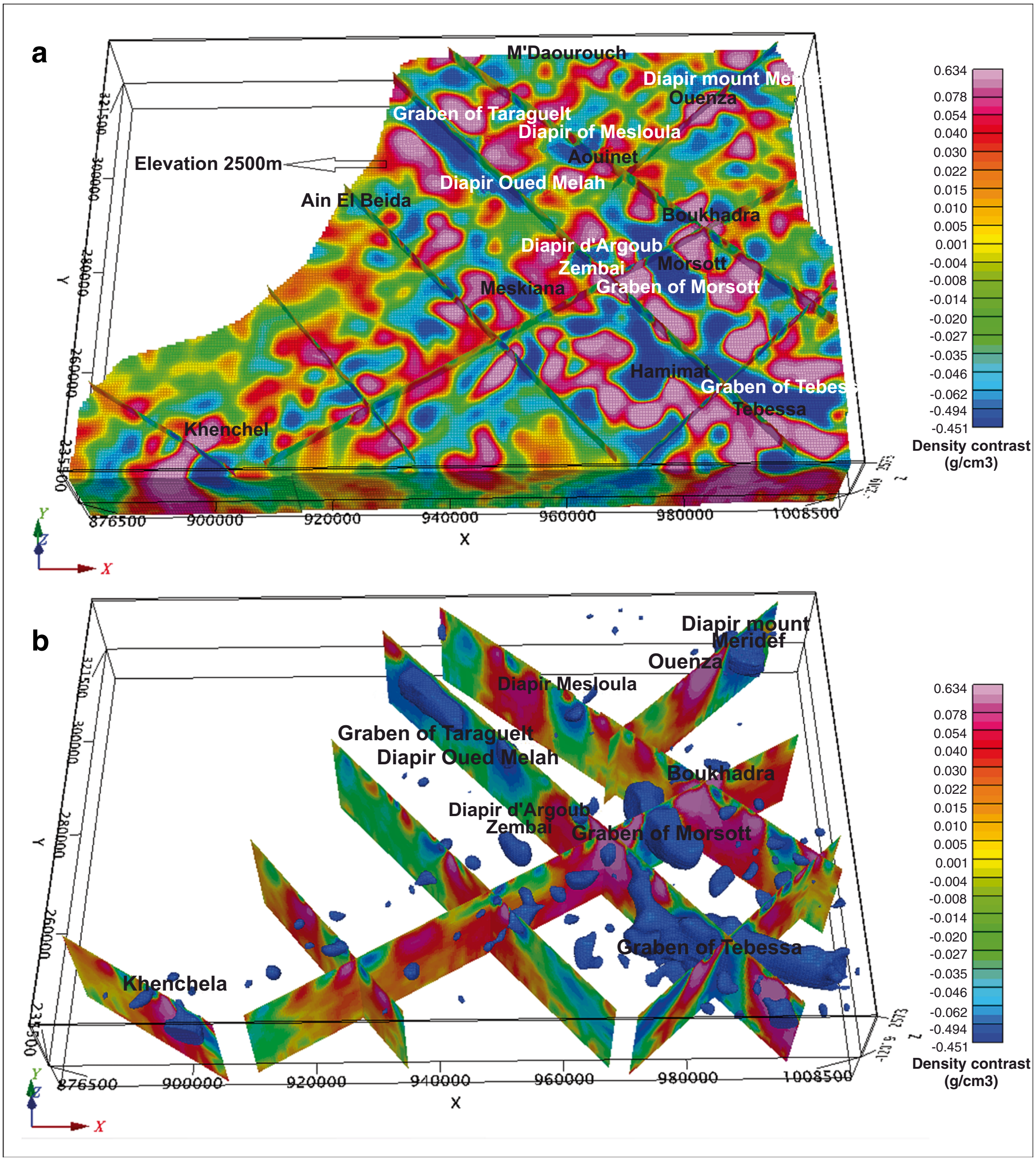

Fig. 6 3D gravity inversion with horizontal (**a**) and vertical (**b**) sections of the density contrast distribution

deeper faults may also control the evolution of Atlasic sedimentary basins (block-tilted system) defined by Herkat (1999) and Vila (1980) or faults that favored the ascent of Triassic salt rocks from the upper Aptian (Bouzenoune 1993; Vila 1980) in northeastern part of Algeria. NW–SE-trending faults (more frequent) are probably attributed to the pronounced deformation during the Atlasic Orogeny (post-Eocene), coeval with NE–SW folded structures of oriental Saharan Atlas, as suggested by Sami (2011) and Haddouche (2010).

Most of the mineral deposits within the study area are located to the boundary of Triassic salt outcrops, along rock contacts (generally, hosted in limestone/dolostone rocks of the lower Cretaceous). Other mineral deposits are related to NE–SW/NW–SE-trending faults that cut the lower and middle Cretaceous rocks and that delimited trough zones (NW–SE-trending faults). The major NE–SW faults delimited sub-basins, which probably provided heat source control on convection of sulfate/base metal-bearing hydrothermal fluids, from which the MVT-type deposits/occurrences were formed (e.g., Haddouche (2010) and Sami (2011)), for the Ain Mimoun and Mesloula ore deposits, respectively. NE–SW/NW–SE-trending fault systems play probably an important role in providing pathways for focusing mineralized fluids into the sedimentary cover (limestone/dolostone sedimentary

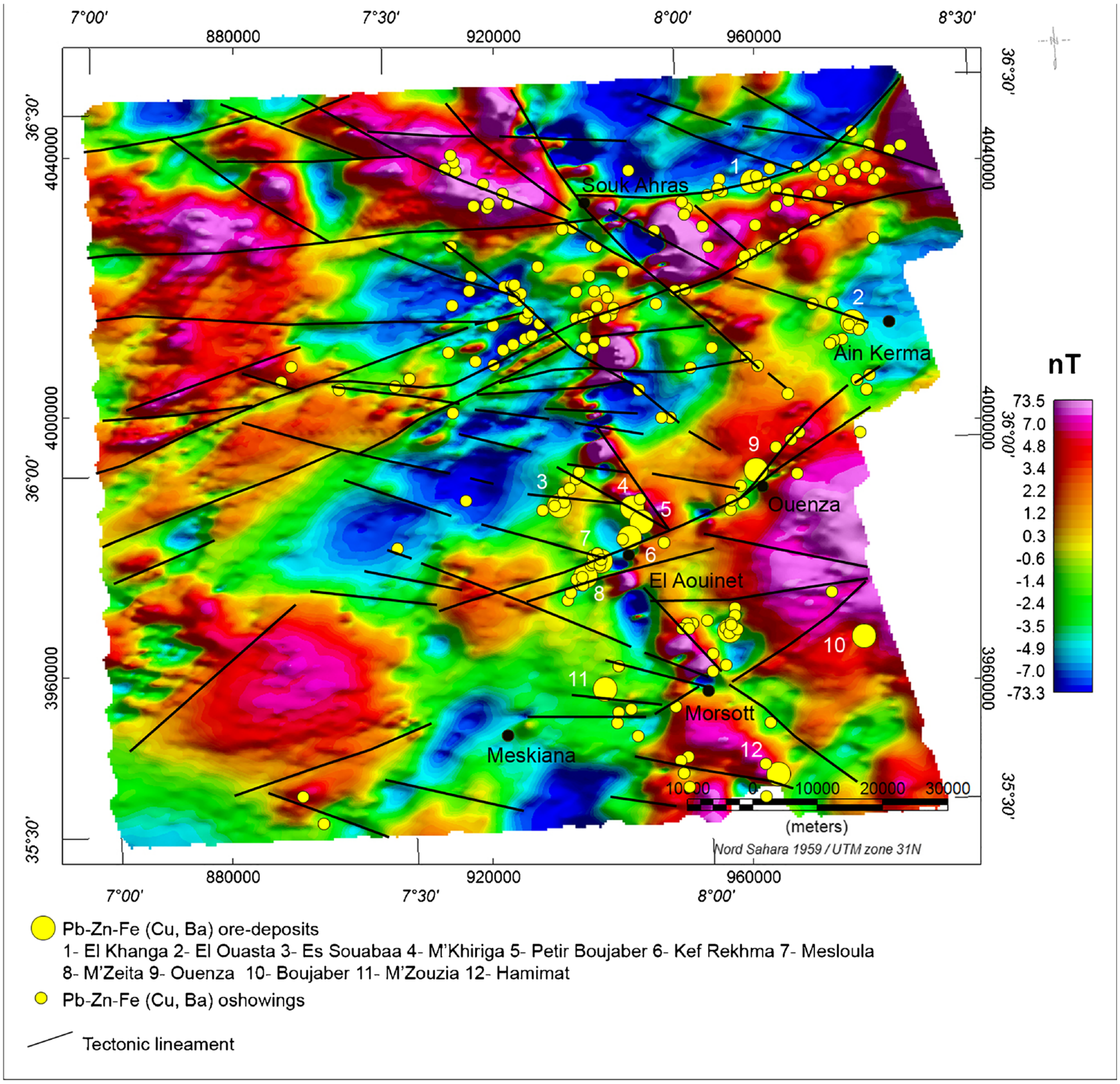

Fig. 7 Interpretation of the airborne magnetic maps. Yellow dots indicate the location of major Pb-Zn-Fe-Ba (±Cu, ±F, ±Sr, ±Au, ±Ag) ore deposits and showings

rocks of the lower and middle Cretaceous) to depositional sites along surface smaller faults (NE–SW, NW–SE, and rarely E–W) or at contact between Triassic salt outcrops and lower Cretaceous units.

Conclusion

The integration of ground gravimetric and aeromagnetic data has helped in mapping concealed geological features which characterize mineralized zones within the study area. Rock boundaries and tectonic lineament trends were interpreted on the bases of gravimetric and magnetic intensities over the study area. The results that were obtained show more information on the geology and notable structural features that have controlled the emplacement of mineralized deposits in this area. Mineral deposits appear to be regionally associated with NE–SW/NW–SE structural trends, preferentially located at the margins of the sub-basins. They are likely to be found along or near major NE–SW/NW–SE deep lineaments, around the peripheries of diapirs (peridiapiric concentrations). Other mineral deposits are related to NE–SW/NW–SE-trending faults that cut the lower and middle Cretaceous formations and that delimited trough zones (NW–SE-trending faults). The deeper NE–SW/NW–SE lineaments have probably controlled kinematic evolution of the geological structures, the sedimentary basins and the ascension of the Triassic rocks from the lower Cretaceous. These major faults seem to play an important role in providing pathways for focusing mineralized fluids into the sedimentary cover (limestone/dolostone sedimentary rocks of the lower and middle Cretaceous). 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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