

Fossil and present-day hydrothermal fluids from North Tunisia: an example of a dynamic fluid evolution

Fluidos hidrotermales fósiles y actuales del Norte de Túnez: un ejemplo de una evolución dinámica de fluidos

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Abstract

More than 95% of metals extracted in Tunisia derive from ore deposits emplaced in three important structural zones located in the North of the country. Geological studies of carbonate-hosted F-Ba-Zn-Pb mineralizations and from the actual thermal sources show that they are associated with main fault systems. The present-day E-W, NE-SW and N-S active fault systems correspond to pathways for fluid circulation and it is also most likely that these systems corresponded also to the main channels for mineralized palaeosystems. To investigate the relationship between fossil fluids, trapped in fluid inclusions (FI) from ore minerals and different calcite generations, and present-day deep groundwater, their physical and chemical characteristics were studied and compared. The hydrothermal fluids and their changes with time and space are compatible with a multiphase and dynamic fluid evolution assumed as responsible, in the past, for the generation of ore deposits. The results may contribute to develop a new strategy in Pb-Zn deposits mineral exploration in northern Tunisia.

Key words: fossil hydrothermal fluids, carbonate-hosted F-Ba-Zn-Pb mineralization, present-day hydrothermal fluids, Tunisia

INTRODUCTION

Northern Tunisia can be considered as subdivided in three structural zones: a "nappe" zone, a diapir zone and an oriental zone. More than 95% of the metals extracted in the country are distributed in ore deposits within these zones.

The geology shows that the multiphase tectonic events played an important role in the sedimentation and structuring of the Northern part of Tunisia. The tectonic history is very complex. For this reason and the scarcity of deep drilling, the knowledge of the basin and its evolution is incomplete and we cannot demonstrate the existence of the necessary stock metal for the formation of the Tunisian ore deposits (SHEPARD *et al.*, 1996).

Ba-F-Pb-Zn mineralization hosted in carbonate rocks is very common in Northern Tunisia. The Hammam Zriba (HZ) and Bou Jaber (BJ) deposits are typical of this mineralization type, which has a simple mineralogy comprising barite, galena, sphalerite and fluorite (AMOURI 1986; BOULHEL *et al.* 1988). Several authors have proposed that these Pb-Zn-Ba-F ore deposits are of Mississippi Valley Type (MVT) (e.g. ROUVIER *et al.*, 1985; CHAREF & SHEPPARD, 1987) and consequently associated with basin margins (BRADLEY & LEACH, 2003). The important Pb-Zn quantities were concentrated by hydrothermal fluids, which leached a large area of the sedimentary basin (ANDERSON & MACQUEEN, 1982) or could result from a polyphasic and dynamic fluid evolution on a limited basin area (CATHLES & SMITH, 1983).

The present-day E-W, NE-SW and N-S active fault systems correspond to pathways for fluid circulation and mineral deposition. The geological studies of fifteen present day

thermal water emergences in northern Tunisia show that hot fluids emerge on these main fault systems. TEBIB HLALI (1992) proved that the emergency position can move from one place to another and this moving can be of some kilometres.

In the fractures spatially associated with the main fault systems, which may correspond to ancient emergencies, occur calcites resulting from older thermal fluids.

Trapped fluids in fluid inclusions (FI), from the different ores and different calcite generations, provide valuable information on the evolution of the thermal fluid physical and chemical compositions in time and space. Most likely these systems correspond also to mineralizing palaeosystems.

In this work the present-day and fossil hydrothermal fluids characteristics were studied and an evaluation of their changes with time and space (dynamic systems) is presented. The study was carried out on several sites distributed over the three structural zones and characterised by the occurrence of ore deposits and/or thermal springs: 1) Dhaoui, H. Bourguiba and Kef-Ettout from the «nappe» zone; 2) Mellègue, Biadha, and Bou Jabeur from the diapir zone; and 3) Hammam Zriba, Jedidi, Oust, Korbouss from the oriental zone (Fig. 1). Based on macroscopic, microscopic and geochemical studies we have established a classification of calcites occurring, near the thermal springs, in the main fracture systems.

The deposition of different of calcite generations corresponds to a dynamic evolution of a hydrothermal system similar to the mineralizing paleosystem. The results will contribute to develop a new strategy in Pb-Zn deposits mineral exploration in Northern Tunisia considering other criteria than the sedimentary ones.

GEOLOGIC SETTING

Northern Tunisia is subdivided in three structural zones (Fig. 1):

(1) The “Nappe” zone, mainly composed of Cretaceous and Oligo-Miocene flysch-type sedimentation, forms the Tell Atlas thrust belt;

(2) The “Diapir zone” characterized by several outcrops of the Triassic evaporitic formation over 300km along the NE-SW trending belt. The Triassic formation is brought to the surface by the Atlasic tectonic events. It is composed of highly deformed evaporitic lithologies consisting of chaotic mass of gypsum, anhydrite, halite, marls, sandstones and carbonates. The post Triassic formations comprise limestones, sandstones and marls.

(3) The Oriental zone is a horst-graben with sediments dominantly composed by limestones, marls and some volcanic rocks.

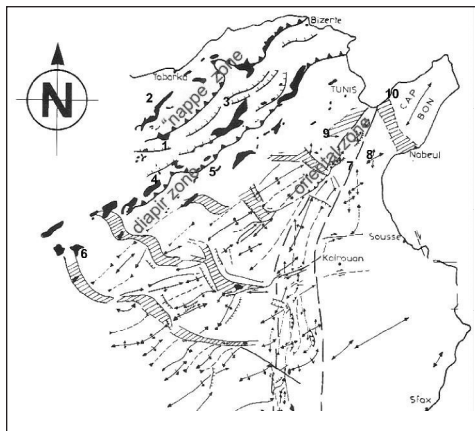


Figure 1: Tectonic map of North Tunisia, after: Bedir & Zargouni, 1986 (Modified). Location of the studied sites: 1- Dhaoui, 2- H. Bourguiba, 3- Kef-Ettout, 4- Mellègue, 5- Biadha, 6- Bou Jaber, 7- Hammam Zriba, 8- Jedidi, 9- Oust, 10- Korbouss

The actual structures in North Tunisia are the results of major dynamic episodes:

(1) During the middle Triassic to early Cretaceous times, rifting affected the northern part of the Tunisian Atlas (PERTHUISOT, 1972, BÉDIR et al. 2001); this Thetyan rifting was controlled by Hercynian E-W, N-S, NW-SE and NE-SW faults;

(2) During the Cretaceous and Cenozoic, compressive and transpressive Pyrenean and Alpine collision affected all North Africa. The main NE-SW structural trends were similar to those of Mediterranean Hercynian. During this period, explosive magmatism and/or major vertical faults affected both basement and sedimentary basins (BOUAZIZ et al. 2002);

(3) A post-Lower to Middle Pleistocene compressive phase and an extensional strike-slip faulting of Tyrrhenian age, reactivated the E-W trending faults (AMARI & BEDIR, 1989; ZOUARI, 1995).

E-W, N-S, NW-SE and NE-SW faults are well observed in all Tunisia except the N-S fractures in the extreme North. Therefore, these fault systems were active during the different tectonic events since the Triassic period. During extensional deformations, salt movement controlled sedimentation distribution (JALLOULI et al. 2005; ZOUAGHI et al. 2005).

The timing of the main episode of ore deposition in Tunisian deposits is not clear; some authors proposed that it was coeval with a period of subaerial karstification during the lower to middle Cretaceous (THIEBIEROZ, 1974; TRUILLET, 1981; AMOURI, 1986), while others consider that it will be unlikely due the tectonic control and/or to the rising trapping temperatures of aqueous fluids associated with fluorite and admitted a Cenozoic age for the hydrothermal karsti-

fication event (GHARBI *et al.* 1981; BEN-CHILLA *et al.* 2003).

The Hammam Zriba (HZ) F-Ba deposit, in the oriental zone, and Bou Jaber (BJ) Pb-Zn-Ba-F deposit in the “zone of the domes” or diapir zone are examples of ore deposits in areas affected by E-W, NE-SW and NS faults.

The deposits of the “province fluorée tunisienne”, such as HZ and Jedidi, are located near a very important structural lineament (NE-SW) corresponding to the Zaghouan fault and consequently in the proximity of the “Jurassic Tunisian dorsal” defined by outcrops of Upper Jurassic limestones. The latter design also a geomorphological alignment (about 70 km) of several mounts (“djebels”). The Zaghouan Djebel is a massif with about 9 km length and 3 km width and corresponds to the second highest summit of Tunisia (1295 m).

The HZ stratiform CaF_2 deposit was the most important of the “province fluorée tunisienne”. The stratigraphy of the area comprises a series of sedimentary rocks from the Tithonian to the upper-Eocene with a hiatus from the Berriasian to the middle-Campanian, corresponding to an emersion period (THIEBIEROZ, 1976). The ore body bed is situated between parareciful massif limestones of Tithonian age, at the bottom, and marls alternating with limestone bankets of middle to upper-Campanian age. The local geology corresponds to a horst striking NNW-SSE limited mainly by two normal faults: one (F1) striking N135°E to N145°E and dipping 50 to 70°NE and another (F2) striking N130°E to N150°E and dipping 50 to 70°SW (GHARBI *et al.* 1981). The sector of HZ is also characterized by present-day seismicity and the existence of a thermal source.

BJ is located, about 250 km West-southwest of the Tunisian capital and 6 km south of the small village of Kalaat-es-Sunam near to the Algerian border, in the “Diapir zone”. The deposit occurs in karst cavities within Aptian limestones and in a N75E fault at the contact between Aptian limestones and Cenomanian black marls (AMOURI, 1986).

Both mineralized areas are characterized by the occurrence of regional faults; some of these are still active and associated with hot springs.

The actual thermal springs are spatially associated with E-W, NE-SW and N-S faults (TEBIB HLALI, 1982; SADKI, 1998). In fractures associated with these faults and in vicinity of thermal springs some veins and vein lets of calcite were found (CHAREF *et al.* 2007).

SAMPLING AND ANALYTICAL TECHNIQUES

To characterize the fossil hydrothermal fluids, petrography and FI studies were carried out on barites and fluorites from HZ and BJ and on calcites collected from the E-W, NE-SW and N-S fractures in the areas surrounding eight thermal springs. Non-destructive methods were applied: microthermometry and micro-Raman spectroscopy. Microthermometric characterisation of FI (ROEDDER, 1984) was performed on doubly polished thick sections (<300 μm) using a “Chaixmeca” freezing stage (POTY *et al.* 1976) and a “Linkam 600” heating stage (SHEPHERD 1981). Both stages were calibrated using natural and synthetic FI. The salinities of FI and the salinities of geothermal emergences are presented in wt.% eq. NaCl. The volatile phase composition (CH_4 , CO_2 and N_2) was analysed by micro-Raman

Spectroscopy using a Labram Dilor-Jobin spectrometer with a He-Ne laser excitation source of 632.8 nm.

For the study of actual hydrothermal fluids, samples of 100 ml of present-day thermal water were collected in polyethylene bottles, filtered using 0.45 μm Millipore membranes, and finally acidified to 1% with nitric acid and the samples were stored at 4°C. Subsequently they were analysed by Atomic Absorption Vario type with graphite furnace and their free gases following the Morette method using Gas Chromatography (MORETTE, 1966).

RESULTS

Mineralogy

At HZ, the mineral assemblage is very simple, mainly composed by barite and several types of fluorite; however, we find some galena, sphalerite, calcite and quartz.

At BJ, mineralization is composed of barite, sphalerite, galena, pyrite, fluorite and calcite. There are two main types of

ores: i) intrakarst massive ore with sulphides (sphalerite and galena), ankerite, barite and fluorite; and ii) fault-controlled “vein” ore composed of sphalerite, galena, barite and violet fluorite. Several types of barite can be distinguished: i) white, radial fibrous, remobilised barite; ii) barite rich “rubané” ore (BJ BII) and iii) well-developed white or transparent barite crystals in the footwall of the massive ore (BJ BIII).

Field observations showed that near the present-day thermal springs occur coloured calcites that precipitate symmetrically at the edges of extensional fractures (Fig. 2). In the E-W fractures precipitate up to four duplicated generations of calcite (Ct1, Ct2, Ct3, Ct4 and Ct'1, Ct'2, Ct'3, Ct'4, respectively). In the NE-SW fractures, a symmetrical distribution of different generations of calcite was observed. These calcites presented different colours controlled by the amount of iron oxides present in the crystal. Petrographic observations showed that Ct1, Ct2, Ct3 and Ct4 are equivalent to Ct'1, Ct'2, Ct'3 and Ct'4, respectively.

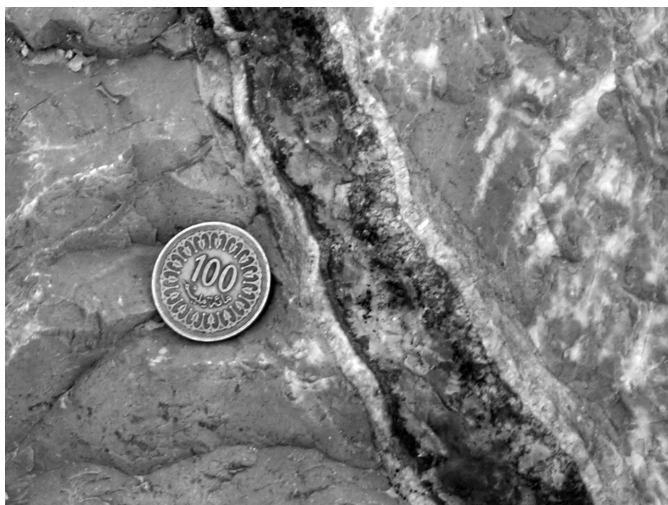


Figure 2: Fracture with different generations of calcite (Hammam Zriba).

Calcite geochemistry

Trace element analysis of Cu, Fe, Sr, Ni, Co and Al were carried out on the different types of calcite.

In Tables 1 it is shown the compositional results of calcites from E-W and NE-SW fractures from Jedidi and Biadha areas.

E-W Jedidi faults	Cu	Fe, %	Sr	Ni	Co	Al
Ct1	15	5.41	680	145	165	4600
Ct1'	13	6.56	553	125	138	4300
Ct2	6	1.23	1021	103	82	507
Ct2'	5	1.16	1120	98	23	465
Ct3	0	2.15	134	4	132	1080
Ct3'	0	1.45	340	0	105	932
NE-SW Jedidi faults	Cu	Fe, %	Sr	Ni	Co	Al
Ct1	9	1.60	1750	178	185	580
Ct2	0	-	406	0	95	1230
E-W Biadha faults	Cu	Fe, %	Sr	Ni	Co	Al
Ct1	10	0.20	435	23	12	630
Ct1'	7	0.50	209	27	15	850
Ct2	14	0.96	1649	254	31	1023
Ct2'	12	0.95	1229	157	42	1043
Ct3	4	0.11	677	24	113	669
Ct3'	3	0.35	749	14	98	436
Ct4	45	0.26	645	18	13	662
Ct4'	61	0.21	864	12	6	306
NE-SW Biadha faults						
Ct1	45	2.60	980	98	65	480
Ct2	0	-	2630	5	45	1131

Table 1: Mean trace element concentrations of different calcite from Jedidi and Biadha faults (values in ppm).

In the E-W faults, the calcites Ctn have similar composition to their symmetrical Ctn' but several differences between each layer.

In Ct1 and Ct'1 from Jedidi (Tables 1), a high content of Al (4300 to 4600 ppm) and Fe (~5%) and low contents of Sr (553 to 680 ppm) were found. On the contrary, the Ct2 and Ct'2 had low content of Al (465 to 507 ppm) and Fe (1,16 to 1.25%) but high content of Sr (1021 to 1120 ppm). However, regarding Ct1 and Ct2 from Biadha we found higher contents of Al and Sr in Ct2 and lower contents in Ct1.

Fluids characterization

Fossil fluids (Fluid inclusions)

Ore minerals

FI studies were carried out on barite and fluorite from HZ and BJ. Aqueous and immiscible petroleum-rich FI were observed in both HZ and BJ deposits. Additionally, in BJ ore deposit, carbonic and aqueous-carbonic fluids were also observed. In both ore deposits a wide variation in the composition of primary aqueous inclusions (found isolated or in the crystals growth zones) was observed.

The fluids showed a wide range of salinities (HZ: 3.1 to 25.2 wt.% eq. NaCl; BJ: 1 to 26.2 wt.% eq. NaCl). In the immiscible petroleum-rich FI liquid, the aqueous phase composition was very similar to the aqueous FI (HZ: 1.9 to 24.0 wt.% eq. NaCl; BJ: 15.2 to 19.6 wt.% eq. NaCl). Aqueous (HZ and BJ) and petroleum-rich FI (HZ and BJ) exhibit similar homogenisation temperatures (HZ: aqueous FI, 99 to 170°C; petroleum-rich FI, 99 to 142°C; BJ: aqueous, 92 to 213°C; petroleum-rich FI, 102 to 110°C and 149 to 190°C; FI: carbonic, 50 to 120°C; aqueous-carbonic, 120 to 200°C).

Micro-Raman analyses were performed on aqueous-carbonic inclusions from BJ. These fluids present a CO₂ composition from 73.3 to 100 mol% and CH₄ from 0 to 26.7 mol%.

Calcite

FI studies were also carried out on calcites precipitated from fossil fluids. The microthermometric data obtained on calcites showed that all FI homogenize into the liquid phase. The homogenization temperatures (Th) of primary FI range from 44 to 190°C (Table 2).

		E-W		NE-SW		N-S	
Zone	Emergency	Th °C	Volatile phase	Th °C	Volatile phase	Th °C	Volatile phase
	Dhaoui	65 -79	CH ₄ -(CO ₂)	50 -63	(CH ₄)-(CO ₂)		
"Nappe"	H. Bourguiba	71 -84	(CO ₂)-N ₂	44 -52	(CO ₂)-(CH ₄)		
	Kef-Ettout	68 -85	CO ₂ -CH ₄	48 -58	(CO ₂)		
Diapir	Mellègue	73 -103	(CO ₂)-(CH ₄)	48 - 69			
	Biadha	70 -122	CH ₄ -CO ₂ -(N ₂)	47 -72	CH ₄ -CO ₂ -(N ₂)		
Oriental	Jdidi	110 -153	CH ₄ -CO ₂	51 -71	CH ₄ -(CO ₂)	151-190	CH ₄ -CO ₂ -(N ₂)
	Oust	81 -96	CO ₂ -CH ₄	49-62	(CO ₂)	95 -171	CH ₄ -CO ₂ -N ₂
	Korbous	44 -143	CH ₄ -CO ₂	58 -70	(CO ₂)-CH ₄ -N ₂	95-153	CO ₂ -CH ₄

Table 2: Th °C and Raman data of fluids trapped in calcites from different fracture systems surrounding the actual emergencies (trace)

The Th of different generations of calcite did not show systematic decrease or increase. For example at Biadha and Jedidi, in the calcite from the NE-SW fault the Th increased from the first to the second generation (52°C to 69°C, 54°C to 66°C respec-

tively). However, in calcite from E-W fault at Biadha, the Th increased from 101 to 119°C and after decreased to 76°C. At Jedidi, the Th decreased always from the first to third generation (142°C to 115°C, respectively) (Table 3).

E-W Jedidi	Te "First melting °C"	Th °C	Volatiles
Ct1	-63	142	
Ct2	-35 to -25	128	CH ₄ -CO ₂
Ct3	-22	115	CO ₂
Ct4			

NE-SW Jedidi	Te "First melting °C"	Th °C	Volatiles
Ct1		54	CH ₄
Ct2		66	CH ₄ -CO ₂

N-S Jedidi	Te "First melting °C"	Th °C	Volatiles
Ct1		179	
Ct2		145	CH ₄ -CO ₂ (N ₂)

E-W Biadha	Te "First melting °C"	Th °C	Volatiles
Ct1	-58 to -65	101	
Ct2	-22	119	CH ₄ -CO ₂
Ct3	-25 to -38	81	CO ₂ (N ₂)
Ct4	-52	76	CH ₄

NE-SW Biadha	Te "First melting °C"	Th °C	Volatiles
Ct1		52	CO ₂
Ct2		69	CH ₄ -CO ₂

Table 3: The repartition of Te and Th °C (average) and the relative abundance of volatiles in different calcite generations on main fracture systems from Jedidi and Biadha

The salinity of the different FI generations varies between 4.2 and 21.2 wt.% eq. NaCl. At Jedidi in Ct1 the observed T_e of -63°C is close to the eutectic temperature of $\text{H}_2\text{O}-\text{NaCl}-\text{CaCl}_2-\text{MgCl}_2$ system; in Ct2, the T_e ranges from -35 to -25°C which correspond to intermediate eutectic temperature between the $\text{H}_2\text{O}-\text{NaCl}-(\text{KCl})$ and the $\text{H}_2\text{O}-\text{NaCl}-\text{MgCl}_2$ systems; the fluids of Ct3 have a T_e of -22°C which corresponds to $\text{H}_2\text{O}-\text{NaCl}$ system (Table 3).

Concerning the calcites from Biadha E-W fault system, T_e data indicate that the fluid trapped in Ct1, Ct2, Ct3 and Ct4 represent, respectively, the $\text{H}_2\text{O}-\text{NaCl}-\text{CaCl}_2-\text{MgCl}_2$, $\text{H}_2\text{O}-\text{NaCl}$ or $\text{H}_2\text{O}-\text{NaCl}-\text{KCl}$, $\text{H}_2\text{O}-\text{NaCl}-\text{MgCl}_2$ and $\text{H}_2\text{O}-\text{NaCl}-\text{CaCl}_2-\text{MgCl}_2$ systems. Therefore, the T_h variations were also followed by fluctuation of fluid composition (Table 3).

On Figure 3 a T_h – Salinity diagram of FI from HZ and BJ fluorites and from the different calcite generations is presented.

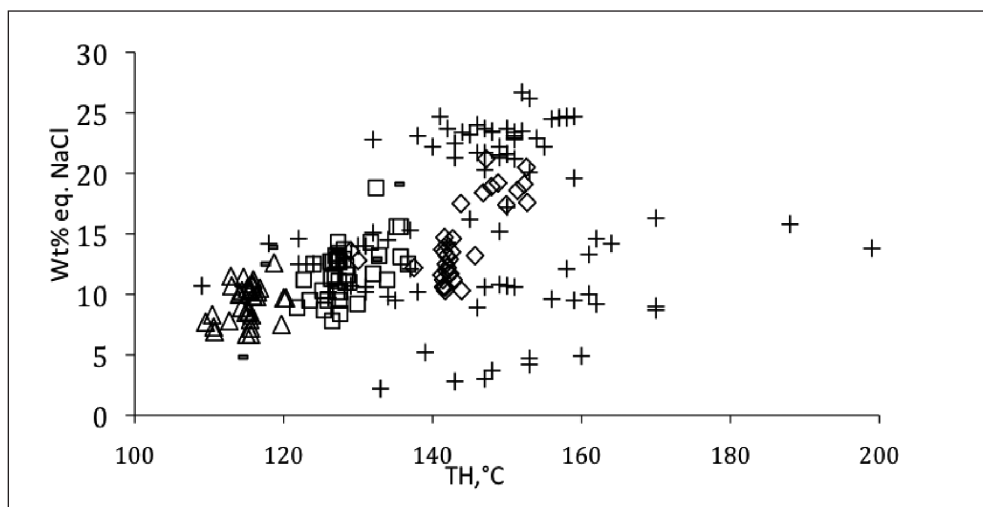


Fig 3: T_h versus Salinity plot of FI trapped in Jedidi calcites from E-W fault system Open triangle - Ct3, Open horizontal square – Ct2 : Open Vertical square – Ct1. Cross – Aqueous fluids from HZ and BJ.

All FI generations were investigated for their volatile content. Due to their small size it is difficult to detect in calcites the carbonic phase by microthermometric analysis. Therefore, to detect the presence of CH_4 , CO_2 and N_2 a micro-Raman spectrometer was used. The results are presented on Tables 2, 3 and 4 and show that the nature of

these compounds in the different calcites is variable within the same fault system.

Present-day geothermal fluids

Water temperature in present-day geothermal emergences, vary between 37 and 58°C and salinities between 0.14 and 6.41 wt.% eq. NaCl (Table 4).

Localities	Present day emergencies					Fluid inclusions	
	Salinity; wt% NaCl	T°C	CH ₄ , ppm	CO ₂ ,ppm	N ₂ ; %V	C compounds	Salinity; wt% NaCl
Dhaoui	5.05	40	10- 30	39-69	<1	CH ₄ - (CO ₂)	7.47
H.Bourguiba	0.14	38	<1	45-76	21 - 31	(CO ₂)- N ₂	0.93
Kef-Ettout	5.99	37	2-10	20-55	30 - 37	(CH ₄)-CO ₂ -N ₂	1.33
Mellègue	0.87	41	<1	<1	<1	-	2.23
Biadha	6.41	41	2350 -3550	45-76	5.5	CH ₄ - CO ₂	8.12
Jedidi	2.01	58	6320-14350	76-87	5.5	CH ₄ -CO ₂	5.26
Oust	1.84	53	1320	127-220	1.2	CO ₂ - CH ₄	5.89
Korbouss	1.50	57	2120	<1	3.4	CH ₄ -(N ₂)	4.74

Table 4: CH₄, CO₂, N₂ concentration and the mean salinity (wt% NaCl) of present day geothermal water emergencies and fluid inclusions.

In Table 4 are presented the temperatures and the composition values, in terms of gases of present day thermal waters.

Dissolved CH₄, CO₂ and N₂ contents showed variable abundances. For example, in Dhaoui, Biadha, Jedidi and Korbouss waters emergencies, the fluids are CH₄-rich. CO₂ and N₂ contents show high fluctuations. (Table 4)

DISCUSSION

The large amount of Pb and Zn on MVT deposits were defended by several authors being transported by: 1) hydrothermal fluids leaching a high volume of sedimentary basin sediments, similar to the Mississippi basin (ANDERSON & MACQUEEN 1982) or to the Rhône basin (RAMBOZ & CHAREF 1988); or 2) physical-chemical mechanisms related to great variation of temperature, pH and composition of the fluids leaching small basins (CATHLES & SMITH 1983).

At HZ we found several types of fluorite and at BJ different types of barite suggesting different stages of deposition. THIEBI-

EROZ (1976) and BOULHEL *et al.* (1988) described several types of ore, where the main one correspond to a banded ore in sub-horizontal plans essentially composed by a white and fibrous barite, a well crystallized fluorite (HZ FI), an intrakarstic ore consisting of fluorite (HZ FII) associated with massive barite and, occasionally, well-developed calcite crystals; and geodic structures, fractures or late veins filled with fluorite (HZ FIII).

The study of FI in HZ fluorite and barite from HZ and BJ show the presence of similar high temperature, high salinity aqueous fluids, with homogenisation temperatures between 120°C and 150°C, eutectic temperatures around -70°C and variable ice melting temperatures with mean values between -20°C and -25°C. Hydrocarbon fluids were also found in fluorites and barites, but along secondary trails. (SOUSA *et al.*, 2007)

FI temperature measurements on fluorites were predominantly between 100 °C and 150°C. The stratiform F-Ba mineralizations resulted from a hot (~150°C) multi-component brine dominated by Na-Ca-Cl-SO₄.

The deposition occurred on an unconformity between the Tithonian and the Campanian and the mineralising fluid circulation was controlled by regional deep faults. The faults acted as channels that allowed fluid circulation from the cover to the deep Triassic and probably also into the crystalline basement. The FI data suggest that in spite their localisation, BJ and HZ mineralization resulted from similar hydrothermal fluid system and from mixing of two aqueous fluids with different salinities.

Evidence of igneous activity contemporaneous with mineralizations in the vicinity of the mining districts is absent. Regional fluid and heat circulation is the most likely explanation for the elevated temperatures. Circulation of groundwater through regional aquifers can give sufficient flow rates that can redistribute heat from deep in the sedimentary basin. We assume that a regional flow at a velocity capable of heat transport is required to explain the thermal history.

The salinity, composition and temperature change from one calcite generation to another, and the wide salinity variation occurred within restricted homogenization temperatures intervals. The results of calcite geochemistry suggest that did not exist a correlation between the behaviour of the different contents and the different sites supporting the existence of different generations of calcite. Therefore, each hydrothermal fluid generation was derived from the same

geologic level. The variation of geochemical composition of the leached geological series during each period is probably on the origin of the salinity fluctuations.

In contrast to fluids in the main stages of mineralization, the calcites contain low-saline fluids. The FI are interpreted to represent conditions that prevailed after decay of the fluid flow system responsible for mineralization (CHAREF et al. 2007).

The fossil fluids were in a dynamic system since they show important fluctuations in Th, salinity and fluid composition and the volatile compound abundances.

The presence of hot springs ($T=46^{\circ}\text{C}$) in HZ and deep lakes with hot water ($T=38^{\circ}\text{C}$) in BJ mines suggests the occurrence of a currently active hydrothermal system and a high geothermal gradient in the region. These waters are dominated by Na-Ca-Cl-(SO₄).

TEBIB HLABI (1992) showed that Tunisian thermal water sources were randomly scattered in the area. He proved that the emergency position could move from one place to another with a displacement of some kilometre. Therefore, the actual position of thermal sources is different from their original position.

Geochemical data indicate that these waters were controlled by at least five dynamic systems which are distinguished essentially by their trace elements contents (SADKI 1998) (Table 5).

	Cu,ppb	Fe,ppm	Ni,ppm	Co,ppm	Sr,ppm
Dhaoui	26	30.3	157	140	35.1
Bourguiba	<dl	4.94	<dl	8	5.85
Kef Ettout	9	13.4	10	16	7.4
Mellègue	13	17	15	16	8.7
Biadha	32	44.4	222	168	43.9
Jedidi	42	25.2	108	56	17.5
Oust	17	20.6	128	58	26.8
Korbous	<dl	18,5	<dl	22	8.6

Table 5: Trace element concentrations of present day thermal waters (Sadki, 1998).

Near HZ old mine and spatially associated with F1 fault there is a thermal source with water temperature of $T=46^{\circ}\text{C}$ and a chlorine-sulphate and sodium-calcium com-

position (Table 6) characterized by $\delta^{18}\text{O}$ values of -5.9 and δD values of -33.6 and assumed to be related to Triassic lithologies (SADKI, 1998).

Na	K	Ca	Mg	Cl	HCO_3	SO_4	SiO_2
mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	g/l
917.7	28	1344	244.8	1618.8	200.0	3610.5	75

Cu	Zn	Pb	Mn	Li	Fe	Co	Sr
ppb	ppm	ppm	ppm	ppm	ppm	ppb	ppm
12	0.3	0.5	0.04	0.2	12.6	18	17.1

Table 6: Chemical composition of present-day thermal waters from Hammam Zriba spa.

There are similarities between the present-day and the fossil fluid types, but the salinities of present-day deep ground waters are lower. In each tectonic event, the new faults and the reactivation of the pre-existing fractures induced changes in the extension of the crack and local rock permeability.

The association with the occurrence of N-S, NE-SW and ENE-WSW faults is a common characteristic of mineralized areas

and thermal springs. The faults provided potential avenues for fluid movement.

Therefore, waters can infiltrate into different geological levels and through different rock compositions acquiring different fluid temperatures and compositions.

The compositional similarity of the FI with the modern hot brines is indicative of a hydrothermal system that has operated since the Lower to Middle Cretaceous. Dif-

ferent extensional tectonic regimes occurred during these periods, producing the fault systems that resulted in the hydrothermal karstification and ore deposition.

CONCLUSIONS

Similarly to CATHLES & SMITH (1983), we also propose that a multiphase and dynamic fluid evolution can be responsible for the generation of ore deposits in a limited basin area. The hydrothermal fluids can leach large quantities of metal from sedimentary columns in a relatively limited area when important variations of temperature and chemical composition of fluids occur. Variation of physical and chemical fluid parameters will contribute to the dissolution and leaching of metals in the sediments.

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REFERENCES

- AMARI, A. and BEDIR, M. (1989). Dynamique des bassins sédimentaires quaternaires du Sahel Central de Tunisie : Genèse et évolution des Sebkhas en contexte dépression compressif et distensif. *Revue Géodynamique* 4: 49-65.
- AMOURI, M. (1986). Le gisement de Bou Jaber (Atlas Tunisien Central). Un exemple de minéralisation Pb-Zn-F-Ba dans un paleokarst. *Rev. Sc. de la Terre* 4, 87-114.
- ANDERSON, G. M. and MACQUEEN, R. U., (1982). Ore deposits models- Mississippi Valley lead-zinc deposits. *Geosci. Canada*, 9, 108-117.
- BEDIR, M. and ZARGOUNI, F. (1986). Structuration post Miocene du Sahel de Mahdia. Analyse géométrique et cinématique des données de sub-surface. *Rev. Sc. de la Terre*, 4, 55-69
- BEDIR, M., BOUKADI, N., TLIG, S., BEN TIMZEL, F., ZITOUNI, L., AL-OUANI, R., SLIMANE, F., BOBIER, C. and ZARGOUNI, F. (2001). Subsurface mesozoic basins in the central Atlas of Tunisia : tectonic, sequence deposit distribution and hydrocarbon potentiel. *AAPG Bull.* 85: 885-907.
- BENCHILLA, L., GUILHAUMOU, N., MOUGIN, P., JASWAL, T. and ROURE, F. (2003). Reconstruction of paleo-burial history and pore fluid pressure in foothill areas: a sensitivity test in the Hammam Zriba (Tunisia) and Koh-i-Maran (Pakistan) ore deposits. *Geofluids* 3, 103-123.
- BOUAZIZ, S., BARRIER, E., SOUSSI, M., TURKI, M. M. and ZOUARI, H. (2002). Tectonic evolution of the North

The present-day geothermal and fossil hydrothermal fluids showed multiphase activity with change of the physical and chemical fluid characteristics. The nature of these hot fluids, which derived from different geological levels, was controlled by the composition of the geological series and tectonic events once the fluid circulation systems had a dynamic evolution.

In this view, ore deposits formed when escaping solutions circulated through a particular escape locality. Near the surface, the metals carried out in the brine precipitate due to cooling or mixing with other solutions.

This study can contribute to develop a different strategy in Pb-Zn deposits mineral exploration in Northern Tunisia, since until now is mainly based on sedimentary criteria.

- Africa margin in Tunisia from paleostress data and sedimentary record. *Tectonophysics* 357: 327-353.
- BOUHLEL, S., FORTUNÉ, J.-P., GUILHAUMO, N., and TOURAY, J. C. (1988). Les minéralisations stratiformes à F-Ba de Hammam Zriba, Jebel Guébli (Tunisie nord orientale) : l'apport des études d'inclusions fluides à la modélisation génétique. *Mineral. Dep.* 23, 166-173.
- BRADLEY, D. C. and LEACH, D. L. (2003). Tectonic controls of Mississippi Valley-type lead-zinc mineralization in orogenic forelands. *Mineral. Dep.* 38: 652-667.
- CATHLES, L. M. and SMITH, A. T. (1983). Thermal constraints on the formation of Mississippi Valley Type lead-zinc deposits and their implications for episodic basin dewatering and deposit genesis. *Economic Geology* 78: 983-1002.
- CHAREF, A. and SHEPPARD, S. M. F. (1987). Pb-Zn mineralization associated with diapirism: fluid inclusion and stable isotope (H, C, O) evidence for the origin and evolution of the fluids at Fedj-el-Adoum, Tunisia. *Chem. Geol.* 61: 113-134.
- CHAREF, A., NORONHA, F. and GUEDES, A. (2007). Present-day geothermal fluids from northern Tunisia: a key for understanding the dynamic of the fossil mineralizing fluids? *Proceedings of the 9th Biennial SGA Meeting*, Dublin. In: "Digging Deeper" C.J. Andrew et al (editors). Vol. 1, 761-764.
- GHARBI, M., BEN AYED, N., and BEN SAID, E. A. (1981). Essai d'interprétation tectonique du champ filonien de Bou-Jaber (Atlas tunisien central). *Actes du Premier Congrès National de la Terre* (Tunis). Tome 1, 393-403.
- JALLOULI, C., CHIKHAOUI, M., BRAHAM, A., TURKI, M. M., MICKUS, K. and BENASSI, R. (2005). Evidence for Triassic salt dômes in the Tunisian Atlas from gravity and geological data. *Tectonophysics* 396: 209-225.
- MORETTE, A. (1966). Rodier J – L analyse chimique et physico-chimique de l'eau (eaux naturelles et eaux usées). *Ann. Pharmaceutiques Françaises*, 24, 5, 404 &
- PERTHUISOT, V. (1972). L'évolution d'un diapir tunisien: le Djebel Echeid. *Rev. Géogr. Phys. et Géol. Dyn.*, 2ème série 14: 145-152.
- POTY, B., LEROY, J. and JACHYMOUITZ, L. (1976). A new device for measuring temperatures under the microscope: the Chaixmeca microthermometry apparatus. *Bull. Soc. Franc. Miner. Cryst.* 99: 182-186.
- RAMBOZ, C. and CHAREF, A. (1988). Temperature, pressure, burial history, and paleohydrology of les Malines Pb-Zn deposit.- reconstruction from aqueous inclusions in barite. *Economic geology*, 83, 4, 784-800.
- ROEDDER, E. (1984). Fluid inclusions. Mineralogical Society of America (Series Editor: Paul H. Ribbe). *Rev. Mineral.* 12, 644p.
- ROUVIER, H., PERTHUISOT, V. and MANSOURI, A. (1985). Pb-Zn deposits and salt bearing diapirs in southern Europe and North Africa. *Economic Geology* 80: 666-687.
- SADKI, O. (1998). Etude des systèmes hydrothermaux du Nord de la Tunisie: Géochimie des interactions Eaux-roches et circulation hydrothermale. Thèse de 3ème cycle. Université de Tunis. pp 246.

- SHEPHERD, T. J. (1981). Temperature programmable heating-freezing stage for microthermometric analysis of fluid inclusions. *Econ. Geol.* 76: 1244-1247.
- SHEPARD, S. M. F., CHAREF, A. and BOUHLEL, S. (1996). Diapirs and Zn-Pb mineralization: A general model based on Tunisian (n. Africa) and Gulf Coast (U.S.A.) deposits. *Society of Economic Geologists Special publication N°4*, 230-243.
- SOUSA, M., GUEDES, A., NORONHA, F., FLORES, D. and CHAREF A. (2007). A contribution to the knowledge of the Hammam Zriba and Bou Jaber ore deposits (Tunisia)". In: C.J. Andrew et al (Eds), *Digging Deeper*. Vol. 2. *Proceedings of the 9th Biennial SGA Meeting*, Dublin, Irlanda, p. 1319-1322. (ISBN 0-950899-4-4).
- TEBIB HLALI, H. (1992). Etude des émergences de la Tunisie Nord-oriental de la Tunisie; Thèse de 3ème cycle. Tunis. pp182.
- THIBIEROZ, J. (1974). Hammam Jedidi et Hammam Zriba: Etude géologique et minière de deux gisements stratiformes dans le cadre de la province fluorée tunisienne; l'association des concentrations fluorées aux surfaces d'émersion. Thèse de 3^e cycle Univ. Paris VI, 432 p.
- THIBIEROZ, J. (1976). Reconstitution chronologique du rôle des surfaces d'émersion dans l'histoire du gisement de fluorine de Hammam Zriba (région de Zaghouan Tunisie). *Mém. H. Série Soc. Géol. France* 7, 33-37.
- TRUILLET, R. (1981). La substitution tectonique de couverture de Hammam Zriba (Tunisie orientale). *C. R. Acad. Sc. Paris* 292, 1319-1381.
- ZOUARI, H. (1995). Evolution géodynamique de l'Atlas Centro - méridional de la Tunisie: stratigraphie, analyse géométrique, cinématique et tectono-sédimentaire. Thèse Univ. Tunis II. 278pp.
- ZOUAGHI, T., BÉDIR, M. and INOUBLI, M. H. (2005). 2D Seismic interprétation of strike slip faulting, salt tectonics, and Cretaceous unconformities, Atlas Mountains, central Tunisia. *Journal African Earth Sciences* 43, 464-486.