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From sandstone- to carbonate-hosted stratabound deposits: an isotope study of galena in the Upper-Moulouya District (Morocco)

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Abstract The Upper Moulouya district displays three main types of lead ores in the Hercynian domain: (1) Aouli vein-type deposits hosted in the Hercynian basement, (2) Zeïda Triassic sandstone-hosted, and (3) Mibladén carbonate-hosted stratabound and karstic mineralisations in the Mesozoic cover. Lead and sulfur isotope studies indicate that the Aouli vein-type and Zeïda sandstone-hosted stratabound mineralisations are formed by a mixing of two fluids, one formed by the leaching of the Aouli granite massif, and the other by leaching of the Saharian basement. These deposits may correspond to the same Triassic metallogenic event, focused along fault systems or within permeable sandstone. Deep fluids were mobilised during the early extensional movements associated with the opening of the Atlas rifting basin. The Mississippi Valley type Mibladén mineralisation is related to a distinct metallogenic event superimposed on the earlier one, and represents a remobilization of earlier concentrations, or a more recent leaching of the same sources, but with a more pronounced contribution of the local organic matter. The Upper Moulouya area demonstrates the close relationship between vein type and sandstone-hosted lead-zinc mineralisations, and their major differences with Mississippi Valley type deposits.

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Introduction

Morocco has been the most important lead producer in North Africa since Roman times (Emberger 1965). Mineralisation is mainly found within, or proximal to the Hercynian chain, and displays various styles: (1) Pb-Zn-Ag vein-type deposits in basements rocks (e.g., Jebel Aouam, Aouli); (2) Pb-only disseminated mineralisation in arkosic sediments (e.g., Zeïda) and (3) stratabound karstic Pb-Zn mineralisation in carbonate facies of Mesozoic age (e.g., Mibladén, Pays des Horsts). Located in the internal part of the Hercynian chain (Fig. 1), the Upper Moulouya district is an exceptional area in which to study the relationship between these three types of deposits. Moreover, it contains one of the largest concentrations of lead in Morocco, with a total output of more than one million metric tons, and is only exceeded by the Pays des Horsts district (Rajlich 1983).

Among the deposits in the Upper Moulouya district, the Zeïda deposit belongs to the large family of sandstone-hosted lead deposits as defined by Björlykke and Sangster (1981), whereas Mibladén is comparable to other carbonate-hosted lead-zinc deposits, sharing numerous characteristics with Mississippi Valley type deposits (MVT). The relationship between these two families of deposits has been disputed. On the one hand, many authors (e.g., Stanton 1972; Rickard et al. 1979) suggest that these two types of deposits are genetically related, and reflect different types of permeability controls. Björlykke and Sangster (1981) conclude that similar fluids were involved during deposition of carbonate-hosted deposits and sandstone-hosted lead deposits. Schrijver (1992) states that "in the case of the galena-cemented sandstone associated with MVT deposits, little doubt exists that the same fluids transported and ultimately precipitated sulphides in both sandstone and dolostone". On the other hand, there is some difference in terms of conditions of deposition and chemistry of the fluids (e.g., dolomitization associated with MVT mineralisation). Moreover, it has been dem-

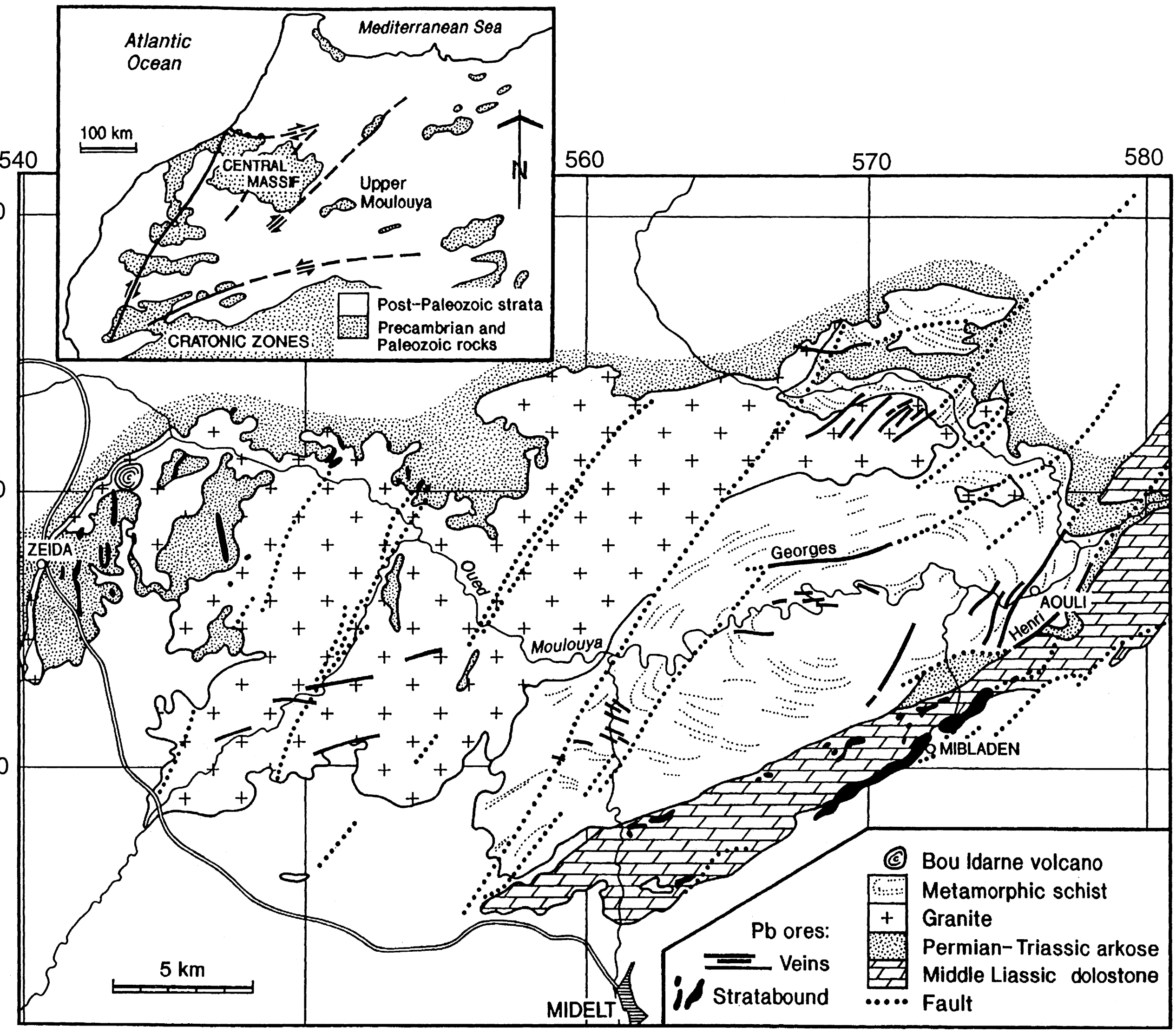


Fig. 1 Location of the Precambrian and Palaeozoic terranes in northern Morrocco. The Upper Moulouya area represents an internal zone of the Hercynian belt, located between cratonic zones of the Saharian domain and mobile external zones of the Central Massif. Geological map of the Upper Moulouya district (modified from Emberger 1961) showing the locations of Pb-deposits discussed in the text

onstrated in the southern Appalachians that the distribution of the deposits reflects two different paleoaquifers (Kesler et al. 1994). Both types of deposits have been related to large-scale fluid migration although different mechanisms of flow have been proposed: sandstone-hosted lead-zinc deposits have been related to warm basinal brines driven out from geosynclinal source rocks during thrusting (Rickard et al. 1979; Romer 1992), whereas similar brines associated with MVT deposits have often been related to rapid subsidence or regional uplift in an extensional context (Bethke and Marshak 1990; Garven 1995).

In the Upper Moulouya area, previous genetic hypotheses proposed either a single mineralising event of Tertiary age (Bouladon 1956) or a multistage process involving lead inheritance since Late Hercynian time (Emberger 1965; Duthou et al. 1976). This study outlines the detailed field geology and lead and sulphur isotopic studies that were performed in order to decipher the complex relationships between the Upper Moulouya deposits, and to develop a model for their genesis. The Upper Moulouya area will therefore provide insight into the relationship between MVT, vein-type and sandstone-hosted lead-zinc mineralisation.

Geological context

The Upper Moulouya lead district is located in the Eastern Meseta domain of Morocco, that lies between the Alpine ranges of the Middle Atlas to the north and the Upper Atlas to the south and southeast (Fig. 1) (Piqué and Michard 1989). The Meseta is composed of Palaeozoic terranes, cut by Late Hercynian granitic intrusions. Basement rock comprises pelite and quartzite, with a few amphibolitic horizons of probable Cambrian age. Three episodes of Hercynian deformation have been documented (Vauchez 1976), and regional metamorphism of lower greenschist facies has been dated at 366 ± 7 Ma (Hoeppfner 1987). A polyphase granitic massif cuts these sedimentary units and was emplaced between 330 ± 2 Ma (granodiorite) and 280 ± 3 Ma (late leucogranite stock) (Oukemeni et al. 1995).

Mesozoic terranes are Triassic to Cretaceous in age (Fig. 1). Sedimentation began during the late Triassic rifting phase, and the major subsidence areas are presently beneath the Central and Middle Atlas mountains. Two successive sequences have been distinguished (Laville et al. 1995): the oldest sequence is of Late Triassic to Earliest Liassic age, and consists of conglomerates, arkoses, sandstones and argillites filling a fluvial basin. Most of the detrital material was derived from the underlying granites and schists (Amade 1965; Felenc and Lenoble 1965; Schmitt 1976). Extensive basaltic flows of tholeiitic composition are interbedded with the argillites and may reach 200 m in thickness (Lorenz 1976). They yielded radiometric ages of 210 ± 2.1 Ma and 196 ± 1.2 Ma (^{40}Ar-^{39}Ar method; Fiechtner et al. 1992). The youngest sequence is mainly composed of carbonates, and is Early to Middle Liassic in age. Within this sequence, carbonates overlie the argillites near the Upper Moulouya topographic high. Tilting of the block occurred during the deposition of the argillites. Locally, the edge of the tilted block has been eroded down to the Palaeozoic basement. The deposition of Jurassic terranes began with conglomerate, marl and gypsum units, followed by thick carbonate horizons (Felenc and Lenoble 1965). The latter indicates that a carbonate platform developed during Middle Liassic time in a rapidly subsiding basin. Limestones were affected by intense karstification processes due to several periods of emergence of short duration in an active tensional tectonic context (Dagallier and Macaudière 1987). Marl and limestone were deposited during Doggerian time. In the Upper Atlas area, low-grade metamorphism occurred around 200 Ma (Huon et al. 1993). This metamorphic episode is probably of hydrothermal origin and may have been related to an increase in the thermal gradient which ceased during Liassic time (Laville and Piqué 1991).

Cretaceous sediments of Cenomanian age were deposited unconformably on the Jurassic and Palaeozoic terranes. They consist of up to 100 m of detrital sediments followed by shaly limestone and evaporites of lagunar origin. The Cretaceous terranes were overlain by Pontico-Pliocene detrital sediments and Quaternary fluviatile terraces (Felenc and Lenoble 1965).

Deformation during the Atlasic orogeny was of limited intensity in the Upper Moulouya area. Several minor tectonic pulses are indicated by reverse and strike slip movements along Hercynian and normal post-Hercynian faults, and by large undulations in the Mesozoic cover. The Upper Moulouya area was therefore a relatively stable tectonic area during the Atlas orogeny. Late faults are Tertiary in age and are associated with two compressive episodes, N-S and N160-N180°, with a morphological inversion related to an intraplate uplift (Laville and Piqué 1991; Giese and Jacobshagen 1992).

Geophysical data suggest that early normal faults could represent the upper termination of major detachment structures (Warme 1988; Laville and Piqué 1991; Giese and Jacobshagen 1992). For example, the Souk el Hajar NNE-striking fault marks the contact between the Aouli granite and Palaeozoic shales, and corresponds to a major Late Hercynian fault of Devonian age which was reactivated during Triassic time as a normal fault during the opening of the Atlas basin (Laville and Piqué 1991).

Mineralisation

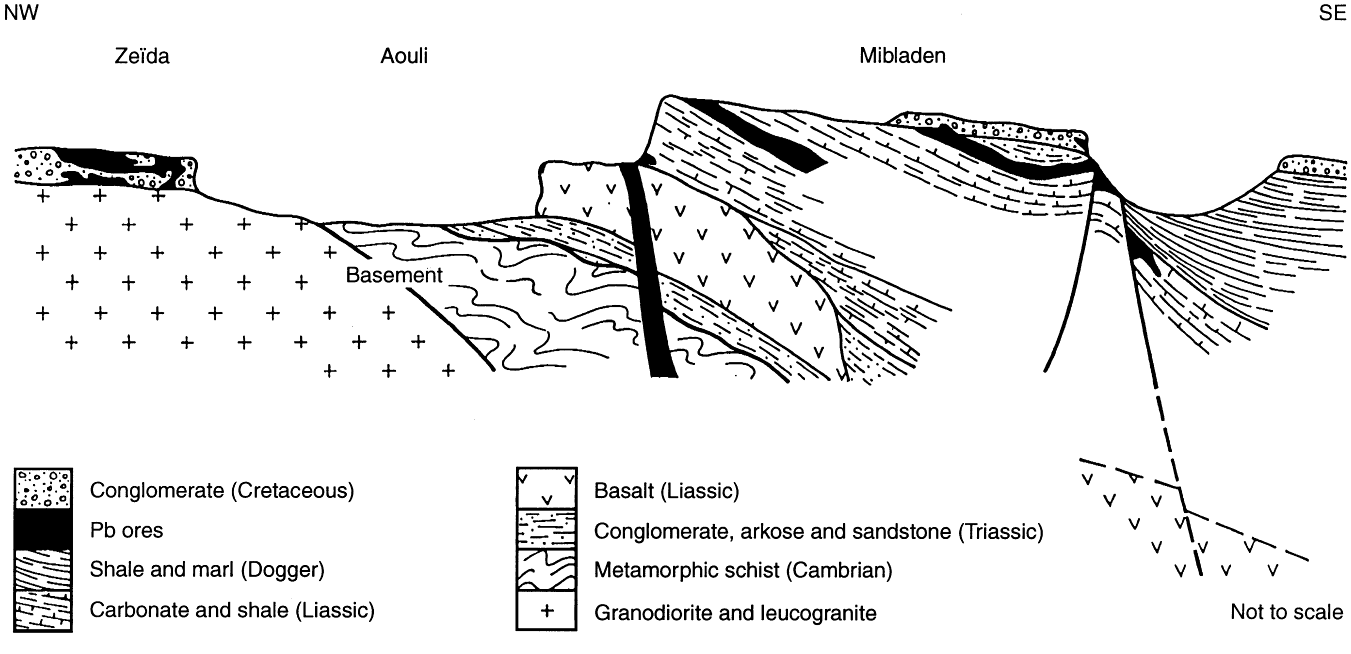
The Upper Moulouya district consists of three major lead deposits: the Aouli vein system, the stratabound sandstone-hosted Zeïda deposit, and the MVT deposit of Mibladén (Fig. 1). Their geological characteristics and schematic relations are summarised in Fig. 2.

Aouli

The Aouli vein network is mainly hosted by Palaeozoic terranes. It comprises two types of ore: (1) large sulphide-dominated veins, up to 40 m thick and 13 km long, striking NE-SW (NNE to ENE)(the George and Henry vein system are two examples), and (2) barite-fluorite- dominated smaller veins, up to 10 m in thickness, striking NE-SW and E-W.

Sulphide-dominated veins are mainly hosted by the basement and by basement shales in particular. They mark the faulted contact between basement and cover, up to the base of Jurassic limestone. The fault can be traced within Early Jurassic basalts which are strongly altered, including some silicification and trace of mineralisation although no economic occurence has been observed

Fig. 2 Upper Moulouya schematic cross section, showing the relationship between Pb-ores of the Zeïda, Aouli and Mibladén deposits (modified from Emberger 1965)



to date. Vein formation comprises several episodes, the earliest of which is an extensive silica flooding of the host-rock, resulting in a network of quartz veins, similar to the giant quartz vein systems described in other Hercynian basements (Jébrak 1984; Joannès et al. 1982; Cheggam 1985) and in Connecticut, USA. (Altamura 1995). Open-space mineral deposition in the veins includes quartz (multiple generations, including crack-and-seal structures and anhydrite replacement; Arnold and Pernett 1980), galena as large aggregates of cubic crystals, and less commonly, green sphalerite with pyrite and chalcopyrite. A late supergene enrichment is shown by the crystallisation of cerusite, malachite and azurite in open space structures.

As demonstrated by Nasloubi (1993), a multistage tectonic history can be recognized in the Henry vein system:

1. Early quartz stockwork formation which appears limited to the Triassic basaltic layers and basement rocks. The silicification occurs in an en-echelon pattern that suggests dextral movement;
2. Quartz and sulphide deposition which is limited to basement rocks and Triassic arkoses. This filling is contemporaneous with normal fault movement, as demonstrated by small displacements, probably of Triassic age;
3. Large open-space filling of pink barite, either with banded textures or as a cement in tectonic breccias. Precipitation occurred during a post-Jurassic normal movement. Barite locally appears as fragments in a tectonic breccia cemented by rock flour, clays and carbonate;
4. Reverse movement and folding in the Triassic, Jurassic and probably Cretaceous terranes forming an anticline with a high angle fault. Such movements are probably much younger (i.e. Cenozoic).

The precise age of the mineralisation is difficult to assess. In the Engil vein, the first deposition of galena appears in association with quartz that contains fragments of Triassic arkosic sediments (Bouçanna and Saïdessalam 1980). Moreover, all the Pb-Ag veins follow Triassic synsedimentary faults which mark the different steps of the Triassic graben. Veins are confined below the Jurassic limestone, and some quartz-barite-malachite veins cut the basalt. However, Pb mineralisation and its associated silicification is strictly limited to the basement, and Pb-ore is not known in basalts or the overlying rocks. This strongly suggests an Upper Triassic age for the lead mineralisation, constrained between arkose sedimentation and the emplacement of the Lower Jurassic basalts. Such an age has been proposed for numerous vein type deposits in the cover rocks of Hercynian basements (Mitchell and Halliday 1976; Johnson et al. 1996).

Limited fluid inclusion measurements from fluorite and quartz of the Marabout vein, at the northern end of the Aouli vein system, reveal an average homogenisation temperature between 120 °C and 150 °C (Jébrak and Benyoub 1980) and the presence of hypersaline fluid. Anhydrite crystallisation in some of the veins could be indicative of a minimum temperature of approximatively 150 °C (Ohmoto 1986). Previous studies show that the geochemical characteristics of the REE distribution in the fluorite is similar to that of the E-veins in the extensional systems of the Massif Central in France, related to brine circulation (Jébrak 1984; Jébrak et al. 1988). The formation of the Aouli deposit fits well with the model of Gehlen (1987) in southwest Germany where surficial brines are convected deep in the crust and mineral deposition occurred along culmination zones.

Zeïda

The Zeïda ore deposit consists of sulphide pods hosted by arkoses of Triassic age. Although on a regional scale the cement composition of these arkoses is siliceous, ferruginous or carbonate-rich, the Pb-mineralisation occurs at the base of the arkosic layers without any cement, or within a barite-rich matrix. Mineralisation follows large runs which correspond to the thickest part of the sedimentary unit, and are interpreted as palaeofluvial channels (Schmitt 1976). Three mineralised layers occur in sandstones, separated by barren yellow sandstone and yellow argillite. Amade (1965) suggested that at least some of the higher grade mineralised zones are controlled by basement fractures. The paragenetic association is very simple, with well crystallised galena and cerussite, along with minor chalcopyrite, pyrite, and large amounts of pink barite and scarce small yellow cubes of fluorite. Barite accounts for approximately 4 wt.% of the ore. Minerals occupy interstitial voids between sand grains. The Zeïda deposit also contains noneconomic barite-galena veinlets which cross-cut the arkosic sediments and the Aouli granite (Amade 1965).

The age of the Zeïda mineralisation is poorly constrained. The presence of mineralisation in synsedimentary faults (Amade 1965) has been taken as an argument for an early timing of deposition. The deposit has therefore been interpreted as syngenetic (Schmitt 1976). There is no information on the fluid inclusions of this deposit because suitable minerals are very rare. However, the occurrence of mineralisation in the hanging wall of the deposit, and comparison with similar deposits, suggests that mineral deposition occurred at the end of, or following host rock deposition.

Mibladén

The lead ore at Mibladén is limited to the Mesozoic units near the present outcrop limit of the formation where the thickness of the sediments is minimal. Most of the ore is hosted by Domerian (= Middle Lias) dolomitic to carbonaceous formations (Felenc and Lenoble 1965). The mineralisation occurred along two mineralized horizons, and is controlled by NE-striking faults at both the district and mining scales (Emberger 1965). These faults, like the Aouli and Amourou faults, feature syn- and post-sedimentary movements. In the orebody, mineralisation is typically disseminated along interstratal joints, or along karstic and/or faulted zones. Galena is usually automorphic and cubic, but often appears oxidised and partially or totally replaced by cerussite and anglesite. Pink and white barite crystallise in open cavities, following galena deposition.

Mineralisation has also been identified in the Cretaceous formations of the Upper Moulouya district. For example, baritic matrix and microkarstic cavities in calcareous pebbles occur in the Cretaceous conglomerate (the "infra-Cenomanian horizon") structurally above the Mibladén deposit near the Amourou fault; baritic cement results from a late, post-pebble deposition hydrothermal event. Also, barite is associated with minor galena in the Cretaceous Assaka Ijdi graben, directly in contact with the Aouli granite, and galena has been mined regionally in the Cretaceous units of the Upper Atlas mountains (Emberger 1965; Felenc and Lenoble 1965; Caia 1976).

In Mibladén, Dagallier and Macaudière (1987) suggested that ore is associated with diagenetic processes near the surface and related to the early stages of dolomitization. However, post-diagenetic structural controls on the mineralisation (i.e. brittle faults) preclude such an interpretation. The porosity of the ore-hosted system was therefore formed prior to the introduction of the mineralising solutions which invaded an already well-developed karst system that acted as a major aquifer. This situation is similar to that demonstrated in the Mascot-Jefferson City district, Tennessee (Haynes and Kesler 1994).

Timing of the mineralisation is not precisely known. Mineralisation is overprinted by barren faults which do not cross-cut the Cretaceous conglomerate, therefore implying a pre-Cretaceous age for some part of the mineralisation (Emberger 1965). The age of the oxidation event remains unknown, but could be related to the descent of an oxidising fluids following the deposition of the Cretaceous sediments.

Isotopic studies

Lead isotopes analyses of galena and feldspars from the Upper Moulouya district were performed at the Geotop laboratories, of the Université du Québec à Montréal, on a VG Sector mass-spectrometer, using single collector and thermal ionization. Analytical methods are given in Fariss (1992). Sulphur isotope analyses of galena were performed at Carleton University, Ottawa, using classic methods. Results are summarised in Table 1.

Lead isotopes

Lead isotope results for Pb-ore galenas and Aouli granite K-feldspars are presented in Fig. 3. Galenas compositions range from 18.11 to 18.27 for $^{206}Pb/^{204}Pb$ ratios, from 15.60 to 15.64 for $^{207}Pb/^{204}Pb$, and from 38.24 to 38.58 for $^{208}Pb/^{204}Pb$. The Upper Moulouya mineralisations define a restrained isotopic field on $^{206}Pb/^{204}Pb$ versus $^{208}Pb/^{204}Pb$ and $^{206}Pb/^{204}Pb$ versus $^{207}Pb/^{204}Pb$ diagrams, indicating a fairly homogeneous isotopic compositions. These galenas are isotopically distinct from those of the Central Morocco ores (Nasloubi et al. 1992). The sample from the Cretaceous Assaka Idji graben also features a distinctive signature, with higher $^{206}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ ratios (18.76 and 39.71 respectively). Compared to values compiled by Touahri (1995), this value is the highest ratio measured in sulfides from the base-metal deposits of Algeria and Morocco. For all other galena samples, two groups may be distinguished on a $^{206}Pb/^{204}Pb$ versus $^{207}Pb/^{204}Pb$ plot: (1) Aouli veins and Zeïda mineralised arkoses which display clustered $^{206}Pb/^{204}Pb$ ratios between 18.11 and 18.25; and (2) the Mibladén deposit which shows slightly higher $^{206}Pb/^{204}Pb$ isotopic ratios (>18.26). On a $^{206}Pb/^{204}Pb$ versus $^{208}Pb/^{204}Pb$ diagram, the results plot significantly above the reference curve of Stacey and Kramers (1975) (Fig. 3). This implies isotopic evolution in a fairly normal continental crust. K-feldspars compositions are significantly lower than those of galenas: measured compositions range from 17.94 to 18.08 for $^{206}Pb/^{204}Pb$ ratios, from 15.51 to 15.585 for $^{207}Pb/^{204}Pb$, and from 37.78 to 38.15 for $^{208}Pb/^{204}Pb$. Due to very low μ ratios of these minerals, correction for in-situ radiogenic enrichment are negligible.

Sulphur isotopes

Combined sulphur and lead isotope for Pb-ore galenas are presented in Fig. 4. A negative correlation is evident, and sulphur isotope values also show a clear distinction between the Aouli-Zeïda deposits ($\delta^{34}S$ between $-10‰$ and $+3‰$) and the Mibladén deposit ($\delta^{34}S < 15‰$). These signatures confirm the presence of two generations of mineralisation in the area. Results indicate that the sulphur in the mineralising fluid was of similar origin

Table 1 Lead and sulphur isotopes compositions of the galenas from Aouli, Mibladén and Zeïda deposits, and lead isotope compositions from the K-feldspars of the Aouli granite (measured ratios, correction for in situ radiogenic enrichment being negligible)

Deposit	Sample	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$	$\delta^{34}S$
Aouli (Engill)	MN 47	18.221	15.613	38.448	
Aouli (Sidi Said)	MN 61	18.170	15.627	38.386	
Aouli (Sidi Ayad)	MN 80	18.237	15.602	38.390	−9
Aouli (Sidi Ayad)	MN 81	18.246	15.613	38.425	
Aouli (Henry)	MN 100	18.127	15.607	38.373	−3.1
Aouli (Henry)	MN 101	18.153	15.610	38.415	−7.6
Aouli (Ansegmir granite)	MN 123	18.179	15.610	38.372	
Aouli (George)	MN 127	18.210	15.601	38.370	−7.7
Aouli (George)	MN 128	18.210	15.621	38.393	1.2
Aouli (Sidi Said)	MN 132	18.208	15.624	38.394	1.5
Aouli	Engil 1010	18.110	15.630	38.530	
Zeïda	MN 130	18.214	15.613	38.412	−7.2
Zeïda	MN 131	18.214	15.622	38.409	
Mibladén (South)	MN 2	18.266	15.623	38.480	−14
Mibladén (West)	MN 3	18.272	15.638	38.526	−20.5
Mibladén	AD 5	18.230	15.620	38.580	
Mibladén	second layer	18.120	15.570	38.300	
Mibladén	S	18.150	15.570	38.400	
Mibladén	T	18.240	15.630	38.500	
Mibladén	Bou el Maden	18.200	15.610	38.410	
Mibladén	Bou el Maden	18.150	15.570	38.240	
Mibladén (Cretaceous)	MN 95	18.763	15.992	39.706	
K-feldspar	MNA RES	17.943	15.577	38.136	
	MNA LES	17.961	15.548	38.002	
	MNG RES	18.027	15.585	38.147	
	MNG LES	18.018	15.525	37.901	
	MNP RES	18.083	15.584	38.042	
	MNP LES	18.060	15.511	37.784	
	MNR RES	18.039	15.570	38.011	
	MNR LES	18.041	15.563	37.986	

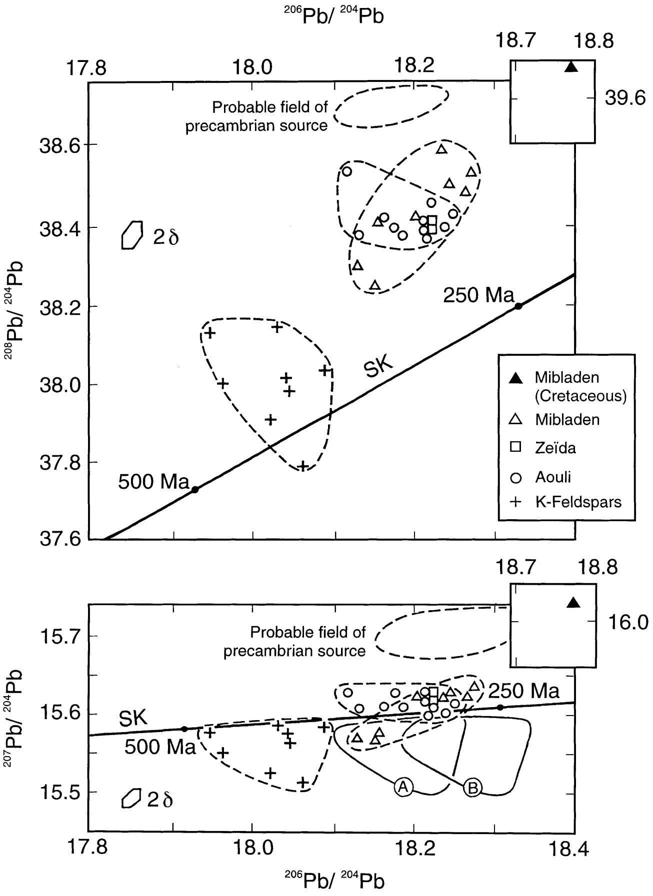


Fig. 3 Lead isotopes diagrams for the different types of lead ore and for K-feldspars from the Aouli granite in the Upper Moulouya district. The *reference curve* of Stacey and Kramers (1975) is shown for comparison (*SK*). Fields *A* and *B* are compositional fields of Aouli granite at 230 and 180 Ma respectively, using $\mu = 9.74$

for the Aouli and Zeïda deposits, although paragenetic studies emphasise the greater geochemical diversity of the hydrothermal solution at Aouli (Table 2). Such differences may be explained by several processes, including: (1) different hydrothermal paths (e.g. through rocks with contrasting compositions), (2) a higher flow rate in the vein systems, or (3) lower temperature conditions in the Zeïda hydrothermal system. However, the combined isotopic sulphur and lead data suggest that the Aouli and Zeïda deposits represent the same hydrothermal event occurring in two domains of different permeability. The same relationship has been observed in southwest Germany where vein-hosted galenas in the basement rocks and sedimentary galenas in the Upper Triassic formations have the same Pb isotope ratios (Gehlen 1987).

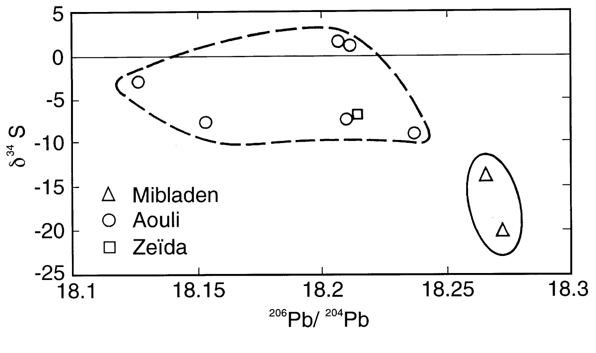


Fig. 4 Plot of $^{206}Pb/^{204}Pb$ isotope ratios versus sulphur isotopes ratios for galena in the Upper Moulouya district

Table 2 List of minerals present in the Aouli, Mibladén and Zeïda deposits, compiled from Emberger (1965), Felenc and Lenoble (1965), Bouçanna and Saaidessalam (1980) and Nasloubi (1993)

Minerals	Aouli	Zeïda	Mibladén
Barite	+	+	+
Calcite	–	+	+
Dolomite	–	–	+
Quartz	+	+	+
Fluorite	+	–	
Galena	+	+	+
Cerussite	–	+	+
Anglesite	–	–	+
Phosgenite			–
Pyromorphite		–	–
Vanadinite		–	–
Wulfenite	–	–	–
Paralaurionite			–
Minium		–	–
native Ag	–		
native Bi	–		
Sphalerite	+		
Covellite	–		
Chalcocite	–		
Chalcopyrite	–	–	–
tennantite-tetrahedrite serie	–		
Cuprite	–		
Malachite	–	–	
Azurite	–	–	
Arsenopyrite	–		
Niccolite	–		
Pyrite	–	–	–
Marcasite	–		
Hematite	–	–	
Geothite	–		
Ankerite	–		

At Mibladén, the sulphur isotope signature shows enrichment in ^{32}S. Sulphur isotope fractionation is controlled by the presence of organic compounds, as well as variations in pH, oxygen and sulphur fugacities, and temperature (Ohmoto 1986). Thermochemical reduction of sulfate under basinal conditions has also been advocated by Orr (1974) and Goldhaber and Nicholson (1993).The most important cause for variations in the isotopic composition of sulphur is the reduction of sulphate ions by anaerobic bacteria, which produces ^{32}S enrichment at low temperatures during the diagenesis (Berner 1984; Sverjenski 1988). The low $\delta^{34}S$ values at Mibladén suggest that the galena may have precipitated as a result of bacterial activity within the carbonaceous shales horizons of the platform sequence.

Discussion

Time of deposition

Field arguments and lead isotope studies suggest that the lead mineralisations in the Upper Moulouya area have been deposited during two different major events. With respect to geological arguments, lead deposition in the Aouli district appears to be of Upper Triassic to Lower Jurassic in age. This age also seems probable for the Zeïda deposit. On the other hand, the age of the Mibladén deposit is more poorly constrained. Mibladén's epigenetic characteristics and slightly more radiogenic lead (within a U-poor host rock) could support a younger age of deposition than at Aouli-Zeïda. The presence of some galena within the Cretaceous conglomerate have also suggested than the mineralizing process was, at least partly, of post-Cenomanian age (Bouladon 1956). If the Mibladén deposit was deposited at the same time as the MVT-deposits of the Pays des Horsts area or of the Betic Cordillera (Arribas and Tosdal 1994; Bouabdellah et al. 1995), it could be as young as Miocene, and possibly related to the alkaline magmatism during the Atlasic orogeny. Two features, however, do not fit with this hypothesis: (1) even if they are located in the same type of rocks, Cretaceous-hosted galena-lead is much more radiogenic than the Jurassic-hosted galena-lead, and clearly indicates that these two mineralisations cannot have resulted from the same hydrothermal event, and (2) structural field evidence reported by Emberger (1961, 1965) precludes an age younger than Cretaceous, although detailed work using a modern structural geology approach is needed to confirm this hypothesis.

To summarise, the Bouladon (1956) hypothesis of only one stage of mineralisation should be abandoned. The Upper Moulouya ore deposits have been deposited during several events following the Hercynian orogeny. Three stages are suggested:

1. A major phase of Triassic mineralisation at Aouliend Zeïda;
2. A second major phase of Jurassic mineralisation in Mibladén;
3. A limited in size, slightly post-Cretaceous remobilization of the lead in the Cretaceous sediments.

Source of lead

The Aouli granite has been considered by several authors as the principal lead source for the Upper Moulouya district (Emberger 1965; Schmitt 1976). K-feldspars from the granite have lower $^{206}Pb/^{204}Pb$ ratios (<18.1) than the galena of the ore deposits. Nevertheless, the granite as a whole is considered to be the possible source-rock, and not only the K-feldspars. Thus, in order to assess the possible relationship between the granite and the ore, it is necessary to calculate the isotopic values of the granite at 180 Ma and 230 Ma (respectively minimum and maximum ages of the mineralisation) by considering the in-situ decay of U and Th in the granite. The following equation is used:

$$\alpha_{t2} = \alpha_{t1} + \mu(e^{\lambda t1} - e^{\lambda t2})$$

where:

α_{t1} = initial $^{206}Pb/^{204}Pb$ at $t1$ (measured in K-feldspars)

α_{t2} = $^{206}Pb/^{204}Pb$ at $t2$

$t1$ = estimated granite age (330 Ma; Oukemeni et al. 1995)

$t2$ = minimum and maximum host-rocks ages (180 Ma for Mibladén; 230 Ma for Ze)

μ = $^{238}U/^{204}Pb$ (9.74, using the average mean continental crust (Stacey and Kramers 1975; Michard-Vitrac et al. 1981).

$\lambda = 0.155125.10^{-9}$/year = desintegration constant.

Pb-Pb diagrams (Fig. 3) show an obvious displacement of the feldspar fields depending on the age of the ore emplacement. If the emplacement of the ore occurred at or after 160 Ma, no compatibility between ore and granitic lead is observed in the $^{206}Pb/^{204}Pb$ versus $^{207}Pb/^{204}Pb$ diagram. A good concordance is observed between lead from the Aouli-Zeïda ores and from the granite feldspars at about $t2 = 230$ Ma (Triassic). The implications are twofold: (1) the granite may have been the main source of lead for the Aouli and Zeïda deposits, by leaching of feldspars around 230 Ma, (2) a complementary lead source is required in order to explain the $^{208}Pb/^{204}Pb$ ratios, and this source would have had a high $^{207}Pb/^{204}Pb$ ratio at the time of mineralisation. Highly radiogenic Precambrian crustal rocks are well known further south in the Saharian domain, but they do not outcrop in the Upper Moulouya district. However, geological and seismic data indicates that such a basement may constitute a large part of the continental crust under the area (Makris et al. 1985; Jacobschagen et al. 1988). Moreover, the Aouli pluton contains inherited Middle to Upper Proterozoic components which have been dated at 1245, 1520 and 1804 Ma (Oukemeni et al. 1995). Therefore, the second lead source may have been a deep crustal Proterozoic basement.

During Triassic time, a major NE-striking detachment fault inherited from the large thrust planes of Hercynian age was reactivated and controlled the location of the detrital basin. Permeability along detachment and normal faults could have provided a pathway for the fluids allowing leaching of the deep Precambrian rocks and the granitic intrusions (Fig. 5). Such faults could be initiated by gravitational sliding in response to abnormal pore pressure in tilted strata (Shelton 1984). In the middle crust, failure may result from instabilities related to asymmetric loading of the crust at the contact zone between dense gneissic-amphibolitic and less dense granitic domains. Abnormal pressure may have initiated expulsion of hot, lead-bearing fluid from the deep Precambrian basement. Mixing probably occurred at depth and the relative homogeneity of the lead isotopes suggests that mixing was complete at the site of ore depo-

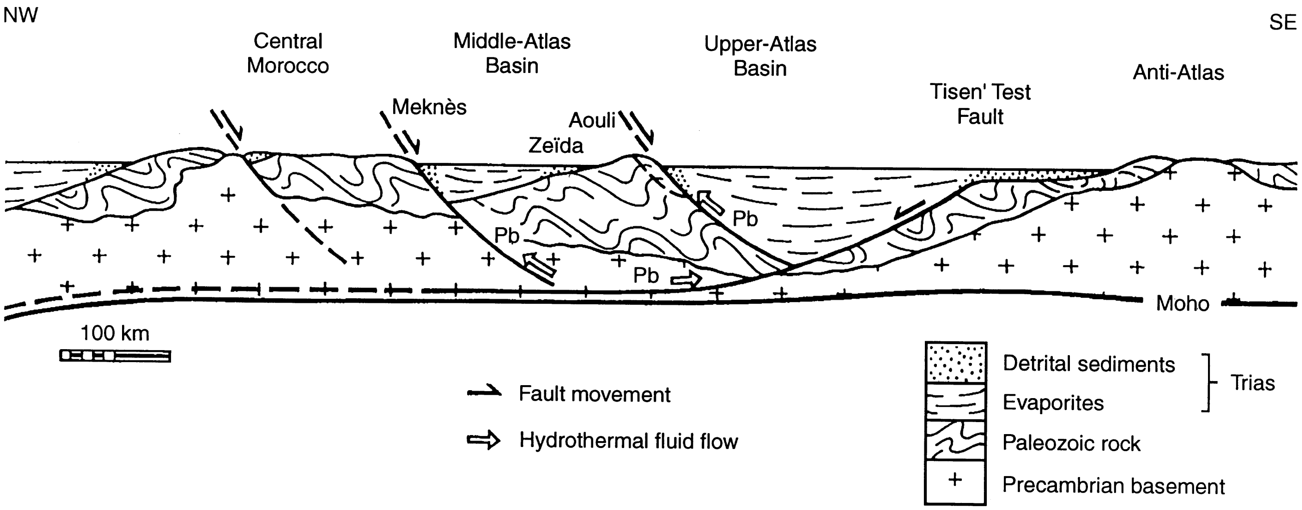


Fig. 5 Metallogenic model for the Aouli-Zeïda lead-silver deposits. The section shows the probable crustal framework at the end of the Hercynian orogeny during the Late Triassic extension, with thick basins filled with detrital and evaporitic sediments. The geometry of the faults is based on the geophysical surveys of Jacobschagen et al. (1988). Vertical scale greatly exagerated

sition. This result is slightly different from the Pyrennés district where synchronous metal events occurred at a smaller scale, but with only partial fluid mixing (Johnson et al. 1996).

Arribas and Tosdal (1994) documented Pb isotopic compositions of galenas from large deposits across Southern Europe. The Aouli-Zeïda lead isotope signatures are similar to those of a group of mainly stratabound F-Pb-Zn-(Ba) deposits in Triassic rocks, such as Gador (Spain), Les Malines (France), Bleiberg and Lafatsch (Austria), Salafossa, Gorno and Raible (Italy), and Mezica (Slovenia). Lead isotope ratios in galenas from the Upper-Moulouya district are slightly lower than the El Abed deposits in Algeria (Touahri 1995): 18.2 versus 18.3 for $^{206}Pb/^{204}Pb$ and 15.60 versus 15.63 for $^{207}Pb/^{204}Pb$. However, the source for all these deposits could have been in the Late Precambrian to Devonian clastic metasedimentary sequences which dominate the Vendée- Cévennes- Dorsendorf terrane (Matte 1991). In this case, the Upper Moulouya district could represent leaching of the old basement, probably initiated by hydrothermal convection associated with Mesogean and Atlantic rifting, and deposition in vein-type or stratabound deposits within the upper crust.

The correlation between the lead and sulphur signatures of the galenas in the Upper Moulouya deposits can be interpreted as an indication of mixing between two main distinct sources, such as the mixing of a deep-seated hydrothermal solution with a more surficial fluid, the latter leaching the Aouli granite. Another illustration of this process can be found in the varied parageneses in the different showings within the Aouli district (Table 2). For instance, fluorite is more abundant in veins within or near the granite, and may indicate variations in the composition of the surficial fluid which is strongly dependant on local equilibria.

The Mibladén mineralisation differs slightly from the Aouli-Zeïda mineralisation and was formed later. Lead isotope for galena results are almost similar to that of the Pays des Horsts district, especially the main galena-dominated ore (Bouabdellah et al. 1995). This allows us to interpret the mineralisation as corresponding to a second pulse of hydrothermal input, or to the remobilization or secondary leaching of the Aouli and/or Ze deposits. The migration of a second hydrothermal fluid may have been related to the tectonic phase associated with the closure of the Tethyan basin during Middle Jurassic time (Charrière 1996) or to a more recent event such as the Atlas deformation. The high $\delta^{32}S$ values for galena could reflect the presence of local fluid formed during diagenesis in an organic-rich low temperature medium.

Relations between the three types of Pb-mineralisation

The Upper Moulouya district displays economic vein-type, sandstone-hosted, and MVT deposits. Field geology and stable isotopes demonstrate that the vein and sandstone-hosted deposits were deposited during the same geological period by solutions derived from the same sources. Their mutual relationship resembles the fluorite-barite deposits of the Massif Central (France), where a geometric continuity can be demonstrated at Chaillac between vein-type deposits in the Hercynian basement, and arkosic sandstone-hosted mineralisation in the Lower Jurassic cover (Yaman et al. 1978; Ziserman 1980; Lhégu et al. 1988). As in Chaillac, the Pb-deposits of the Upper-Moulouya area feature different parageneses indicating small variations in the fluid chemistry, probably related to mixing between local and deep sources. As in other low temperature vein-type deposits, these deposits reflect the role of basement fault zones and permeability heterogeneities as major controlling factors.

Sandstone-hosted and carbonate-hosted deposits reflect different metallogenic events in the Upper Moulouya district. Both of them are probably related to basin brine migration (Bethke and Marschak 1990; Romer 1992; Schrijver 1992), but at different times during the Atlasic basin evolution. The Zeïda deposit formed in association with half-graben formation and detachment faulting during the early opening stages of the basin. Hydrothermal fluid flow could have been provoked by fluid buoyancy related to a thermal event during lithospheric thinning (as indicated by the basaltic volcanism), or by a modification of the hydraulic head associated with differential uplift which produced gravity-driven fluid flow. The former hypothesis is preferred because hydrothermal convection would have permitted more effective leaching of the granitic rocks. However, both mechanisms remain possible and evidence for hydrothermal fluid flow should be sought in the Upper Atlas mountains.

The Mibladén deposit was formed during a later stage of the Atlasic orogeny, probably at a time when fluids were mostly topographically driven. A similar situation occurred in the southern Appalachians where contrasting lead isotope signatures in galena reflect two major paleoaquifers (Kesler et al. 1994; Jones et al. 1996). It is therefore probable that the difference in radiogenic lead in galena is reflecting the connectivity of the plumbing system and hydraulic gradients during a specific time interval.

Conclusions

The Upper Moulouya area offers the possibility of deciphering the relationship between three main types of lead ores in the Hercynian domain: (1) vein type deposits hosted in the Hercynian basement, (2) sandstone-hosted and (3) carbonated-hosted stratabound mineralisations in the Mesozoic cover.

The Aouli vein-type and Zeïda sandstone-hosted strata-bound mineralisations are formed by a mixing of two fluids, one coming from the leaching of the Aouli granite massif, and the other from the leaching of the Saharian basement. These deposits could correspond to the same Triassic metallogenic event, expressed by either the fault system or the sandstone permeability. Deep fluids were mobilised during the early extensional movements associated with the opening of the Atlasic rifting basin. The principle mechanisms involved may have been a modification of the hydraulic head as a result of the differential uplift, or more probably, a thermal convecting event in relation to the basaltic volcanism. The MVT Mibladén mineralisation is related to a distinct metallogenic event superimposed on an earlier one.

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