Research article

Fluid flow and polymetallic sulfide mineralization in the Kettara shear zone
(Jebilet Massif, Variscan Belt, Morocco)

I. N'Diaye¹, A. Essaifi¹*, M. Dubois², B. Lacroix³, K. M. Goodenough⁴, L. Maacha⁵

¹Geology Department, Cadi Ayyad University, B.P. 2390, Marrakech 40000, Morocco
²LGCgE (EA 4515) / Université Lille 1, building SN5, 59655 Villeneuve d'Ascq CEDEX, France
³Institut des Sciences de la Terre, Université de Lausanne, 1015 Lausanne, Switzerland
⁴British Geological Survey, Murchison House, West Mains Road, Edinburgh EH9 3LA, UK
⁵Managem group, BP5199, Casablanca, 20100 Morocco

*Corresponding author: Abderrahim Essaifi
email: essaifi@uca.ma
Tel +212 5 24 43 46 49 (work) +212 5 24 49 05 61 (home) Fax +212 5 24 43 74 11
Abstract

The Kettara shear zone is a regional wrench shear zone within the Jebilet massif of Western Morocco, part of the Variscan orogenic belt. This massif is characterized by bimodal magmatism, largely intrusive, and by a number of polymetallic massive sulfide deposits. A syntectonic mafic-ultramafic intrusion and an adjacent, deformed pyrrhotite-rich massive sulfide deposit are located within a ‘compressional jog’ of the shear zone. Hydrothermal alteration in both the intrusion and the wall rocks adjacent to the deposit is characterized by syntectonic replacement processes leading to formation of chlorite-schists and quartz ± calcite veins. Fluid inclusions in mineralized (pyrrhotite-bearing) quartz veins from the wall rocks adjacent to the deposit and in veins associated with chlorite-schists within the intrusion indicate a prevalence of H₂O-CO₂-CH₄-N₂ and H₂O-salt fluid systems. In the mineralized veins the fluid shows reducing conditions, with gas dominated by CH₄ and N₂ and salinities around 7.5 wt.% NaCl, whereas in the chlorite shear zones fluid is CO₂ dominated and salinities are higher than 23 wt.% NaCl. Hydrogen and oxygen isotopic compositions of chlorite and quartz are similar and demonstrate involvement of metamorphic water in both the deposit and the intrusion.

The data are consistent with a regional metamorphic fluid flow through the Kettara shear zone. The migrating metamorphic fluids were reduced in the organic matter-rich host rocks leading to deposition of sulfides in the mineralized veins. There are two possible hypotheses for the origin of these mineralized veins: either they were formed during deformation and remobilization of a syn-sedimentary massive sulfide deposit, or they were formed synchronously with the sulfide deposit during development of the Kettara shear zone.

Keywords Kettara · Shear zones · Massive sulfide deposits · Stable isotopes · Fluid inclusions · Variscan Belt · Morocco
1. Introduction

Crustal shear zones form narrow zones of low strength and high permeability within the upper crust, and may serve as fluid pathways, capable of focusing ore-forming processes (Oliver, 1996; Cox et al., 2001; Chernicoff et al., 2002). The association of many hydrothermal mineral deposits with shear zones and crustal discontinuities is widely documented in the literature (e.g., Groves et al., 1998; Sillitoe, 2000). Examples of mineralization that display a spatial relationship with fault and shear zones include orogenic gold deposits (e.g., Sibson et al., 1988; Cox et al., 1991; Bouchot et al., 2000). Polymetallic sulfide mineralization associated with shear zones has been described at a range of structural levels (Glen, 1987; Nicol et al., 1997; Gaouzi et al., 2001; Piessens et al., 2002; Bellot, 2004) and emphasizes the importance of this type of mineralization in collisional belts. Hydrothermal fluid flow associated with syntectonic intrusions may be concentrated along shear zones and, when combined with a precipitation mechanism operating in a restricted space (e.g., Hedenquist and Lowenstern, 1994), may lead to ore deposition. This work focuses on a shear zone hosting a mafic-ultramafic intrusion and a massive sulfide deposit in the Variscan belt of Morocco, and considers the relationship between deformation, fluid flow and sulfide mineralization.

The central unit of the Jebilet massif, in the Marrakech region of Western Morocco, is a block of Carboniferous sedimentary rocks deformed during the Variscan orogeny. The block is located along the southern branch of the West Meseta shear zone (Piqué et al., 1980; Lagarde and Michard, 1986). This block and its southern extension (the Guemassa massif) host a bimodal intrusive magmatic suite (Bordonaro, 1983; Essaifi et al., 2014) and significant massive sulfide mineralization (Huvelin, 1972; Bernard et al., 1988). The origin of the massive sulfide deposits is the subject of continuing debate. They have been variously considered as deformed syngenetic VMS or SEDEX bodies (Belkabir et al., 2008; Marcoux et
The Kettara deposit is a pyrrhotite-rich, near-vertical massive sulfide lens located near the mafic-ultramafic Kettara intrusion. Both are located within a shear zone interconnected with a regionally anastomosing network of sub-vertical shear zones (Essaifi et al., 2001; Essaifi and Hibti, 2008). The deposit has previously been interpreted as a mineralized dyke filling a sub-vertical fracture (Agard et al., 1952), or as a deformed pre-tectonic, synsedimentary deposit (Huvelin, 1970).

The Kettara deposit was the first massive sulfide deposit to be discovered and mined in central Jebilet. The gossan was exploited for limonite and ochre from 1938–1963. The extracted quantities are 150,000 t grading 45–52% Fe and 50,000 t grading 50–58% Fe, respectively (Essaifi, 2011 and references therein). Below the gossan a cementation zone with mineralization composed of native copper, pyrite, chalcocite (Cu2S), covellite (CuS), with traces of gold and silver (Souaré, 1988) is present. Pyrite was extracted from this zone between 1955 and 1966, and used in the manufacture of sulfuric acid with recuperation of Cu contained in chalcocite and covellite. Its total reserves have been estimated as 180,000 t grading 38% sulfur. Below the cementation zone, the primary mineralization is pyrrhotite-rich (up to 95%) and forms an elongate sub-vertical lens 500 m deep, 40–70 m thick and 1500 m long (Huvelin and Permingeat, 1980; Bernard et al., 1988). The ore reserves are estimated as 30 Mt of pyrrhotite grading 0.7% Cu; with 8 Mt extracted between 1964 and 1982, and used in the manufacture of sulfuric acid. Difficulties related to pyrrhotite storage (fast oxidation), poor sulfur content (25%), and to the volume of mine wastes resulted in the closure of the operation in 1982.

This paper presents new structural, chemical and fluid inclusion evidence of regional fluid migration along the Kettara shear zone, leading to synkinematic hydrothermal alteration.
around the polymetallic sulfide mineralization, and discusses the significance of this fluid migration on the genesis of the Kettara massive sulfide deposit.

2. Geological Framework

2.1. The Moroccan Meseta

The Variscan orogenic belt of Morocco is subdivided into the eastern and western Meseta domains (Fig. 1A, B), which were folded and metamorphosed respectively during late Devonian and late Carboniferous (mainly early Westphalian) Variscan tectonic events (Hollard, 1978; Hoepffner et al., 2005; Michard et al., 2010). The Jebilet massif, together with the Rehamna and the central Paleozoic massifs to the north, and the high Atlas Paleozoic block to the south, form the Western Meseta. A late Devonian-early Carboniferous foreland sedimentary basin was developed in the western Meseta and was bounded by relatively rigid blocks to the north (Sehoul block) and west (Coastal block) and by the Anti-Atlas and West African craton to the south (Piqué and Michard, 1989; Hoepffner et al., 2006; Burkhard et al., 2006). Basin closure during the late Carboniferous was accompanied by strongly heterogeneous ductile deformation. Narrow, highly deformed regional shear zones of low to medium metamorphic grade contrast with wide moderately deformed areas with very low-grade metamorphism (Piqué et al., 1980, Lagarde and Michard, 1986; Piqué and Michard, 1989). The narrow deformed zones and are commonly spatially associated with syn- to late-kinematic granitic intrusions (Lagarde et al., 1990). Among these shear zones, the western boundary of the Devonian-Carboniferous basin is a major lithospheric structure, the West Meseta Shear Zone (WMSZ), which extends from Rabat in the north to the High Atlas in the south (Piqué et al., 1980; Lagarde and Michard, 1986). Most geodynamic models relate formation of the Moroccan Meseta to a westward continuous compression of the Variscan foreland in which the Rheic suture is hidden at the eastern boundary of the eastern Meseta.
(Kharbouch et al., 1985; Boulin et al., 1988; Roddaz et al., 2002, 2006; Essaifi et al., 2014).

Recent structural and geochronological work in the Rehanma Massif by Chopin et al. (2014) indicates a more complex (polyphase) history beginning with southward thrusting, followed by N-S directed bulk crustal shortening, in turn followed by E-W crustal shortening, all occurring from late Carboniferous to Lower Permian times.

2.2. The Jebilet massif

The Jebilet massif, just north of Marrakech provides an E-W section through the western Meseta domain. It is composed of three structural units (Fig. 1C):

i) The western Jebilet unit is a weakly deformed block composed of unmetamorphosed Cambro-Ordovician limestones, shales and sandstones with north-south trending kilometer-scale folds. It is part of the Coastal block, which was emergent since Devonian times (Piqué et al., 1980).

(ii) The central Jebilet unit consists of a schistose low-grade metamorphosed (anchizone and epizone) block of marine Visean shales (the Sarhlef schists) deposited in an anoxic platform setting (Beauchamp, 1984). This unit is also characterized by the occurrence of massive sulfide deposits together with numerous magmatic mafic and felsic intrusions which form a bimodal magmatic association (Bordonaro, 1983; Essaifi et al., 2014). The boundary between the central and western Jebilet is a NNE–SSW dextral thrust-wrench shear zone (Le Corre and Boulton 1987; Mayol and Muller, 1985), and this is the southern extension of the West Meseta Shear Zone (WMSZ, Fig. 1B, C).

(iii) The eastern Jebilet unit is a weakly metamorphosed to unmetamorphosed block separated from the central unit by a sinistral shear zone with a NNW-SSE trend, the Marrakech Shear Zone (Lagarde and Choukroune, 1982). It is composed of Upper Visean syntectonic ‘flysch’ (Kharrouba flysch) including olistostromes and inliers of Ordovician to Devonian sedimentary rocks. Such Carboniferous syntectonic deposits also characterize the eastern part
of central Morocco and were deposited in a compressional retro-foreland basin (Bouabdelli and Piqué, 1996; Ben Abbou et al., 2001; Roddaz et al., 2002).

Two syntectonic calc-alkaline granite plutons intruded by leucogranite sheets are spatially associated with the Marrakech shear zone (Lagarde and Choukroune, 1982). Westphalian-Permian continental conglomerates (Huvelin 1977) rest unconformably upon the Variscan folded sequence in western and eastern Jebilet (Fig. 1C).

3.3. Central Jebilet

The intersection of the SSE-oriented Marrakech Shear Zone with the major NNE-trending WMSZ delimits a trapezoidal block (central Jebilet) where the metasedimentary rocks have been deformed during a very low- to low-grade greenschist facies regional metamorphism contemporaneous with post-Visean shortening (Piqué and Michard, 1989; Hoepffner et al., 2005; Michard et al., 2010). Regional ductile deformation is marked by the development of a widespread subvertical axial plane schistosity (S1) associated with NE-SW-trending, large-scale upright and subhorizontal folds. The schistosity trajectories progressively curve into an array of anastomosing shear zones (Fig. 2A), accompanied by increasing strain and metamorphic grade. These shear zones show a close spatial association with the bimodal intrusions and rotate anticlockwise by about 90° into the SSE trending Marrakech Shear Zone. These ductile shear zones evolve laterally into brittle faults that cut the schistosity. The most important of these is the Mesret dextral fault (Fig. 1C). Greenschist facies regional metamorphism during foliation development is indicated by white mica, chlorite, albite and quartz.

Carboniferous magmatism in the central Jebilet is dominated by intrusive rocks and includes a tholeiitic-alkaline bimodal association and two calc-alkaline cordierite-bearing granodioritic plutons intruded by leucogranite sheets (Le Corre and Saquaque, 1987; Mrini et al., 1992;
Essaifi et al., 2014). The bimodal intrusions are limited to the central Jebilet block, and the granodioritic plutons are spatially associated with the Marrakech Shear Zone (Fig. 1C).

The bimodal association (two-thirds mafic compositions, the remainder felsic) is syn-tectonic and was emplaced at 330.5 ± 0.7 Ma (Essaifi et al., 2003) at high crustal levels. The granodioritic plutons were also emplaced at c. 330 Ma, but the cross-cutting leucogranite sheets were intruded at c. 300 Ma (Mrini et al., 1992). The bimodal magmatic association is dominated by intrusive rocks forming dykes, small stocks and elongated intrusions of a few hundred meters width and a few kilometers length. The bimodal magmatic rocks are arranged into N–S- to NE–SW-trending lineaments that are broadly parallel to local schistosity and shear zones (Fig. 2A). Intrusion of these magmatic pods resulted in low-pressure contact metamorphism of the surrounding pelites, reaching the hornblende hornfels facies, and their emplacement was accompanied by significant hydrothermal activity (Essaifi, 1995).

The massive sulfide deposits of the Moroccan Meseta are restricted to the central Jebilet block and its southern extension, the Guemassa massif. They are Cu and Pb-Zn massive sulfide deposits dominated by pyrrhotite (Huvelin, 1970; Bernard et al., 1988; Essaifi and Hibti, 2008). In the central Jebilet, the deposits are steeply dipping elongate lenses aligned broadly parallel to the general trend of the regional structures (folds, schistosity) (Fig. 2A). Locally the deposits cut at a low angle across the regional schistosity and the mafic dykes of the bimodal magmatic association (Huvelin, 1972). At regional-scale the ore bodies and their gossans form north-south to NE-SW near-vertical lineaments, parallel with the bimodal magmatic lineaments, and they are generally located at a constant distance (~ 1 to 1.5 km) from the bimodal intrusions (Bernard et al., 1988; Essaifi and Hibti, 2008). The Kettara intrusion lies within one such magmatic lineament (Fig. 2). Two massive sulfide deposits in the area are currently mined: the Draa Sfar deposit on the southern margin of the central Jebilet block (Belkabir et al., 2008; Marcoux et al., 2008; Moreno et al., 2008), and the Hajjar
deposit (Leblanc, 1993; Hibti and Marignac, 2001) in the Guemassa massif, some 30 km to
the south. The Koudiat Aïcha deposit close to Kettara has also been the subject of recent study
(Lotfi et al., 2008; 2010).

The sulfide bodies have not been directly dated. Hydrothermal alteration in the Hajjar sulfide
deposit has been dated at c. 300 Ma, and attributed to proximity to a buried leucogranitic
intrusion (Watanabe, 2002). In contrast, hydrothermal alteration associated with the Draa Sfar
derposit is dated at c. 331 Ma (Marcoux et al., 2008), within error of the age of the bimodal
intrusions.

2.4. The Kettara area

The Kettara mafic-ultramafic intrusion, located 1 km to the south of the Kettara massive
sulfide deposit (Fig. 2), is a stratified intrusion composed of medium- to coarse-grained mafic
and ultramafic cumulates, surrounded by a narrow zone of fringing microgabbros at the
contact with the host rocks (Aarab, 1984; Jadid, 1989; Essaifi, 1995). The magmatic minerals
consist of olivine, clinopyroxene, plagioclase, spinel, ilmenite and apatite. The ultramafic
cumulates (plagioclase-bearing wehrlites, troctolites and olivine-bearing gabbros) are cross-
cut by mafic cumulates (massive and layered leucogabbros), and enclaves of troctolites are
found within leucogabbros. Numerous near-vertical felsic and mafic dykes cut across the
intrusion and the host rocks (Fig. 2B, C and Fig. 3). Studies of the finite strain field and
petrostructural analysis have demonstrated a syn-tectonic emplacement of the Kettara
intrusion, which is transected by a series of anastomosing cm- to m-scale shear zones (Ait-
Tahar, 1987; Essaifi et al., 2004). The intrusion lies within the Oled Har-Kettara_Safsafat
magmatic lineament (Fig. 2B).

The Kettara sulfide deposit forms an elongated sub-vertical, pyrrhotite-dominated
massive sulfide lens, approximately 1.5 km long and 500 m deep, parallel to the NE-SW
regional structural trend (Essaifi and Hibti, 2008), and indicated at the surface by a well-
developed gossanous zone up to 50 m in width (Fig. 2). It crops out approximately one kilometer north of the mafic-ultramafic Kettara intrusion (Fig. 2).

The host rocks of the Kettara intrusion and deposit are weakly metamorphosed pelites with thin-bedded sandstone and local sandstone and limestone layers (Sarhlef schists; Huvelin, 1977), which are crosscut by numerous mafic and felsic dykes belonging to the bimodal magmatic association. Geochemical data for the Sarhlef schists indicate that they are likely to be derived from an active continental margin (Moreno et al., 2008; Essaifi et al., 2014). Around the Kettara massive sulfide deposit, these host rocks are cut by numerous quartz and quartz-calcite veins, some of which are sulfide-bearing. Due to the limited availability of underground samples at Kettara, this research focuses on these veins to understand the fluids that circulated around the massive sulfide deposit. 60 rock samples including host rocks, mineralized veins and ore samples were collected from outcrops, ore stockpiles present in the mine site and drill core from the Kettara deposit.

3. Deformation and hydrothermal alteration

3.1. Structure

The Kettara region exemplifies the style of deformation in the central Jebilet. The Kettara deposit and intrusion are located within the network of anastomosing ductile shear zones that characterize the central Jebilet block (Essaifi et al., 2001) (Fig. 2A). They are located to the south of the Mesret Fault termination, marked by a number of SE-trending synthetic dextral faults showing a horsetail pattern (Fig. 1C and Fig. 2A). To the south-west of Kettara lies the Oled Har intrusion and to the northeast the Safsafat intrusions, together these form a N-S magmatic lineament which is curved in the Kettara area (Fig. 2A). The Oled Har and Safsafat intrusions are emplaced along N-S sinistral shear zones (Fig. 2B). The Kettara intrusion and
deposit are located in a step-over zone between the end of the N-S strike-slip Oled Har shear
zone and the beginning of the N-S strike-slip Safsafat shear zone (Fig. 2B).

Within the Kettara sector, the structures observed include both ductile structures related to the
main Variscan shortening and brittle structures related to later stages of the Variscan
deformation (Fig. 2B). The post-Visean main Variscan shortening has caused regional folding
as well as a progressive transposition of the original bedding ($S_0$) into a single and penetrative
sub-vertical chlorite-muscovite bearing schistosity ($S_1$), contemporaneous with a low-grade
greenschist facies regional metamorphism. This regional schistosity is axial planar to upright,
moderately to gently (60–20°) NE-plunging folds (Fig. 3), and bears a gently plunging
stretching lineation, which becomes down-dip near the intrusion (Fig. 3; Essaifi et al., 2001).

In plan view, schistosity trajectories in the Kettara area display progressive curvatures from
the NNE–SSW regional direction towards ENE–WSW directions indicating dextral shearing
(Fig. 2B, C). Strain gradients accompany the curvatures of the $S_1$ cleavage trajectories. The
zones of most intense shearing are marked by very intense $S_1$ schistosity, thinning of original
beds, and isoclinal folding (Fig. 3). In the host schists located between the deposit and the
intrusion (Fig. 4A), bedding is transposed into the penetrative $S_1$ schistosity, which is
characterized by a strong S-fabric of quartz grains and by well-developed pressure shadows
around oxide minerals (ilmenite, anatase and hematite; Fig. 5A, B). Kink bands and micro-
scale S/C shear bands (Berthé et al., 1979) are well developed in the zones of most intense
shearing where phyllites are intensively stretched along S and C planes. The host sandstone
layers are progressively boudinaged and transposed into the $S_1$ cleavage. Numerous sigmoidal
quartz veins cross-cutting the schistosity at low angles are observed in the wall rocks adjacent
to the deposit (Fig. 3 and Fig. 4B). On the northern side of the deposit (the hanging wall),
deformation decreases progressively northwards. Thin calcareous beds intercalated within the
metapelites are increasingly thinned as the gossan is approached, varying from centimeter- to
meter-scale lenses of fine-grained bioclastic limestone and calcareous sandstone proximal to
the deposit, to a coarse-grained layered calcareous sandstone bed that forms a stratigraphic
horizon located 1.5 km from the deposit (Fig. 2C).

In the Kettara intrusion, deformation is very heterogeneous. Meter to centimeter-scale
anastomosing shear zones bound lenticular meter to 100 m-scale domains of weakly deformed
to undeformed gabbros (Fig. 2C and Fig. 3). Numerous subvertical felsic and mafic dykes cut
across the intrusion and the host rocks. Mafic dykes up to 10 m wide cross-cut the schistosity
in the vicinity of the Kettara deposit, but are locally deformed at their margins and
boudinaged into lenses. One dyke appears to be cross-cut by the gossan of the Kettara deposit;
and Huvelin (1977) describes meter-scale lenses of dolerite within the massive orebody,
suggesting that the dyke pre-dated the sulfide deposit.

To summarize, we interpret that the Kettara area is located between two adjoining en échelon
shear zones and has been deformed in order to accommodate continued strike-slip
displacement. In this model, a short ENE-WSW trending dextral shear zone connects the
terminations of 2 N-S striking en échelon shear zones. In agreement with sinistral shear sense
criteria inferred from schisotosity trajectories, and attested by multiscale S/C shear bands and
various microscale shear criteria as rotation of contact metamorphism porphyroblasts or
asymmetric pressure shadows along the Oled Har and Safsafat en echelon shear zone
segments (Essaifi, 1995), the Kettara step-over zone is inferred to have acted as a
compressional ‘jog’ or a ‘push-up’ area.

3.2. Hydrothermal alteration in the Kettara intrusion

The structural relationships between the intrusion and the host rocks show that the Kettara
intrusion was emplaced in a zone of regional dextral shearing (Ait Tahar, 1987; Essaifi 1995).
Two periods of deformation and subsequent hydrothermal alteration have been distinguished
within the intrusion (Essaifi et al., 2004). The first of these occurred during cooling of the
intrusion, with formation of cm-scale shear zones. Introduction of fluids rich in Si, Ca and Mg, pervasive throughout the intrusion, led to the formation of amphibole-rich ultramylonites from original gabbros (Essaifi et al., 2004). The second episode followed the thermal re-equilibration of the intrusion. Fluid flow was focused along the shear zones with retrogression to chlorite and leaching of Na, Si, Ca and Mg (Essaifi et al., 2004).

Two types of mesoscopic veins are associated with shear zones in the Kettara intrusion (Essaifi et al., 2004): (a) quartz-chlorite veins up to 10 cm wide at the center of the chlorite-rich shear zones, and (b) up to 30 cm wide quartz-calcite ‘en echelon’ or sigmoidal veins (Fig. 4D), with quartz at the vein boundaries and calcite along the center of the veins. These veins strike at 45° relative to the direction of the shear zones in low strain areas, but they are progressively reoriented and deformed in the vicinity of those shear zones (Essaifi et al., 1995). Such geometric relationships indicate that formation of quartz-calcite veins was contemporaneous with shear zone development.

The quartz veins are stretched parallel to shear zones and show evidence of recrystallization of quartz grains. According to the geometric relationships between the veins and the shear zones, the quartz veins in the inner parts of the shear zones are considered to be the earliest ones and served as nucleation sites for the shear zones (Segall and Simpson 1986), whereas those oblique to the foliation (the quartz-calcite veins) were emplaced slightly later during widening of the shear zones (Gates and Speer, 1991). Thus the quartz-chlorite veins would be relatively earlier than those filled by quartz-calcite (Fig. 3), indicating the fluid evolution within the Kettara intrusion.

3.3. Hydrothermal alteration in the host rocks

In the Kettara area, the schists are devoid of any volcanic units and are dominantly composed of light grey pelites (black shales) intercalated with thin beds of fine-grained sandstone and limestone, with a well-developed schistosity. The pelites are dominated by a muscovite-
quartz-chlorite-albite mineral assemblage (Fig. 5A), with muscovite grains showing pressure
shadows and an oblique orientation to S1. In the sandstone layers, mineralogy is dominated by
quartz and feldspar with quartz having an average grain size of 50 µm and forming up to 95
vol. % of the rock.

Approaching the intrusion boundaries, a low pressure/high temperature syntectonic contact
metamorphism assemblage is developed: chlorite crystals increase in size while crystals of
biotite appear along the cleavage plane. About 15m from the contact with the leucogabbros,
contact metamorphic minerals (andalusite or cordierite) are developed. They form elliptical
spots flattened and stretched along the cleavage plane. Hydrothermal alteration in the contact
metamorphic aureole is very intense. It is marked by retrogression of the contact metamorphic
minerals into secondary minerals. Biotite grains in the matrix are chloritized; cordierite and
andalusite porphyroblasts are completely altered to chlorite, muscovite and quartz.

Approaching the Kettara gossan, the pelites become greenish then purple in the gossan. At the
margin of the deposit muscovite is aligned along the schistosity plane (S1); Fe-rich chlorite
appears at a distance of 10 m from the gossan and its abundance increases towards the gossan
in both footwall and the hanging wall. Sericite is locally oblique to the foliation plane, and its
content increases towards the gossan, especially in the hanging wall of the deposit. The
adjacent areas of the gossan are also characterized by the occurrence of numerous centimeter-
scale quartz ± calcite mineralized veins. These mineralized veins have gradational to sharp
boundaries and cut the schistosity in the host rocks (Fig. 3 and Fig. 4B), but are affected by
kink bands and also carry a recrystallized quartz fabric, indicating their syn-tectonic nature.
The veins have the same mineralogy as the massive pyrrhotite ore body, being composed of a
quartz-chlorite gangue enclosing grains of pyrrhotite, chalcopyrite, sphalerite, arsenopyrite,
galena, and native bismuth. Phosphate minerals and zircon are also found in the mineralized
veins. In some veins the sulfide minerals develop in layers that are in continuity with the
pelite layers of the host schists. They occur between the quartz grains or in association with
chlorite in the vein margins. Thus the pelite banding persists through the veins by alternation
of sandstone layers composed of fine-grained quartz (0.1 mm) and layers composed of coarse-
grained quartz associated with chlorite and sulfides which have replaced former pelite layers.
The structural relationships indicate that these veins were emplaced towards the end of the
ductile deformation phase. These quartz-chlorite-pyrrhotite-bearing veins are crosscut by
carbonate and pyrite-bearing veins (Fig. 4F). The massive pyrrhotite is cross cut by carbonate
veins (Fig. 4E). However quartz-chlorite veins cutting across massive pyrrhotite have never
been observed. The field relationships now observed indicate that the chlorite-schists
developed around the Kettara deposit result from syntectonic hydrothermal alteration of the
host rocks. According to Bernard et al. (1988), this metasomatic alteration was accompanied
by leaching of Si and Ca that subsequently crystallized as quartz-calcite veins within the wall
rocks of the orebody.

3.4. The Kettara massive sulfide deposit

The core of the Kettara deposit is a massive sulfide lens dominated by pyrrhotite, but with
gradational margins. These margins are clear in core from inclined borehole K101, which
extends to a depth of 193 m through the Kettara deposit, intersects the central part of the ore
body at depths of 159–179 m, and shows the contact between the sulfide lens and the pelitic
host rocks. The margins of the mineralized horizon contain numerous fragments of foliated
wall rocks surrounded by irregular veins of pyrrhotite, and aligned parallel to the foliation
(Fig. 4E). Pyrrhotite has crystallized parallel to the main schistosity and also fills fractures
that cut across the foliation in the host rocks at the boundaries of the ore body (Fig. 4E).
Moving inwards from the margin, the wall-rock fragments become smaller and less abundant.
Away from the margins, the core of the deposit is dominated by massive pyrrhotite including
only patches of the host rocks (Fig. 5C).
Study of mineralized samples, from core and from the stockpile, has allowed characterization of the primary mineralization of the Kettara deposit. The main mineralization is represented by fine-grained massive to semi-massive pyrrhotite. It is composed of pyrrhotite (70-90%), chalcopyrite (5-25%), magnetite (3-5%), sphalerite (2%), arsenopyrite (<1%) and traces of galena and native bismuth (Fig. 5D). The gangue minerals are quartz and chlorite, which can be associated with talc and mica, or enclose phosphate minerals and Ti-oxides. The semi-massive ore is characterized by a chlorite-rich gangue and pyrrhotite oriented parallel to the main schistosity (Fig. 5C).

Pyritic ore occurs as cm-scale veins or pods cutting the semi-massive to massive pyrrhotite, the pyrrhotite mineralized veins and the host schists (Fig. 5E, F). It is composed of centimeter-scale brecciated pyrite cubes together with rare marcasite and chalcopyrite associated with a gangue of carbonates. The pyritic ore has been affected by deformation within brittle to semi-brittle shear zones (Brown and McClay, 1993) but is clearly unaffected by ductile deformation. Pyrite crystals are locally fractured and brecciated (Fig. 5F), but lack features associated with ductile deformation such as pressure shadows. These microstructural relationships indicate that the pyritic ore post-dates the main period of ductile deformation (Marshall and Gilligan, 1993). Euhedral crystals of pyrite are also disseminated in the hanging wall of the ore lens.

Field and textural relationships show that two successive mineralizing fluids contributed to the formation of the Kettara deposit (Fig. 6): (i) the first fluid led to formation of a pyrrhotite-chalcopyrite-sphalerite-magnetite-arsenopyrite paragenesis and a quartz-chlorite gangue. This mineralogical association is affected by ductile shearing, marked by orientation of pyrrhotite and chalcopyrite along the schistosity and shearing planes; and (ii) the second fluid led to deposition of pyrite and carbonates, which are affected by brittle cataclasis.
Chlorite, the main alteration product in the shear zones of the Kettara intrusion, is also the main gangue mineral in the Kettara massive sulfide deposit. Chlorites associated with the mineralization are Fe-rich (0.5 ≤ XFe ≤ 0.85, Souaré 1988), in common with the shear zones inside the intrusion (0.46 ≤ XFe ≤ 0.48, Essaifi et al., 1995). This similarity in chlorite composition was the first suggestion that the same fluid led to the formation of the massive sulfide and the chlorite schists of the Kettara intrusion (Essaifi et al., 1995; Essaifi and Hibti, 2008).

It is clear from the field relationships that there was significant hydrothermal fluid flow in the Kettara area associated with the Variscan deformation, and with the syn-tectonic intrusions in the area. This has led to hydrothermal alteration and veining around both the Kettara intrusion and the deposit. However, it is not evident from field relationships alone whether the Kettara sulfide deposit was formed prior to this deformation period, with its own hydrothermal aureole, and was then subsequently deformed; or whether it formed at the time of intense late-tectonic hydrothermal activity. In order to investigate this question, we have studied fluid inclusions and isotopic compositions in the hydrothermally altered rocks of Kettara.

### 4. Sampling and analytical techniques

Fluid inclusions were analyzed in order to characterize the composition of the hydrothermal fluids and to estimate their entrapment conditions. Five samples were studied, two from the mineralized veins adjacent to the Kettara deposit and three from the mafic-ultramafic intrusion. Microthermometric fluid inclusions study was performed at Cadi Ayyad university using a Chaixmeca microthermometry apparatus (Poty et al. 1976), calibrated by standard synthetic fluid inclusions: i/ H₂O-CO₂ inclusions with the melting of solid CO₂ at 56.7 °C, ii/ pure H₂O inclusions (ice melting at 0.0 °C), and iii/H₂O-NaCl with eutectic temperature at −21.2 °C. These data have been verified at Lille 1 University where additional
microthermometric data were obtained using a FLUID INC (USGS-type) heating and freezing stage, calibrated by standard synthetic fluid inclusions: i/ H2O-CO2 inclusions with the melting of solid CO2 at -56.6 °C, ii/ pure H2O inclusions (ice melting at 0.0 °C) and iii/ homogenization temperature of pure H2O inclusions at 374.1 °C. The precision of measurement is ±0.1 and ±0.5 at low- and high-temperature respectively. Semi-quantitative compositional data of inclusion gases were calculated from Laser Raman spectra at Lille 1 University. The Raman spectra were measured using a LabRam HR800 Jobin-Yvon_ microspectrometer equipped with 1800 g/mm gratings and using 532.28 nm (green) laser excitation. Acquisition time span varied from 20 to 60 s during three accumulating cycles. The spectra regions scanned were in the range 1000-1500 cm⁻¹ for CO2, 2250–2750 cm⁻¹ for N2 and H2S and 2750–2950 cm⁻¹ for CH4.

O/H isotope analyses were conducted on quartz and chlorite separated from the intrusion, the deposit, and the mineralized vein adjacent to the deposit. Measurements of oxygen isotope compositions were performed at the stable isotope laboratory of the University of Lausanne following the procedures described by Lacroix and Vennemann (2015). Oxygen isotope compositions are given in the standard δ-notation, expressed relative to VSMOW in permil (‰), and the average precision is ±0.1‰. Measurements of hydrogen isotope compositions of chlorite were performed at the University of Lausanne following the procedures described by Leclère et al. (2014). The results are given in the standard δ-notation, expressed relatively to VSMOW in permil (‰), and the precision is better than ± 2‰.

5. Stable isotopes

Chlorite and quartz from both the Kettara deposit and the intrusion have been studied for their oxygen and hydrogen isotope compositions. Hand-picked chlorite crystals from samples of the massive pyrrhotite ore yield δ¹⁸O and δD values of 6.24‰ (VSMOW) and -48‰.
(VSMOW), respectively (Table 1). Chlorite separated from the pyrrhotite bearing mineralized-veins yield respectively $\delta^{18}$O and $\delta$D values of 7.8‰ (VSMOW) and -52‰. Chlorite separated from the quartz-chlorite veins associated with the shear zones in the intrusion has $\delta^{18}$O=4.4‰ and $\delta$D=-52‰. Chlorite separated from the chlorite schists in shear zones within the Kettara intrusion has $\delta^{18}$O=6.01‰ (Essaifi et al., 2004). The oxygen isotopic composition of chlorite from the Kettara deposit is thus very similar to that from the mineralized veins in its wall rocks and to the chlorite-rich shear zones cross-cutting the Kettara intrusion, supporting the hypothesis that alteration in the deposit, its wall rocks and the intrusion could be related to the same hydrothermal activity.

Hand-picked quartz crystals from the mineralized veins at the margins of the Kettara deposit yield $\delta^{18}$O values of 9.1‰, and quartz from the veins associated with the shear zones in the Kettara intrusion yields $\delta^{18}$O values of 9.8‰ (Table 1). The similarity between the $\delta^{18}$O isotopic compositions of quartz from the mineralized veins in the wall rocks of the Kettara deposit and from quartz-chlorite veins associated with the shear zones within the intrusion indicates that formation of both the mineralized and un-mineralized veins could be related to the same fluids.

Composition of the hydrothermal fluid in the intrusion and the deposit has been calculated using the oxygen fractionation between chlorite and water determined by Cole and Ripley (1998) and Zheng (1993), at temperatures corresponding to the upper greenschist facies (300–400°C). The results give similar values of the hydrothermal fluid, for both calibration curves, between 6.0 and 7.2 ‰ (VSMOW). Such fluid compositions could either correspond to magmatic water or metamorphic water (Sheppard, 1986) (Fig. 7). For hydrogen, the chlorite-water calibration of Taylor (1974) was chosen. The $\delta$D values of the fluid are calculated to be between −14.5‰ and −10.5 (VSMOW), which corresponds more clearly to metamorphic water (Fig. 7).
6. Fluid inclusions

Fluid inclusion studies have been studied in both the quartz-bearing unmineralized veins of the Kettara intrusion and the mineralized veins adjacent to the sulfide deposit. The descriptions below are based on criteria proposed by several authors to classify and determine the origin and content of fluid inclusions (e.g., Bodnar, 2003; Van Kerkhof and Hein, 2001). The vapor-filling ratio ($R_{flv}$) has been estimated at the ambient temperature based on Shepherd’s chart (Shepherd et al., 1985).

In the Kettara intrusion fluid inclusion studies were conducted on quartz and calcite from two quartz-chlorite veins ($V_{q-cl}$) and one quartz-calcite vein ($V_{q-calc}$). According to the phase number at room temperature, many fluid inclusion types have been identified. Microthermometric analysis and Raman spectrometry allowed classification of these inclusions into five types (Table 2): type 1 = H$_2$O-CO$_2$-Salt, type 2 = CO$_2$-N$_2$-CH$_4$, type 3 = H$_2$O-(Salt), type 4 = H$_2$O-N$_2$-CH$_4$ and type 5 = H$_2$O. Type 2 inclusions exist in both the quartz-chlorite and the quartz-calcite veins. The quartz-chlorite veins ($V_{q-cl}$) contain also type 1 and type 3 inclusions whereas the quartz-calcite vein ($V_{q-calc}$) contains type 4 and type 5 inclusions (Fig. 8 and Fig. 9).

Type 1 inclusions are dominantly three-phase inclusions (2 liquids and a vapor, L1+L2+V). They coexist with two-phase inclusions with a thick vapor meniscus and numerous multiphase inclusions containing a solid phase (L1+L2+V+S). Their size varies from 10 to 40 µm and $R_{flv}$ from 5 to 10%. The melting temperatures of carbon dioxide ($T_{mCO2}$) are distributed between $-61.1$ and $-56.7$°C with a mean value at $-58.5$ °C, which are close to the TmCO$_2$ of pure CO$_2$ ($-56.6$ °C) (Fig. 10A). Clathrate melting temperatures $T_{m(cl)}$ are overall between $-9.6$ and 10.5 °C. The lower values of $T_{m(cl)}$ were recorded by three-phase (L1+L2+V) inclusions ($\sim-8$ °C) whereas the higher $T_{m(cl)}$ were collected in multiphase
(L1+L2+V+S) inclusions (≈ 9.2 °C). Homogenization of CO$_2$ occurs either in the liquid phase, with $T_{h(CO2)(L)}$ ranging from 24.6 to 29.9 °C, or the vapor phase, with $T_{h(CO2)(V)}$ ranging from 26.3 to 28.7 °C (Fig. 10B). Ice melting temperature $T_{m(ice)}$ values are between −25.3 and −22.7 °C (mean = −24.1 °C) (Fig. 10C). Bulk homogenization temperature ($T_h$) occurs either into liquid ($T_h(L)$) or critical phase $T_h(c)$. $T_h(L)$ is between 300 and 366 °C, $T_h(c)$ ranges from 321 to 409 °C. Decrepitation occurs sometimes before bulk homogenization and decrepitation temperatures ($T_d$) are between 326 and 416 °C (Fig. 10D).

**Type 2 inclusions** are one-phase inclusions encountered in the quartz-chlorite veins ($V_{q-cl}$) and the quartz-calcite vein ($V_{q-ccl}$) as well. These inclusions are less abundant and are often associated with type 1 inclusions. In $V_{q-cl}$, $T_{mCO2}$ occur between −58.3 and −57.1 °C and homogenization occurs in the liquid phase with $T_{hCO2}$ ranging from 11.2 to 26.2 °C (Fig. 10E, F). The inclusions are composed of CO$_2$, N$_2$ and CH$_4$. According to the semi-quantitative composition (X in mole percent) of gases calculated from Raman spectrum areas, XCO$_2$ varies from 84.6 to 97.9 mol %, XN$_2$ from 0.4 to 9.6 mol % and XCH$_4$ from 0 to 5.9 mol %. In $V_{q-ccl}$, type 2 inclusions exist either as primary inclusions with a dark appearance or as secondary inclusions in transgranular plans. The secondary inclusions have a bright appearance and coexist with FIA of type 3. $T_{m(CO2)}$ and $T_{h(CO2)}$ of primary inclusions are −58.7 and −14.0 °C respectively and the values collected on one secondary inclusion are −57.4 and 5.7 °C respectively (Fig. 10E, F). The average proportion of gases in primary inclusions is XCO$_2$ = 59 mol %, XN$_2$ = 35 mol % and XCH$_4$ is about 6 mol %, and for secondary inclusion XCO$_2$ = 78 mol %, XN$_2$ = 19 mol %, XCH4= 3 mol %.

**Type 3 inclusions** are two-phase at room temperature and are present in the quartz-chlorite veins ($V_{q-cl}$). They are composed of two-phase inclusions sometimes presenting a solid phase. These fluid inclusions occur as primary and as secondary inclusions. The primary inclusions have a size of 5 to 15 µm. They have an irregular shape with often a very thin tip elongated in
the crystal. The largest inclusions are commonly shredded. Their average vapor-filling ratio \( R_{flv} \) is around 10\%, but can reach 20\% when the solid phase is missing. \( T_m(ice) \) are between −24.3 and −17.0 °C with a mean value of −22.2 °C (Fig. 11A). Considering the small size of this fluid inclusion population, we could observe only one solid melting at a temperature \( T_s \) of 278.2 °C. \( T_h(L) \) range from 149 to 261 °C with a mean value at 216 °C (Fig. 11B). Secondary inclusions have a small size (about 5 µm). Their average \( T_m(ice) \) is around −21.8 °C and their \( T_h(L) \) range from 135 to 169 °C with a mean value of 156 °C (Fig. 11A, B). Using either \( T_m(ice) \) or \( T_s \), calculated salinities of primary fluid inclusions are 23.8 and 36.7 wt. % NaCl respectively (Bodnar and Vityk, 1994).

**Type 4 inclusions** consist of two-phase (L, V) fluid inclusions located in growth zones of quartz crystals of the quartz-calcite veins \( V_{q-cc} \). The inclusions are generally shredded or have irregular shapes. They are essentially two-phase inclusions with a dark appearance, \( R_{flv} \) from 5 to 30 \% and a mean size of 10 µm. \( T_m(ice) \) values are between −4.0 and −0.5 °C with a mean value of −1.9 °C in \( V_{q-cc}(\text{Fig. 11C}) \). \( T_h(L) \) range from 205 to 255 °C with a mean value of 240 °C (Fig. 11D). The vapor phase is mostly composed of nitrogen and methane with average mol fractions at 86.1 and 13.9 mol% respectively.

**Type 5 inclusions** occur in \( V_{q-cc} \) where they have a pseudo secondary or secondary origin in quartz and a primary origin in calcite. In quartz they are located in microcracks showing intragranular grain boundaries-grain internal or transgranular trails according to descriptions of Van den Kerkhof and Hein (2001). Their average size is about 5 µm with a constant \( R_{flv} \) in all inclusions (≈5\%). In calcite, they are generally elongated concurrently with the calcite growth direction. Their \( R_{fl} \) are about 5\% and their size range from 4 to 15 µm. The mean value of \( T_m(ice) \) is −0.1 °C in the quartz and around −1.5 °C in calcite (Fig. 11C). The average \( T_h(L) \) is 180 °C in quartz, while in calcite \( T_h(L) \) are a bit lower and range from 131 to 187 °C.
with a mean value of 156 °C (Fig. 11D). The corresponding salinities are relatively low, 0.2 wt. % NaCl in quartz and around 2.6 wt. % NaCl in calcite (Bodnar and Vityk, 1994).

In the mineralized veins adjacent to the Kettara deposit fluid inclusions were studied in quartz associated with pyrrhotite mineralization from a quartz mineralized vein crosscut by carbonates ($V_{m-\text{qc}}$) and a quartz-chlorite mineralized vein ($V_{m-\text{qcl}}$). Carbonates associated with pyrite mineralization were not suitable for fluid inclusion studies because they are less transparent and poor in fluid inclusions. Based on petrographic observations, microthermometric analysis and Raman microspectrometry, different fluid inclusion types have been distinguished and are summarized in table 2.

According to petrographic observation, fluid inclusions in the two mineralized veins consist mainly of two phase and one-phase fluid inclusions at room temperature and scarce inclusions containing a solid phase. After microthermometric and Raman spectrometry analyses, six fluid inclusion types have been identified, not all present in the same sample. Type 1 consists of H$_2$O-CO$_2$-N$_2$-CH$_4$ fluid inclusions; type 2 inclusions are composed of CH$_4$-N$_2$-CO$_2$; type 3 of H$_2$O-salt, type 4 of H$_2$O-CH$_4$; type 5 of N$_2$-CH$_4$ and type 6 of CH$_4$ (Fig. 12). The type 3 inclusions exist in both the quartz-chlorite and the quartz mineralized vein crosscut by carbonates. The quartz mineralized vein crosscut by carbonates ($V_{m-\text{qc}}$) contains also types 1 and 2 whereas the quartz-chlorite mineralized vein ($V_{m-\text{qcl}}$) contains types 4, 5 and 6.

**Type 1** inclusions are two-phase at room temperature with $R_{fb}$ between 5 and 10%. Their size varies from 5 to 50 µm (mean of 20 µm). The inclusions have a rounded or rectangular elongated shape. In these inclusions $T_{m(\text{ice})}$ ranges from $-9.1$ to 0.0 °C with a mean value of $-3.6$ °C (Fig. 13A), $T_h$ is between 178 and 230 °C with an average of 210 °C (Fig. 13B), and $T_{m(\text{cl})}$ ranges from 2.9 to 10.1 °C with a mean value of 6.2 °C. The vapor phase of these inclusions is composed of variable proportions of carbon dioxide, nitrogen and methane. CO$_2$ and CH$_4$ are present in all inclusions whereas nitrogen is often missing or its content is lower.
than the detection limit. $X_{CO2}$ varies from 8.7 to 84.1 mol %, $X_{CH4}$ varies from 8.4 to 51.5 mol %, and when nitrogen, is detected $X_{N2}$ ranges from 17.9 to 79.0 mol %. Their average composition is 44.0 mol % CO$_2$, 21.7 mol % CH$_4$ and 34.4 mol % N$_2$.

**Type 2** inclusions are one phase at room temperature and are commonly observed in the same fluid inclusion assemblages (FIA, Goldstein and Reynolds 1994) than type 1. They are less abundant and have a dark appearance with often an exceptional large size of 60 µm. No visible aqueous phase was detected during microthermometric experiments. Only $T_h$ has been measured in these inclusions. It occurs either into liquid or vapor phase, with values of $T_{h(L)}$ ranging from −99.4 to −70.4 °C (mean = −91.4 °C) and $T_{h(V)}$ from −95.9 to −78.3 °C (mean = −88.9 °C). Raman analysis shows that they are composed of CO$_2$ (from 11.5 to 27.0 mol %), N$_2$ (from 21.0 to 38.1 mol %) and CH$_4$ (from 36.1 to 67.5 mol %). The mean values of these gas show the predominance of methane ($X_{CH4} = 48.0$ mol %) followed by nitrogen ($X_{N2} = 31.9$ mol %) and then by carbon dioxide ($X_{CO2} = 20.0$ mol %).

**Type 3** inclusions exist in both the quartz mineralized vein crosscut by carbonates ($V_{m-qc}$) and in the quartz-chlorite mineralized vein ($V_{m-qcl}$). They have a bright aspect and contain two phases at room temperature. In $V_{m-qc}$ their size is generally about 5 to 30 µm with relatively large $R_{flv}$ (5 to 20%). In $V_{m-qcl}$ they have an irregular shape with sometimes a thin tip oriented in the crystal growth direction which could indicate a primary origin of these inclusions. Their $R_{flv}$ range from 5 to 10% and the $T_{m(ice)}$ are between −7.9 and −2.0 °C in $V_{m-qc}$ and between −17.4 and −0.6 °C in $V_{m-qcl}$, with mean values of −4.7 and −6.3 °C respectively (Fig. 13D). Their $T_h$ range from 176 to 258 °C (mean = 224 °C) for $V_{m-qc}$ and from 174 to 260 °C (mean = 218 °C) for $V_{m-qcl}$ (Fig. 13F). So, in $V_{m-qc}$ salinities are between 3.4 and 11.6 wt.% NaCl and in $V_{m-qcl}$ they range from 1.1 to 20.5 wt.% NaCl. According to the frequency plot of $T_{m(ice)}$ (Fig. 13E), the maximal frequency of $T_{m(ice)}$ corresponds to the mean value in $V_{m-qc}$ (−4.7 °C),
whereas in $V_m$-qcl the value of maximal frequency is a bit lower than the mean value and is around $-5.0 \, ^\circ C$. The salinities from these values are 6.9 and 7.9 wt. % NaCl respectively.

**Type 4** inclusions are two phase fluid inclusions showing a regular shape. They appear dark and are particularly abundant in quartz wrapped by sulfides. Their average size is about 10 $\mu$m with an $R_{flv}$ around 5 and 20 %. One inclusion of this group contains exceptionally a solid phase, which is considered as accidental solid due to the lack of other solid phases in the surrounding inclusions. $T_m(\text{ice})$ range from $-19.2$ to $-0.3 \, ^\circ C$ with a mean value of $-6.0 \, ^\circ C$ (Fig. 13A). $T_h$ range from 212 up to 376 $^\circ C$ with a mean value around 290$^\circ C$ (Fig. 13B), and the mean value of $T_m(\text{cl})$ is around 8.6 $^\circ C$. The Raman analysis indicates that the vapor phase is composed exclusively of methane and the accidental solid is graphite.

**Type 5** inclusions are represented by dark monophase fluid inclusions and form sometimes FIA with type 4 inclusion. They are more abundant in some quartz crystals and have a sub-regular shape. During cooling runs these inclusions showed only a $T_h(V)$ ranging from $-124.1$ to $-105.2 \, ^\circ C$ with a mean value of $-120 \, ^\circ C$, and one $T_h(L)$ observed at $-121.1 \, ^\circ C$ (Fig. 13C). The Raman analysis indicates the presence of nitrogen and methane with $X_{N_2}$ varying between 49.8 and 60.4 mol % and $X_{CH_4}$ between 39.6 and 50.2 mol %.

**Type 6** inclusions consist of monophase secondary fluid inclusions located along transgranular trails with inclusion sizes reaching 40 $\mu$m. As in type 4 inclusions, one inclusion of this group contains an accidental solid. Their microthermometric data are: $T_h(CH_4(V))$ between $-97.4$ and $-93.4 \, ^\circ C$ and $T_h(CH_4(L))$ between $-85.5$ and $-82.0 \, ^\circ C$ (Fig. 13D). The higher limit ($-82.0 \, ^\circ C$) is almost equal to the critical temperature of methane ($T_{\text{critical}} = -82.1 \, ^\circ C$, Ruano 2008). The Raman analysis indicates that these inclusions are filled only by CH$_4$ and that the accidental solid is graphite.

7. Discussion
7. Sources of fluid inclusions

The microthermometric study and Raman analysis showed a wide variety of fluid inclusion types in the mineralized veins adjacent to the massive sulfide ore and the unmineralized veins in the mafic-ultramafic intrusion, but also at the sample scale. The main systems encountered in the veins can be grouped into $\text{H}_2\text{O}$-$\text{CO}_2$-$\text{Salt}$, $\text{CO}_2$-$\text{N}_2$-$\text{CH}_4$, $\text{H}_2\text{O}$-$\text{N}_2$-$\text{CH}_4$, and $\text{H}_2\text{O}$-$\text{Salt}$ systems. They belong to three main fluid types: 1/ a $\text{H}_2\text{O}$-salt fluid with extremely variable salinities, from pure water to quasi-saturated brines; 2/ a volatile-rich ($\text{CH}_4$-$\text{N}_2$-$\text{CO}_2$) fluid with variable proportions of each component ranging from pure component (pure $\text{CH}_4$), binary mixtures ($\text{CH}_4$-$\text{N}_2$) to ternary mixtures ($\text{CO}_2$-$\text{CH}_4$-$\text{N}_2$); 3/ a mixed $\text{H}_2\text{O}$-salt-volatiles fluid; note that $\text{H}_2\text{S}$ was never found. These fluids can be linked to three distinct sources (Sheppard, 1986): (i) metamorphic fluids ($\text{H}_2\text{O}$-$\text{CO}_2$-$\text{CH}_4$-$\text{N}_2$); (ii) magmatic fluids ($\text{H}_2\text{O}$ - salt (Na, K, Li)); and (iii) basinal fluids ($\text{H}_2\text{O}$-hydrocarbon-salt).

According to Thiéry et al. (1994), the ternary $\text{CO}_2$-$\text{CH}_4$-$\text{N}_2$ system is common in fluid inclusions representative of diagenetic, hydrothermal and metamorphic fluids. $\text{CH}_4$ or a mixture of $\text{CH}_4$ and $\text{N}_2$ always dominates the volatiles in the mineralized veins, whereas $\text{CO}_2$ occurs in minor proportions or is absent. In contrast $\text{CO}_2$ is always the dominant species relative to $\text{CH}_4$ and $\text{N}_2$ in the unmineralized veins associated with the shear zones within the intrusion (Fig. 14). $\text{CH}_4$ and $\text{CH}_4$-$\text{N}_2$ indicate reducing conditions, which seem to characterize the mineralized veins adjacent to the deposit.

The variability of compositions, homogenization temperatures and salinities may be attributed to three main phenomena: cooling, boiling or fluid mixing in addition to post-trapping processes. The graphical representation of $T_h$ versus $T_{m(ice)}$ of fluid inclusions containing an aqueous phase allows us to identify the major trends of these mechanisms (Fig. 15).

In the mineralized veins adjacent to the Kettara deposit, the co-existence in the quartz mineralized vein crosscut by carbonates ($V_{m-qc}$), of water+volatile ($\text{H}_2\text{O}$-$\text{CO}_2$-$\text{N}_2$-$\text{CH}_4$, type 1)
and volatile-rich (CH$_4$-N$_2$-CO$_2$, type 2) inclusions in the same FIA is probably an indication of boiling or mixing. This hypothesis is corroborated by the slight evolution of $T_{m(ice)}$ relative to $T_h$, (Fig. 15A). In addition, the composition of the vapor phase (CH$_4$-N$_2$-CO$_2$) of type 1 inclusions is similar to type 2. Final homogenization temperatures of type 1 and type 3 inclusions are almost identical (210–220 °C respectively), which also supports a boiling process by which the separation of volatile phases from the liquid phase occurred, causing the salt concentration in the residual liquid. Fluid inclusions resulting by this process give a similar $T_h$ range. Accordingly the $T_h$ of both types (210–220°C) can be considered as the minimal trapping temperature of the inclusions.

In the quartz-chlorite mineralized vein ($V_{m-qcl}$), there is a linear distribution of type 3 and type 4 fluid inclusions along the $T_h$ axis indicating a more significant variation of $T_h$ than salinities. This distribution mode is characteristic of cooling for both fluid inclusion types (Fig. 15B). On the other side, we also observe that relatively high $T_h$ are recorded by type 4 fluid inclusions (up to 370 °C) compared to type 3 (< 270 °C). This highest $T_h$ suggests the trapping of two immiscible phases in type 4 inclusions (H$_2$O-CH$_4$) and indicates a mixing process probably between those of type 3 (H$_2$O) and type 5 (N$_2$-CH$_4$). After Holloway (1984), the immiscibility between CH$_4$ and H$_2$O could result in the common occurrence of methane as natural gas in low-grade metamorphic terranes. Otherwise, the absence of N$_2$ in type 4 inclusions remains unexplained.

In the Kettara intrusion, the distribution of fluid inclusion data in quartz-chlorite veins ($V_{qcl}$) shows a decrease of $T_h$ at nearly constant salinity, in favor of a cooling in the system. This is valid for primary type 3 ($T_{m(ice)}$ = −22.2 °C, $T_h$ = 220 °C), but also for secondary type 3 fluid inclusions ($T_{m(ice)}$ = −21.8 °C, $T_h$ = 160 °C) (Fig. 15C). Type 1 inclusions belong to the general system H$_2$O-CO$_2$-salt. Their relatively high $T_h(L)$= 350 °C, their homogenization in the critical phases and their high salinity evident from their low $T_{m(ice)}$ (−24.1 °C) can be explained
by the trapping of a fluid in an immiscible state, probably resulting from mixture between a 
magmatic fluid represented by type 3 (H$_2$O-salt) inclusions and a metamorphic fluid 
represented by type 2 (CO$_2$-N$_2$-CH$_4$) inclusions. A mixing processes can therefore explain the 
presence of the type 1 and types 2 inclusions in the same FIA. Whilst boiling is not ruled out, 
the absence of water in the type 2 inclusions is incompatible with phase separations during 
this process (e.g., Lawrence et al., 2013), unless the water meniscus is not visible.

In the quartz-calcite vein, the relationship between inclusions containing an aqueous phase is 
difficult to establish because they do not belong to the same generation and do not have the 
same compositions (Type 3, 4 and 5). The presence of type 4 (H$_2$O-N$_2$-CH$_4$) and type 2 (CO$_2$-
N$_2$-CH$_4$) inclusions in quartz lead us to consider a boiling process. This would explain the 
absence of CO$_2$ in type 4 inclusions. However, it does not explain the apparent absence of 
water in type 2 inclusions although the most recently formed are generally close to aqueous 
bearing inclusions (Fig. 8). However, a small amount of invisible water can be present along 
the rims of these fluid inclusions (Roedder, 1984).

The types of volatile phases and the salinities of the fluid inclusions are compatible with a 
model involving mixing of metamorphic H$_2$O - (CO$_2$, N$_2$, CH$_4$) and magmatic (H$_2$O-Salt) 
fluids in the Kettara shear zones. This is consistent with the stable isotope data, which also 
indicate a metamorphic origin for the hydrothermal fluids. The Kettara shear zones represent 
pathways for upwardly directed and focused fluid flow, and their interconnection allowed 
fluid flow to be channeled at the regional-scale (Essaifi et al., 2004). However, a key question 
is how this fluid flow relates to the formation of the Kettara massive sulfide deposit.

7.2. Microstructural timing of mineralization

It is clear that the Kettara pyrrhotite massive ore has been affected by the ductile Variscan 
deformation. However, the overall relationships are potentially compatible with either: i) 
remobilization of a pre-tectonic, syngenetic ore body; or ii) syn-deformational, epigenetic
emplacement of the ore body (Marshall and Gilligan, 1993). A significant contrast in rheology exists between sulfide minerals and silicate and carbonate host rocks at low metamorphic grades, with the common sulfides (galena, pyrrhotite, sphalerite, chalcopyrite) being less competent than silicate and carbonate host rocks, while pyrite and magnetite are more competent (Marshall and Gilligan, 1993; Rosière et al., 2001). The Kettara pyrrhotite-rich massive sulfide lens is less competent than the surrounding wall rocks and this difference in mechanical behavior should lead to concentration of deformation in the weaker material (pyrrhotite ore body), with possible fracturing and boudinage of the more competent material and shear-strain concentrated along ore-host rock contacts. Such deformation partitioning is not observed at Kettara. On the contrary, pyrrhotite truncates the S1 cleavage (Fig. 4E), and the ore contacts are controlled by fracture and cleavage directions, suggesting replacement of the host rock, while cleavage was overprinted by pyrrhotite and associated sulfides. Such syntectonic replacement could potentially be attributed to redistribution in and around a precursor ore body by local dissolution and precipitation processes (remobilization). However if the main part of the sulfides were pre-tectonic, the more competent sulfide minerals should be boudinaged in a softer matrix of different composition (Gilligan and Marshall, 1987; Aerden, 1994), and pressure shadows should develop around rigid objects like pyrite and magnetite crystals (Passchier and Trouw, 1996; Ramsay and Lisle, 2000). No such evidence is seen at Kettara. In addition, the microstructural control and the progressive gradation from wall rocks-rich ore (semi massive pyrrhotite) to texturally identical wall rocks-poor ore (massive pyrrhotite) suggests that massive ore differs from semi massive ore by the extent of replacement only (Perkins, 1997; De Roo, 1989; Aerden, 1994). Following the guidelines of Marshall and Gilligan (1993), the microstructures at Kettara show little evidence for solid-state mechanical remobilization of original sulfides.

7.3. Emplacement of the Kettara massive sulfide deposit
The fluid inclusion compositions presented here for both the mineralized veins adjacent to the deposit and the shear zones-related veins in the intrusion are compatible with mixing of magmatic and metamorphic fluids. This is supported by the oxygen and hydrogen isotope data for chlorite and quartz from these veins, and aligns well with field and microstructural relationships, which clearly indicate that the veins were formed during deformation and metamorphism. The oxygen and hydrogen isotopic composition of quartz and chlorite in the mineralized veins adjacent to the deposit are similar to those of quartz and chlorite from the shear zones cutting across the Kettara intrusion and support interaction with the same hydrothermal fluid. Calculated hydrogen and oxygen isotope compositions clearly demonstrate involvement of metamorphic water in both the mineralized veins adjacent to the deposit and the shear zones cutting across the intrusion (Fig. 7). The field, microstructural, isotope and fluid inclusion evidence clearly link the hydrothermal alteration around the Kettara deposit and intrusion, including the formation of the mineralized veins, to a fluid flow focused along the Kettara shear zone. The difference recorded in fluid inclusions composition between the unmineralized and mineralized veins can be related to migration of metamorphic fluids through the interconnected regional shear zones into host rocks rich in organic matter where their reduction contributed to precipitation of sulfides. Crystallization of pyrrhotite instead of pyrite in the mineralized veins probably arises from the organic-matter driven reducing conditions during metamorphism as has been observed in graphitic sulfide-rich schists from south-central Maine (Ferry, 1981) and Late Precambrian Lower Dalradian Ballachulish Slate Formation metasediments (Hall et al., 1987).

The major question that remains is the relationship of this syn-metamorphic hydrothermal episode to the formation of the Kettara massive sulfide deposit. The deformational history of many massive sulfide deposits within the Variscan belt has been a subject of much debate.
(e.g. Marignac and Cathelineau, 2006; Sanchez-Espana et al., 2006; Marcoux et al., 2008; Essaifi and Hibti, 2008) between proponents of syngenic versus epigenetic models.

At Kettara, the mineralized veins may hold the key to answering this question. The presence of sulfides within the mineralized veins indicates a genetic relationship with the deposit, but does not yet prove that they formed at the same time. The mineralized veins could have derived their sulfide content by syntectonic remobilization (dissolution and reprecipitation) of a preexisting syngenic massive sulfide deposit. However, the textural evidence for syntectonic sulfide replacement of foliated host rock plus the structurally controlled localization of the deposit in a step-zone between regional shear zones favor a model in which veins and massif sulfides formed synchronously from the same fluid. It could still be argued in this case that this deformation episode completely remobilized an earlier syngenic massive sulfide deposit, but although no field or textural evidence remains to support this hypothesis. The 331 and 300 Ma ages obtained for alteration minerals around similar deposits in Central Jebilet and Guemassa massifs (Marcoux et al., 2008; Watanabe, 2002) support emplacement of these massive sulfide deposits during regional deformation metamorphism.

Late-stage pyrite and carbonate veins within the Kettara shear zone are only affected by brittle deformation, clearly indicating that metal-bearing hydrothermal fluids continued to circulate in the Kettara area as deformation evolved from ductile to brittle conditions. Formation of the Kettara mineralized veins was thus realized through a protracted period of deformation and sulfide mineralization.

8. Conclusion

Central Jebilet represents a major massive sulfide province of significant economic importance. The clear association of the massive sulfide deposits with bimodal magmatism and shear zones is exemplified in the Kettara area where a massive sulfide deposit and a
A mafic-ultramafic intrusion are located within a “compressional jog” of a regional wrench shear zone. Field and textural evidence clearly indicate that mineralized veins adjacent to the deposit developed during shearing, and that hydrothermal fluid circulation continued into the brittle deformation regime. Hydrothermal alteration in both the intrusion and the wall rocks adjacent to the deposit are similar and related to the same hydrothermal fluids, i.e. a mixture of metamorphic H₂O - (CO₂, N₂, CH₄) and magmatic fluids (H₂O-Salt). We conclude that if the mineralized veins are an integral part of the Kettara deposit, then emplacement of the pyrrhotite-rich massive sulfide deposit occurred during deformation and metamorphism. The metamorphic fluids scavenged sulfur and metals from the country rocks and were channeled through active shear zones, depositing massive sulfides in reducing environments offered by organic-rich host rocks. The alternative interpretation that the mineralized veins represent remobilization products of a pretectonic orebody is possible but not supported by our data for Kettara. Further work is undoubtedly needed to assess mineralization models at the scale of the whole central Jebilet.

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Figure Captions

Fig. 1A) The Jebilet massif in the framework of the Palaeozoic outcrops of North Africa (in grey), B) Location of the Jebilet massif in the frame of the Variscan fold belt of Morocco, C) Geological sketch map of the Jebilet massif (modified after Huvelin 1977). Box encloses area covered by Figure 2.

Fig. 2 A) Shear zone pattern in Central Jebilet (modified after Essaifi and Hibri, 2008), B) Schistosity trajectories and deformation kinematics around the Oled Har-Kettara-Safsafat magmatic lineament. Regional schistosity displays curvatures that indicate N-S sinistral
wrenching interconnected by an east-northeast dextral shear zone in the Kettara area, C) Geological and structural map of the Kettara area. Location of the cross-section shown in Fig. 3 is indicated.

**Fig. 3** Vertical cross-section through the Kettara intrusion and Cu deposit. See location in Fig. 2C. The diagrammatic sections illustrate meter-scale shear zones in the Kettara mafic-ultramafic intrusion and the relationships between deformation and quartz ± calcite veins in both the intrusion and the gossan. Stereographic diagrams show equal area, lower hemisphere projections of planar and linear structures. S0 (bedding) and Le (stretching lineation) in the Kettara intrusion were measured respectively at the bottom of the intrusion and in the contact aureole around the intrusion. The S1 stereonet represents the regional schistosity in the whole Kettara area.

**Fig. 4** Representative field exposures of the Kettara intrusion and deposit and drill core specimen of the Kettara deposit. A) Panoramic view from the Kettara intrusion, looking northwest to the Kettara deposit, and showing the relief of the Kettara gossan and the remnants of old workings, B) Mineralized quartz-chlorite vein cutting the schists at a low angle in the Kettara gossan, C) Quartz mineralized vein crosscutting wall rocks composed of alternating pelites (black) and sandstone (grey) layers. Note that mineralization within the vein lie in continuity with the pelite layers., D) Sigmoidal quartz-calcite vein in a chlorite-rich shear zone of the Kettara intrusion, E) Specimen from the drill core K101 showing the contact between the pyrrhotite lens and the host schists. Pyrrhotite (PO) cuts across the contact, contains enclaves of the host schists (HS) and is crosscut by carbonate (CC) veins, (F) Specimen from the drill core K101 showing a mineralized quartz-chlorite vein crosscut by a carbonate (CC) vein (scale piece is 24 cm across).
Fig. 5 Photomicrographs of the Kettara ore and its host rocks. A) Metapelites located 170 m to the south of the deposit, showing the stratification ($S_0$) and schistosity ($S_1$) planes, B) Chloritized metapelites located 2 m from the southern boundary of the deposit, showing pressure shadows around ilmenite grains (Ilm), C) Semi-massive pyrrhotite ore showing chloritized wall rocks with $S_1$ cleavage truncated by pyrrhotite, D) Polymetallic assemblage of pyrrhotite, chalcopyrite (Ccp), sphalerite (Sph), arsenopyrite (Asp) replaced by carbonates (Car), E) Replacement of a pyrrhotite-chalcopyrite assemblage by carbonates and euhedral pyrite (Py), F) Cataclastic deformation of pyrite resulting in comminution breccias. A, B (transmitted light), C, D, E, F (reflected light).

Fig. 6 Paragenetic successions of the main mineralizing fluids in the Kettara massive sulfide deposit. 1 and 2 are respectively the first (pyrrhotitic ore) and the second (pyritic ore) main phases of mineralization.

Fig. 7 Plot of $\delta D$ vs. $\delta^{18}O$ values of chlorite (white star) and the calculated mineralizing fluid (white square). Fluid composition was calculated using oxygen and hydrogen fractionation between chlorite and water from Zheng (1993) and Cole and Ripley (1998) for oxygen, and from Graham et al. (1987) for hydrogen. Compositions of Primary igneous water, metamorphic water and sedimentary rocks are from Sheppard (1986).

Fig. 8 Photomicrography and sketch of some fluid inclusions in quartz-chlorite veins of the Kettara intrusion. A) Assemblage of aquo-carbonic ($H_2O-CO_2$-Salt) fluid inclusions composed by two phases and three phases ($L, V1, V2$) fluid inclusions (type 1). B) Sketch showing an aqueous-saline ($H_2O+Salt$) fluid inclusions, composed by two phases and three phases ($S, L, V$) primary (I) and secondary (II) fluid inclusion plans of type 3. C) Two phases aqueous-saline fluid inclusions of type 3 (I) showing irregular shapes and oriented along the elongation of quartz crystal (photomicrography of the central part in B).
Fig. 9 Photomicrography of main fluid inclusions in quartz (A-D) and calcite (E) of quartz-calcite vein of the Kettara intrusion. A) two phases H₂O-N₂-CH₄ fluid inclusions (type 4). B) One phase CO₂-N₂-CH₄ primary fluid inclusions (type 2 (I)). C) Intragranular plans of two phases aqueous fluid inclusions (type 5). D) Assemblage of secondary fluid inclusion plans including one phase CO₂-N₂-CH₄ fluid inclusions (type 2 (II)) and two phases fluid inclusions (type 5). E) Aqueous fluid inclusions (type 5) in calcite, which is considered as secondary with respect to the vein formation.

Fig. 10 Histogram frequency of microthermometric data of fluid inclusions in veins from the shear zones of the Kettara mafic ultra-mafic intrusion. (a-b) \( T_{m(CO2)} \) (a) and \( T_{h(CO2)} \) (b) of aqueous gas-bearing fluid inclusions (type 1). (c-d) \( T_{m(ice)} \) (c) and \( T_h \) (d) of aqueous gas-bearing fluid inclusions (type 1 and type 4). (e-f) \( T_{m(CO2)} \) (e) and \( T_{h(CO2)} \) (f) of aqueous gas-rich fluid inclusions (type 2). Homogenization occurs either into liquid phase (l) or vapor phase (v), as critical (c) or decrepitation (d). \( V_{qcl} \) : quartz-chlorite veins, \( V_{qcc} \) : quartz-calcite vein.

Fig. 11 Histogram frequency of microthermometric data of fluid inclusions in veins from the shear zones of the Kettara mafic ultra-mafic intrusion. (a-b) \( T_{m(ice)} \) (a) and \( T_h \) (b) of primary (I) and secondary (II) aqueous saline fluid inclusions (type 3). (c-d) \( T_{m(ice)} \) (c) and \( T_h \) (d) of aqueous fluid inclusions (type 5). \( V_{qcl} \) : quartz-chlorite veins, \( V_{qcc} \) : quartz-calcite vein. * indicates the measures collected in calcite.

Fig. 12 Photomicrographs of fluid inclusions in mineralized veins of massive sulfide in transmitted light. A) quartz±carbonates mineralized vein: assemblage of two phase H₂O-N₂-CO₂-CH₄ inclusions (type 1) and one phase CH₄-N₂-CO₂ inclusions (type 2). (B-E) quartz-chlorite mineralized vein, B) Two phase aqueous fluid inclusions showing a thin tip in crystal growth direction of quartz (type 3), C) two phases H₂O-CH₄-(Salt) fluid inclusions in quartz.
wrapped by sulfides (type 4, figure 3f), D) one phase N2-CH4 fluid inclusions (type 5). E) Secondary plan of one phase CH4 fluid inclusions (type 6).

**Fig. 13** Histogram frequency of microthermometric data of fluid inclusions in mineralized veins of the Kettaramassive sulfide. (a-b) Tm(ice) (A) and Th (B) of aqueous gas-bearing fluid inclusions (type 1 and 4). (C-D) Th of gas-rich fluid inclusions (type 2, 5 and 6). (E-F) Tm(ice) (E) and Th (F) of aqueous fluid inclusions (type 3). Homogenization occurs into liquid phase (l) or vapor phase (v). Vm-qc: quartz±carbonates mineralized vein, Vm-qcl: quartz-chlorite mineralized vein.

**Fig. 14** Ternary diagram showing the repartition of gas phases in fluid inclusions of the mineralized veins of the Kettara massive sulfide deposit and the veins of the shear zones in the Kettara intrusion. A) Aqueous gas-bearing inclusions ((H2O-gas-(Salt)), type 1 and type 4 of all veins) showing a sparse repartition of gases. B) Gas-rich fluid inclusions (type 2 of all veins and type 5 and type 6 in mineralized veins) showing the prevalence of CH4 and N2 in the mineralized veins and CO2 in the veins associated to the shear zones of the intrusion.

**Fig. 15** Plot in $T_h$ vs $T_{m(ice)}$ binary diagram of representative microthermometric data of type 1, type 3, type 4 and type 5 fluid inclusions of the veins associated to the shear zones of the Kettara intrusion (see description in the text).
TABLE 1. Oxygen ($\delta^{18}O$) and hydrogen ($\delta^D$) isotope composition of chlorite and quartz of the Kettara deposit, the mineralized veins and the shear zones of the Kettara intrusion

<table>
<thead>
<tr>
<th>Location</th>
<th>Lithology</th>
<th>Sample</th>
<th>$\delta^{18}O$ (%)</th>
<th>$\delta^D$ (%)</th>
<th>$\delta^{18}O$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kettara deposit</td>
<td>Massive pyrhotite</td>
<td>KET5</td>
<td>6.24</td>
<td>-48</td>
<td></td>
</tr>
<tr>
<td>Kettara deposit</td>
<td>Mineralized vein</td>
<td>KIM7-2</td>
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<td>-52</td>
<td>9.1</td>
</tr>
<tr>
<td>Kettara intrusion</td>
<td>Quartz-chlorite vein</td>
<td>KTG2</td>
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<td>-52</td>
<td>9.8</td>
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<td>Kettara intrusion</td>
<td>Chlorite schist$^1$</td>
<td>MK3</td>
<td>6.01</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$^1$from Essaifi et al. (2004)
TABLE 2. Summary of microthermometric and Raman spectrometric data of fluid inclusions in mineralized veins of the Kettara massive sulfide deposit and in veins associated with shear zones of the Kettara mafic-ultra mafic intrusion

<table>
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<tr>
<th>Fluid inclusion type</th>
<th>Range</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Average</th>
<th>N</th>
<th>Size µm</th>
<th>CO₂ %</th>
<th>N₂ %</th>
<th>CH₄ %</th>
<th>Others</th>
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<tr>
<td><strong>H₂O-CO₂-N₂-CH₄</strong></td>
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<tr>
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<td>178</td>
<td>5</td>
<td>5</td>
<td>8.7</td>
<td>0.0</td>
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<td>10</td>
<td>10</td>
<td>84.1</td>
<td>/9.0</td>
<td>51.7</td>
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<td>6.2</td>
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<td>17</td>
<td>44.0</td>
<td>34.4</td>
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Marrakech
0 50 Km
Eastern Jebilet
Central Jebilet
Western Jebilet

(A)

Atlantic Ocean
Mediterranean sea
Anti Atlas

(B)

Anti Atlas

(C)

Western Meseta: Late Devonian fold belt
Eastern Meseta: Late Carboniferous belt
Main Hercynian granitoid plutons
Relatively rigid blocks
A: Sehoul block
B: Coastal block
Pre-Sahara foreland
Post-Visean shortening
Main transcurrent faults
WMSZ: West Meseta Shear Zone
SMFZ: South Meseta Fault Zone

Marrakech shear zone (MSZ)
thrust-wrench fault (West Meseta shear zone, WMSZ)
fold axes, anticline (a), syncline (b)

Fig. 2a
A pyrrhotite-rich deposits felsic intrusions mafic intrusions ductile shear zones brittle shear zones regional schistosity pyrrhotite-rich deposits


pelite with sandstone (a) and carbonaceous layers (b) massive sulphide deposit mine wastes Kettara mafic-ultramafic intrusion Kt. Delaa felsic intrusion

Fig. 3 Mafic dykes Felsic dykes Quartz veins Schistosity strike a (near-vertical) b (inclined) meter-scale shear zones brittle shear zones
**Kettara Intrusion**

- Leucogabbros
- Peridotites
- Chlorite-rich shear zones

**Limestone Sandstone**

- Carboniferous schists
- S1 cleavage
- S0

**Dolerites**

- Qtz-Chl vein
- Qtz-Cal vein

**Pyrrhotite Deposit**

- Mineralized Qtz vein

**Kettara Gossan**

- Qtz vein
- Mineralized Qtz vein

**Legend**

- Leucogabbros
- Peridotites
- Sandstone
- Limestone
- Carboniferous schists
dolerites
- Pyrrhotite deposit
- Chlorite-rich shear zones

**Microfabrics**

- Kettara Intrusion
- Kettara Gossan

- S0
- Le
- S1
- Le
- S0

- n=60
- n=19
- n=251
- n=21
- n=60
A. Kettara Gossan

Lower Carboniferous schists

Kettara intrusion

B. Qtz + Chl

S1

C. Pelite layer

Sandstone layer

D. Qtz + Cc

E. 20 mm

S1

F. Qtz + Chl
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Relative timing
Meteoric Water Line

Sedimentary rocks

Massive ore

Mineralized quartz-chlorite vein

Quartz-chlorite vein in shear zones of the Kettara intrusion

δD‰VSMOW

δ18O‰VSMOW

Sea water

Metamorphic water

Primary igneous water

Sedimentary rocks
A  

Mineralized veins  
Veins in shear zones of the intrusion

B  

Mineralized veins  
Veins in shear zones of the intrusion
Highlights:

Kettara shear zone hosts a mafic-ultramafic intrusion and a Cu-deposit

A regional metamorphic fluid flow occurred through the shear zone

Reduction of fluids induced sulfides precipitation in wall rocks of the deposit