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# GENETIC IMPLICATIONS OF THE AIN SEDMA IRON MINERALIZATION, NE ALGERIA

**Purpose.** To reconstruct the geological evolution of the Ain Sedma magnetite lodes, located in NE Algeria.

**Methodology.** The petrographic and elemental composition of the ores were determined using energy dispersive spectroscopy and elemental mapping whilst oxygen isotope ratios were measured on rock samples and high purity mineral separates from the Ain Sedma iron.

**Findings.** Petrographic observations show massive texture, spherulitic lamellae, skeletal growths, dendritic branching, and rare vesicular crystals. Major constituents are iron oxides with quartz being the most dominant gangue mineral. Oxygen isotope analysis for both host rock and iron ores gave $\delta^{18}O$ values ranging from 19.1 to 22.5 ‰ V-SMOW and 15.9 to 20.3 ‰ V-SMOW, respectively. These results support the involvement of an $^{18}O$-rich and Fe- rich component in the genesis of the host rock and the associated mineralization.

**Originality.** The present study is the first to combine geochemical data and petrographic observations to establish the genesis processes the mineralization and the host rock have passed through, from the beginning of partial melting until magma eruption.

**Practical value.** These results are the first geochemical analysis delivered in the area which focuses mainly on the genetic model of the host rock and the mineralization as well as their mutual relationships.

**Keywords:** *Ain Sedma, chemical composition, iron ore, metamorphic basement, oxygen isotopes, rhyolite*

**Introduction.** The earth's lithosphere is composed of a mosaic of plates, which move on and sink into the earth's mantle along subduction zones. The energy generated during lithospheric subduction constitutes the most plausible engine that drive the plates and cause mid-ocean ridges to spread. As the hydrated oceanic plate sinks down into the asthenosphere, metamorphic dehydration reactions begin with the breakdown of hydrous minerals such as amphibole and micas. Thus, water released from the dehydration of subducting sediments and oceanic crust into the overlying mantle wedge triggers the depression of the peridotite solidus followed by its partial melting. The role of these fluids released from the slab is crucial for the transport and concentration of ore metals. It is another hot topic in earth science because the processes leading to the formation of large-scale ore metals from the beginning of subduction to the genesis, storage, and eruption of arc magma remain rather obscure. It is well known that the aqueous solutions derived from the dehydration of subducting plates contain various amounts of solutes such as $CO_2$, Cl, Na and F, responsible for dissolving and transporting metals. This process leads to the precipitation of different ore deposits associated with the magma generated in the mantle wedge beneath arc volcanoes. However, temperature, pressure, oxygen fugacity, and pH, can significantly influence the chemical state of fluids and metals and thus, that of ore deposits. In order to deal with these parameters, a huge number of authors prefer to use stable isotopes such as O, S, C, and H as a determinant tool to decipher the fluid-rock interactions, and the source of ore-forming fluids. Given that oxygen is a major component of a wide variety of earth materials, oxygen isotope ratios may supply important insights about ore formation processes and evolution, including temperature and fluid source. Moreover, oxygen isotopes have been largely used to unravel the origin and the formation conditions of igneous rocks from the beginning of partial melting until magma eruption [1]. The Miocene magmatic chain that extends along the Algerian coast is believed to be the consequence of a slab break-off process. The upwelling of the enriched plume-type asthenospheric mantle through the slab window generated by slab break-off during the Neogene subduction regime triggered decompression-induced partial melting [2]. The generated melts experienced variable degrees of fractional crystallization and crustal contamination during their ascent, leading to the formation of metaluminous mafic to intermediate and highly differentiated peraluminous products [3], followed by a powerful circulation of thermal fluids. This activity is thought to be the trigger of the formation of the different mineralization occurrences along the North Algerian coast. Next to the chromite associated with the alpine-type peridotite of the Bougaroun basement [4], which is apparently the result of fractional crystallisation, other mining sites, belonging to the same district such as Ain Sedma iron ores, are interpreted to be the product of magmatic immiscibility. Magmatic-related iron deposits are mostly associated with calc-alkaline magmatic rocks such as andesites, dacites, and rhyolites which point to a subduction affinity. In spite of the substantial number of studies carried out on the magmatic rocks of the Bougaroun area, the related Fe-mineralization of Ain Sedma has not received sufficient exploration. Our attention will be, therefore, centred on the genetic relationships between the host rock and iron deposits using the stable oxygen isotope variations in host rock and ores.

***Regional geology.*** The Bougaroun massif, located in NE Algeria, is the largest igneous exposure ever known in the magmatic alpine belt, outcropping along the North African coast. The majority of the granitoids clustered in this region are interpreted to have originated through the assimilation of metapelitic material by a relatively less peraluminous magma [2]. According to the same authors, these rocks could be produced in areas of high heat flux related to the input of a mantle derived magma into the crust, possibly in a slab break-off tectonic setting. In terms of trace elements and REE composition, a wide range of these rocks, including mafic and intermediate items, share similar characteristics with the most differentiated ones. Indeed, mafic rocks (dolerites and gabbros) from the same area exhibit LREE enrichment with $La_N/Yb_N$ ranging from 2.9 to 6.0 and a prominent negative Eu anomaly. Moreover, these rocks reveal high Ba, Th, and U contents and a distinct Nb-Ta negative anomaly. Associated intermediate and felsic rocks share the same character with a rather fractionated REE pattern [2, 3]. According to these authors, the Bougaroun igneous rocks seem to be derived from the same mafic source. Finally, these igneous rocks intrude the Bougaroun basement made up almost exclusively of high-grade metamorphic rocks (kinzigites) and serpentinized lherzolites with the occurrence of rare relicts of dunite [4]. These lithologies are locally crosscut by marble lenses, most of which have been transformed into skarns by thermal metamorphism induced during the emplacement of the Bougaroun igneous rocks [5].

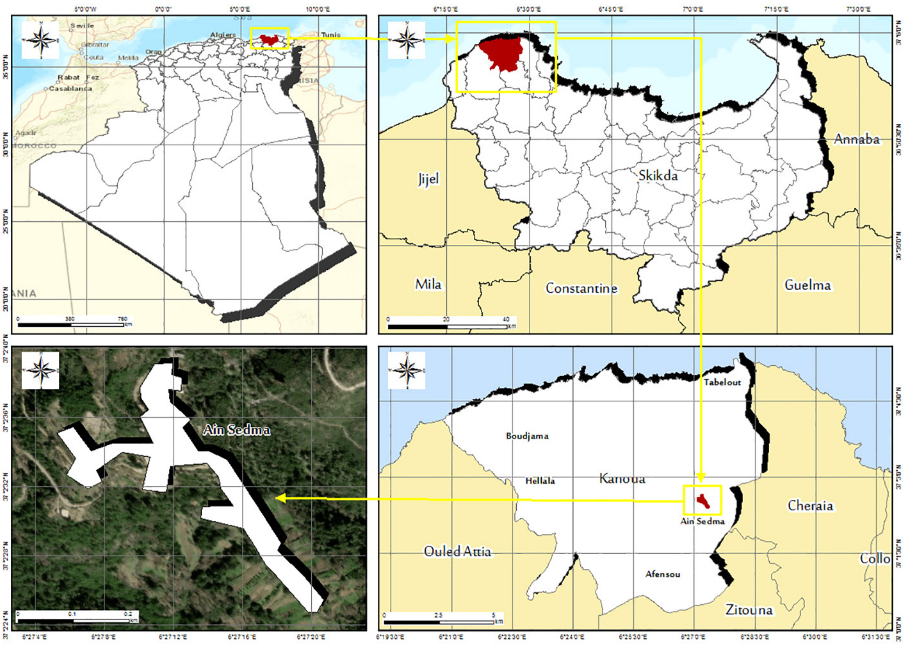


*Fig. 1. Geographic situation of Ain Sedma*

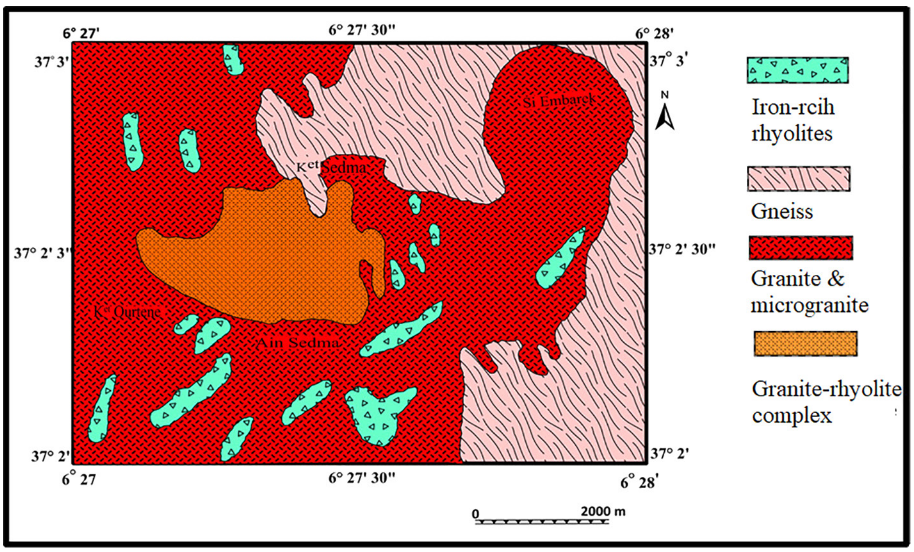


*Fig. 2. Simplified geological map of Aïn Sedma (after* [3]*), modified, showing the different lithologies*

The Ain Sedma rhyolites are highly siliceous (>80 % $SiO_2$), which suggests the involvement of an important crustal material in their genesis process [3].

***General features of the Ain Sedma iron ores.*** The magmatic model proposed to explain the genesis of the Ain Sedma Fe deposit was developed using field and microscope observations, enhanced by a thermomagnetic study of host rocks (rhyolites). In fact, the $Fe_2O_3$ content of the host rocks increases when we approach the magnetite lodes. Nevertheless, no appreciable changes have been observed in the rocks' mineralogy. This may reflect the fact that iron genesis is unrelated to the evolution of the nearby skarns. As regards to Ain Sedma iron ores, the lack of any geochemical data and excessive hydrothermal alteration degrees makes this assumption quite suspicious. Since other mining sites, which are believed to be similar in age and genetically and spatially related to the same magmatic chain such as the Oued Amizour zinc deposit or Oued El Kébir, were attributed to the Kuroko type, it is of primary importance from our point of view to reveal the oxygen isotopic composition of the Ain Sedma ores and host rocks in order to reconstruct their origin. The discovery of the Ain Sedma iron mine is attributed to the Roman era. Still, a limited number of studies have been undertaken thus far. The main ore deposit of Ain Sedma is associated with the rhyolitic dykes. The upper part of the massive ores contains veinlets filled with calcite and quartz. The latter occurs as well-developed crystals in the holes. The uppermost part of the orebody is formed of magnetite and limonite. Drilling works reached a depth of 35 m vertically, and it was seemingly the deepest point ever reached in the area before the mining company stopped metal extraction. This lower part is actually wholly covered by vegetation. Under microscope, magnetite shows 1) elongated skeletal crystals (Figs. 3, *a–d*); 2) needle-like laths grouped as spherulites (Figs. 4, *a*, *b*, *e*); 3) common dendritic growths (Figs. 4, *c*, *g*, *h*); 4), vesicular crystals (Fig. 4, *d*); finally, 5) quartz crystals filling up the holes in magnetite lamellae (Fig. 4, *f*).

**Materials and methods.** SEM-EDS analysis was implemented for the purpose of identifying the ore texture and chemical composition using a Quanta-250 FEI scanning electron microscope at the National Higher School of Technology and Engineering, Annaba, Algeria. Results are given in Figs. 5 and 6. The oxygen isotopes ($\delta^{18}O$) ratios of rhyolites and associated ores separates were determined by reacting approximately 20 mg of powdered material with 100 % anhydrous phosphoric acid at 72 °C for 4 hours. The $CO_2$ released was analysed using a Thermo-Finnigan DeltaPlusXP Continuous-Flow Isotope-Ratio Mass Spectrometer (CF-IRMS) coupled to a Thermo-Finnigan Gas Bench II. The $\delta^{18}O$ values are reported in Table using the delta (δ) notation in permille (‰), relative to the Vienna Standard Mean Ocean Water (V-SMOW), with precisions of 0.2 ‰. (Department of Geological Sciences, Miller Hall, Queen's University Kingston, Ontario, Canada).

**Results and discussion.** ***Textural analysis.*** The SEM-EDS mapping images show the distribution of elements in different samples. The results are consistent with petrographic observations showing a homogeneous distribution of the main elements. Iron (Fe) is the predominant element and is uniformly distributed in the matrix,

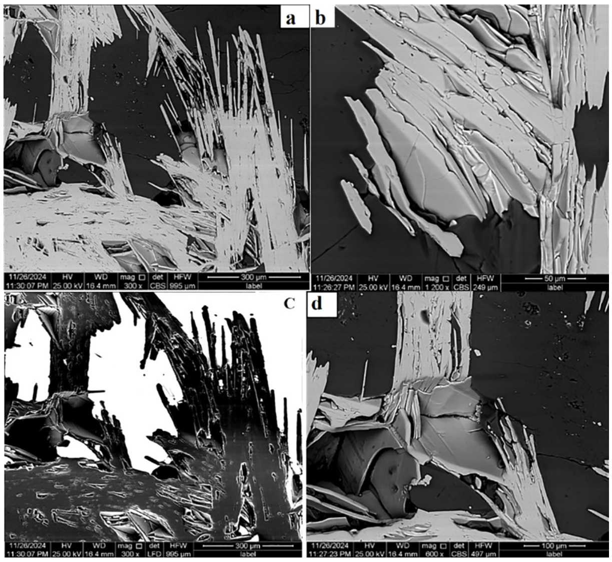


*Fig. 3. SEM micrographs showing different textures of magnetite crystals:*

*a, c, d – magnetite crystals forming skeletal growths with needle-like lamellae developed at their edges. these needles crosscut each other forming skeletal like corps of magnetite; for many authors, these structures may indicate a quick growth from a supersaturated lava; b – stacked magnetite slats "coated" with quartz. These two different habitus characterizing magnetite crystals indicate at least two stages of ore formation. Abbreviations: Mag: magnetite; Qz: quartz*

confirming that iron minerals are the main mineralogical constituent. Oxygen (O) is also well distributed with high percentages, consistent with its presence in iron oxides. The presence of carbon (C) indicates the presence of carbonate compounds such as calcite despite the absence of calcium (Ca) due to its high mobility speed. The presence of silicon (Si) suggests a notable contribution from quartz as a predominant gangue mineral. The presence of aluminium (Al), even with low percentages, reveals the presence of feldspars. The absence of potassium (K) is due to its high mobility speed. Oxygen isotope. Oxygen isotopic compositions of whole rock and high purity mineral separates are given in Table. All analysed samples show very high values of $\delta^{18}O$ for both host rock and mineralization. The rhyolites from the Ain Sedma complex gave $\delta^{18}O$ values ranging from 19.1 and 22.5 ‰ V-SMOW, while associated magnetite separates cover a larger interval with $\delta^{18}O$ ranging from15.9 to 20.3 ‰ V-SMOW. The lowest values of $\delta^{18}O$ in magnetite separates and host rocks were recorded in samples AS02C and AS03A respectively.

***Ore petrography.*** Textural observations show that quartz is a late phase precipitated after magnetite (Fig. 7, *f*). Dendritic branching, spherulitic and skeletal textures obtained from SEM images (see above), the replacement of holes in massive ores by calcite and automorphic quartz may reflect a rapid crystal growth from supersaturated melts. In terms of mineralogy, the Ain Sedma ores share many features with the IOA deposits including massive magnetite and host rock (calc-alkaline volcanic rocks). However, apatite is not as abundant in the mineralization as it is in IOA deposits. This fact may hold some kind of clue about the difference between their genetic model. In fact, the presence of mag-

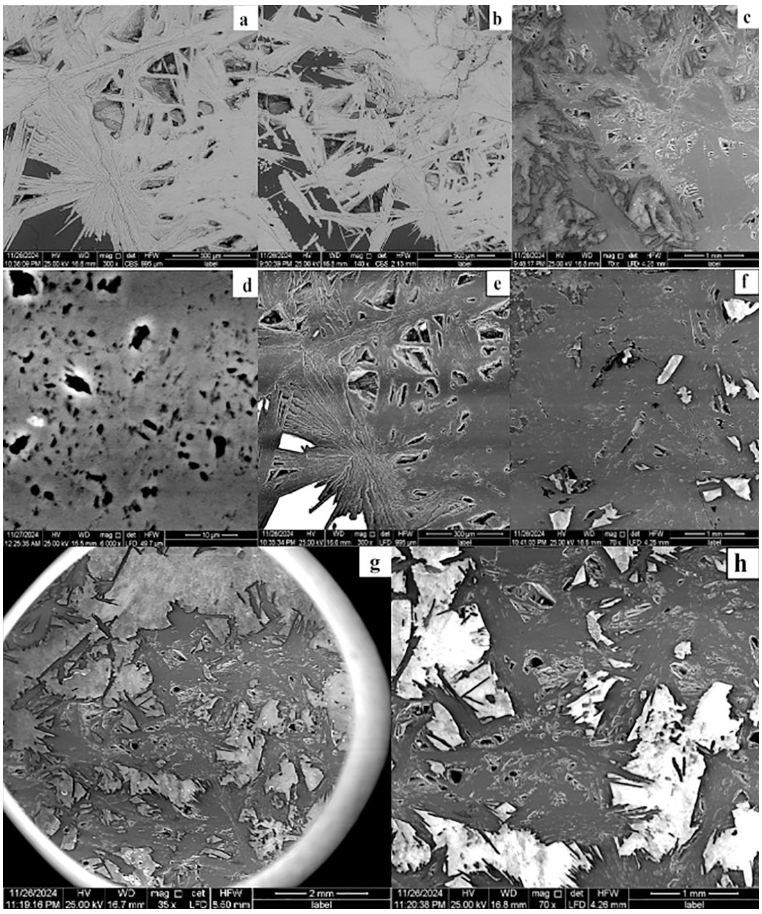


*Fig. 4. SEM micrographs showing different textures of magnetite:*

*a, b, c, and e — demonstrate spherulites growths formed within magnetite crystals in a skeletal texture; d — illustrates vesicular magnetite that is considered as one of the distinctive criteria for magmatic magnetite; f — quartz crystals filling holes in magnetite; h, g — magnetite lamellae forming dendritic branching with sharp edges and empty holes in the magnetite crystals. The gangue is mostly formed of quartz slightly replaced by calcite*

*Table*

Oxygen isotope ratios measured on whole rock and associated iron mineralization

| Rock sample ID | Location | lithotype | $\delta^{18}$O ‰ vs VSMOW |
|---|---|---|---|
| AS 04 B | Ain Sedma | Rhyolite | 22.5 |
| AS 02 A | Ain Sedma | Rhyolite | 22.4 |
| AS 03 A | Ain Sedma | Rhyolite | 19.1 |
| AS 06 A | Ain Sedma | Rhyolite | 22.4 |
| AS 02 B | Ain Sedma | Magnetite | 20.3 |
| AS 03 | Ain Sedma | Magnetite | 20.3 |
| AS 04 | Ain Sedma | Magnetite | 18.5 |
| AS 02 C | Ain Sedma | Magnetite | 15.9 |

netite in the Ain Sedma skarns may well fit a hydrothermal origin, given that their formation has been assigned to the emplacement of the same volcanic complex. These skarns have been affected by variable hydrothermal events, including sulphuration, oxidation and hydroxylation that changed their primary mineralogy. The sulphuration phase induced the destabilization of iron pyroxene into andradite-pyrite-quartz and calcite. The oxidation phase is characterized by the breakdown of garnet into iron oxide-quartz and/or calcite-quartz and pyrite in iron oxide. The hydroxylation phase is mainly characterized by the replacement of pyroxene by amphibole and/or ilvaite [5]. If the adjacent iron ores associated with volcanic rocks were formed the same way the skarns' related magnetite did, the transition from altered rhyolite into massive ores would have left some relicts of the different paragenetic sequences the protolith passed through (e.g. amphibole, clinopyroxene, garnet, iron oxides). Since none of the magnetite lodes hosted by the volcanic rocks show this character, these ores are unlikely to be formed from post-magmatic hydrothermal alteration of rhyolites. Furthermore, the % of Fe increases in the rhyolites contiguous to the iron ores. However, no appreciable changes of mineralogical composition have been observed in the host rock. It is thus inconceivable that magnetite related to the Ain Sedma skarns and those associated with the rhyolites could have formed the same way.

***Stable isotopes.*** The oxygen isotope ratios measured on the whole rock (rhyolite) are unusually higher than what is expected for similar volcanic rocks, ranging from +19.1 to +22.5 ‰ V-SMOW (mean = 20.8 ‰) and mark the highest $\delta^{18}$O ever identified in the North African magmatic belt.

Generally, high oxygen isotope ratios observed in felsic rocks are believed to be the consequence of a signifi-

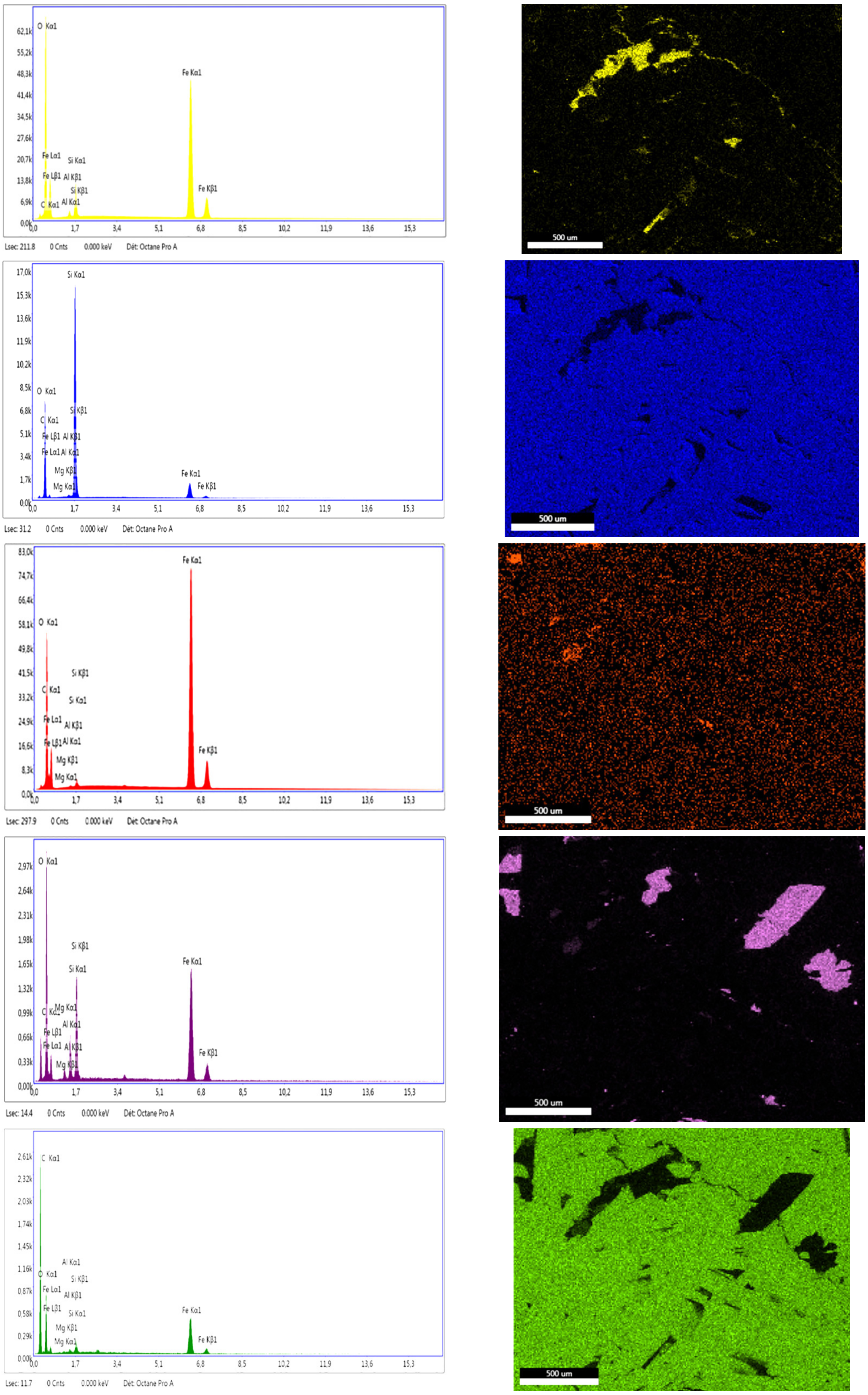

*Fig. 5. SEM elemental mapping and corresponding energy dispersive spectroscopy graphs showing the chemical composition of magnetite lodes from Ain Sedma Iron Mine (AS03B)*

cant involvement of high $^{18}$O metasedimentary material or reworked volcanic rocks in the melting process. High $\delta^{18}$O ratios of volcanic rocks are documented in the NE Algeria volcanic rocks [2] and many other similar outcrops in the world (e.g. UAE-Oman granites [1]. [2] assigned the unusually high $\delta^{18}$O of Cap Bougaroun peraluminous rocks ($\delta^{18}$O = +9.3 to +13 ‰) to an important assimilation of metapelites by a less aluminous parental magma. Given that the Ain Sedma volcanic rocks represent by far the most altered rocks of the Bougaroun magmatic exposure, a primary explanation for such anomalously $\delta^{18}$O values would be the high levels of silicifica-

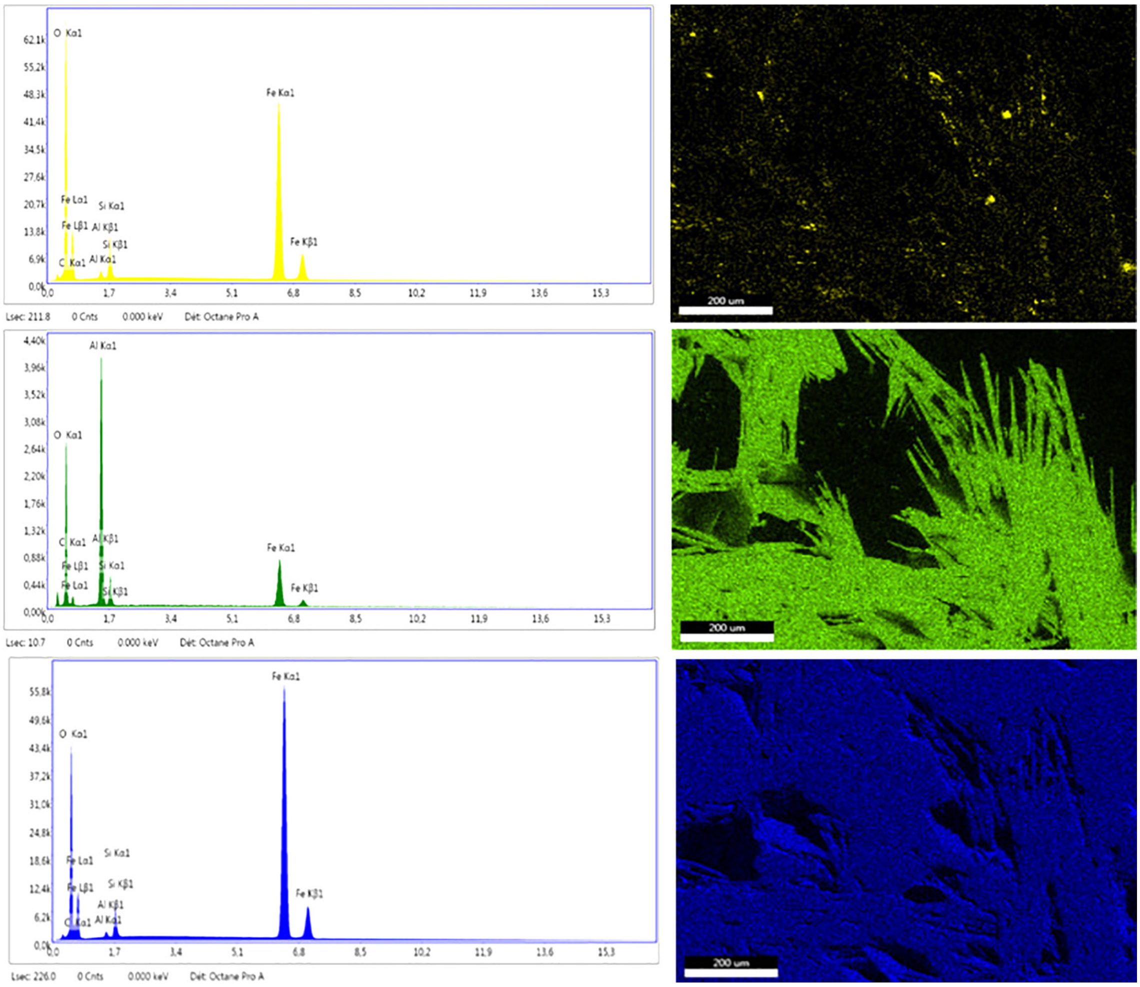

*Fig. 6. Scanning electron microscopy (SEM) elemental mapping and energy dispersive spectroscopy graphs showing chemical composition of iron mineralization from Ain Sedma (sample 02 C)*

tion they have experienced. All their geochemical data are consistent with the S-type granite, including high $SiO_2$ (74.93 to 76.70 wt. %), low Fe, Mg, Ca, peraluminous character (ASI > 1.39), normative corundum, the presence of aluminous minerals (biotite, muscovite), and low Na contents, ($1.67 < K_2O/Na_2O < 3.42$) [3]. The S-type granitoids show variable $\delta^{18}O$ contents which probably reflects the difference of their protolith and/or their evolution history. The S-type granites crystallise from magmas with $\delta^{18}O$ ranging between +9.5 and +11.4 ‰ (mean = 10.6 ‰), whereas mineral separates may display much higher. These values are thought to be directly related to their metasedimentary source [6]. Nevertheless, the oxygen isotope values obtained from Ain Sedma rhyolites are much higher than expected for such a source. Hence, identifying the metasedimentary material as a unique source for their unusual $\delta^{18}O$ remains quite doubtful. The peridotites of the Bougaroun basement yielded typical mantle $\delta^{18}O$ ranging from +3 to +5.9 ‰ V-SMOW, whereas serpentinized peridotite recorded lower $\delta^{18}O$ values (<+4.4 ‰ V-SMOW), indicating the effect of high-temperature fluid circulation [4]. This excludes low hydrothermal alteration as a possible source that would have instead elevated the $\delta^{18}O$ of the altered peridotites [7] and then contributed to the formation of base metal related to the Miocene granitoids. A worldwide investigation of $\delta^{18}O$ whole rock values characterizes shale ($\delta^{18}O$ up to +26 ‰) [8] as the most likely high-$\delta^{18}O$ source that would yield peraluminous granite when melted. Other possible high-$\delta^{18}O$ sources include oceanic carbonates ($\delta^{18}O$ = +25 to +42 ‰ V-SMOW) and siliceous oozes ($\delta^{18}O$ = +35 to +42 ‰ V-SMOW [10]. Since no appreciable volume of these lithologies is exposed near the Ain Sedma volcanic outcrop, the kinzigitic formations of the Bougaroun basement are presumably a good source to elucidate their $\delta^{18}O$ enrichment. Indeed, the kinzigites of the Ivrea mafic complex (Italy) gave whole rock $\delta^{18}O$ ranging from +10 to +14.1 ‰ V-SMOW and included quartz grains with $\delta^{18}O$ ranging from +9.1 to +17.2 ‰ V-SMOW [9]. These rocks have been interpreted as the most likely source of the high $\delta^{18}O$ peraluminous S-type granite associated with the Ivrea mafic complex. The S-type granites are thought to be formed by hybridisation of original magma and anatectic melts. Since the Filfila pluton is the only igneous massif that resulted from anatectic melts ever identified in NE Algeria, the MASH (Melting-Assimilation, Storage-Homogenisation) model proposed by [3] for Ain Sedma rhyolites is therefore consistent with an extensive assimilation of the kinzigitic materials forming the Bougaroun basement. It is worth being mentioned here that high $\delta^{18}O$ values were also observed in some of the volcanic rocks of Chetaibi-Cap de Fer (andesites; +13 and +15.7 ‰) [9], having no spatial relationship with the Bougaroun basement. The extraordinary diversity of the North Algerian margin volcanic products is thought to have occurred in a slab rollback and slab break-off setting. In the Bougaroun area, the pronounced subduction-related geochemical imprint observed in a wide range of magmatic is most likely the result of the melting of a mantle that has been altered by subduction-related inputs. This process was followed by the contamination of these melts by the lower and upper continental crust [2]. In such a complicated geodynamic setting, the subducted sediments of the downgoing slab, such as mudstone, are the favourite source to explain the genesis of some peraluminous rocks [11]. Moreover, peraluminous S-type granites of the Oman–United Arab Emirates displayed unusually high $\delta^{18}O$ values for whole rock (+14 to +23 ‰) and quartz (+20 to +22 ‰), and yielded the highest $\delta^{18}O$ zircon values known (+14 to +28 ‰ V-SMOW). According to [1], The exceptionally large oxygen isotope ratios of these rocks clearly distinguish the protholit as high-$\delta^{18}O$ marine sediment (pelitic and/or siliceous mud), as no other source could produce granite with such anomalously high $\delta^{18}O$ in a slab rollback setting. These authors attributed the formation of high-$\delta^{18}O$, S-type granite to a substantial melting of oceanic sediments within the mantle wedge. Indeed, recent studies argued that oceanic sediment may contribute significantly in the partial melting of the mantle wedge using (Ba/Th) vs. (La/Sm) and zircon saturation temperature to argue for a substantial contribution of oceanic sediments [12]. In fact, [3] were the first to highlight a possible involvement of the fluids derived from the dehydration of oceanic sediment in the oxygen isotopic signature of some volcanic rocks in NE Algeria. However, the overwhelming $^{18}O$ values observed in Ain Sedma volcanic rocks require direct partial melting of oceanic sediments (probably mudstone) in a slab roll-back setting, followed by a substantial oxygen isotopic exchange between primary rhyolitic lava and crustal lithologies rich in $^{18}O$ at different levels during their ascent.

***Ore mineralization.*** The Fe-mineralization related to Ain Sedma volcanic complex yielded $\delta^{18}O$ values ranging between +15.9 and +20.3 ‰ V-SMOW (mean = 18.1 ‰), which is by far higher than magmatic magnetite (1–4 ‰ V-SMOW [13, 14]. A logical explanation would be that the processes responsible for the $^{18}O$ signature of Ain Sedma volcanic rocks are the same as those responsible for the $^{18}O$ enrichment of the ore deposits. In other words, the magmatic liquid and the liquid from which this mineralization is deposited are almost in equilibrium. The temperature of metasomatic fluids that generated Ain Sedma skarns ranges from 400 to 510 °C. Given that these skarns are magnetite-rich metasomatic rocks, a general impression might be that they have a link in common with the nearby magnetite lodes hosted by rhyolites. This may sound consistent with the anomalous $\delta^{18}O$ values observed in iron ores, knowing that skarns display high $\delta^{18}O$. In fact, whole-rock $\delta^{18}O$ values generally increase in volcanic environment as a result of relatively low-temperature hydrothermal alteration (≤250 °C), whilst their oxygen isotopic composition tends to decrease if they undergo high temperature fluid circulation (≥400 °C) or meteoric water infiltration [7]. Post-magmatic hydrothermal alteration responsible for the transformation of Fe-garnet into magnetite in this skarn corresponds to 288 to 355 °C for the oxydation phase and 300 °C for the sulphuration phase [5]. These temperatures are higher than those wherein $\delta^{18}O$ is supposed to increase (low hydrothermal alteration). Besides, the peridotites of Bougaroun basement with typical mantle $\delta^{18}O$ values (+3 to +5.9 ‰) and serpentinized peridotite with lower $\delta^{18}O$ (+4.4 ‰) indicate the effect of high-temperature metasomatic fluids [4]. Regardless of how the ore deposit formed, these conclusions exclude low hydrothermal alteration as a possible source that would have significantly elevated the $\delta^{18}O$ value of the Ain Sedma iron ore.

Magmatic magnetite recorded $\delta^{18}O$ ranging from +1 to +4 ‰ V-SMOW [15], which is largely lower than $\delta^{18}O$ recorded in magnetite separates of Ain Sedma mining district. Therefore, their isotopic signature appears to be related to the genetic evolution of their host rock. In other words, the process(es) responsible for the enrichment of rhyolite dykes and associated Fe-mineralisation in $^{18}O$ might be quite similar. The difference in isotopic composition between host rock (mean = 20.8 ‰ V-SMOW) and iron ores (mean = 18.1 ‰ V-SMOW) of Ain Sedma has also been observed in El Laco silicate lava and related iron ore deposits. The difference in $\delta^{18}O$ between iron ores and silicate lavas is anticipated in systems involving immiscible liquids of these compositions, as experimental studies have demonstrated that iron-rich liquids have lower oxygen isotope ratios than iron-poor liquids.

According to these observations, the $^{18}O$ signature of Ain Sedma iron ore is most likely the result of an exchange between the high $^{18}O$ kinzigitic formations and the low $^{18}O$ magnetite as no other source could produce such overwhelming values during their long-time residence in the crust.

***Genesis model.*** As mentioned previously, the rhyolitic formations of Ain Sedma are interpreted to be derived from a LREE-rich mafic source generated by partial melting of the lithospheric mantle earlier metasomatized during a previous subduction event. This magma evolved then by fractional crystallization and crustal contamination according to the MASH model (Melting-Assimilation-Storage-Homogenisation) to produce the rhyolitic formations. Markedly, these rocks share the same REE patterns with the mafic rocks of Bougaroun (gabbros and dolerites) and the same Eu negative anomaly. These geochemical features are interpreted to be clear evidence for their derivation from the same mafic source [2, 3]. The genetic model proposed for the genesis of Ain Sedma iron mineralization suggests that magnetite inclusions were first clustered and separated from the parental rhyolitic magma. These droplets are

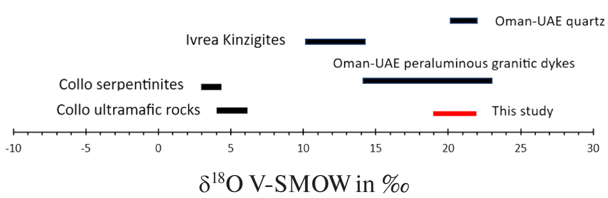


*Fig. 7. The oxygen isotope data of Ain Sedma rhyolites compared to other igneous rocks from various locations worldwide. Oman-UAE granites measured on whole rock and quartz separates from* [1]; *Collo serpentinites and peridotites from* [4]; *Ivrea Kinzigities (Italy) from* [9]

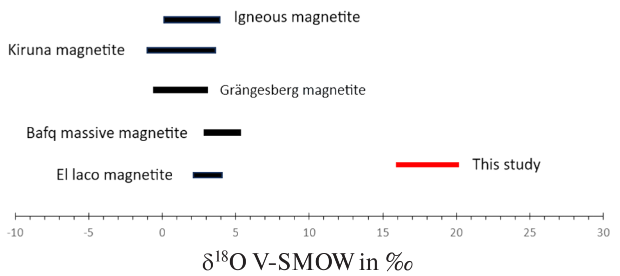


*Fig. 8. Oxygen isotope composition for Ain Sedma magnetite (NE-Algeria) compared to global* $\delta^{18}O$ *recorded on magnetite separates* $\delta^{18}O$ *composition of El Laco (Chele) magnetite from* [15] *Grängesberg magnetite from* [15]; *Bafq massive magnetite (Iran) from* [14]; *Kiruna magnetite from* [13]

then transported by gas bubbles and solidified at near-surface temperatures to give massive magnetite. This model is similar to the model given by [16] for Los Colorados IOA deposit in the Chilean iron belt. In fact, the petrographic features, including skeletal and dendritic textures observed in Ain Sedma magnetite, suggested to be diagnostic of magmatic origin, are in good agreement with this theory [17]. According to the same authors, the occurrence of similar rapid-growth textures in the apatite iron ore deposits demonstrates a magmatic origin with the emplacement of ore magmas at or near the surface. Conversely, $\delta^{18}O$ values of Ain Sedma ores ($\delta^{18}O$ = 15.3 to 20.3 ‰) largely overlap those of magnetite separates from the Kiruna mining district ($\delta^{18}O$ = –1.0 to +4.1 ‰) [13] and El Laco magnetite ($\delta^{18}O$ = +2.3 and 4.2 ‰, [15]. Magmatic immiscibility requires an important enrichment of magma in metal solutes such as Na and volatiles such as $CO_2$, F, B, and Cl. Moreover, the variation of $H_2O$ contents, oxygen fugacity ($FO_2$), pressure, and temperature during magma crystallisation is supposed to produce immiscible liquids rich in ore metals. Additionally, a substantial number of studies have shown that phosphorus is a major controlling factor on silicate lava immiscibility and may play an important role in concentrating Fe-rich melts. The mechanisms proposed for the formation of magmatic magnetite and immiscibility of Fe-rich melts from a silicate magma include: 1) crystal fractionation; 2) magma mixing; 3) crustal contamination. A logical explanation would thus be that both ores and rock from Ain Sedma inherited their O isotopes from another phase having $\delta^{18}O$ higher than initial mafic magma and magmatic $H_2O$ such as oceanic sediment [9, 1] or the Bougaroun basement kinzigitic rocks. This contribution took place either by direct assimilation of these materials by the magma or the infiltration of their derived fluids into the magma chamber. Indeed, a triple oxygen isotope variation in magnetite from iron-oxide deposits study, central Iran, recorded magmatic fluid interaction with marine sedimentary rocks (carbonates and evaporates) in the formation of iron ore with high $^{18}O$ values [18]. Common sources of Fe include mafic rocks and sedimentary rocks with high Fe content, such as iron formations. On the other hand, the addition of volatiles such as $CO_2$, $H_2O$, F, or $SO_3$ can reduce the melting temperature of iron-rich melts to more geologically plausible levels (< 1,200 °C) thereby expanding the immiscibility field to encompass compositions with higher iron content. Since no Fe-rich sedimentary formations have been identified near the Ain Sedma district, the underlying ultramafic rocks are undoubtedly the source of Fe. Therefore, the enrichment of primary melt in volatiles (e.g. $H_2O$, $CO_2$, and $SO_3$) through crustal contamination during their ascent is the most plausible trigger of iron-rich melt immiscibility in the Ain Sedma volcanic complex. At shallower depths, felsic melts become Fe-rich by: 1) assimilating variable amounts of peridotitic material of the Ain Sedma basement. The deep alteration these rocks went through may have lowered their fusion point making the assimilation process easier; 2) dissolving a substantial amount of Fe by thermal erosion. The lower $^{18}O$ content of altered peridotite ($\delta^{18}O$ < +4.4 ‰,) [4] is supposed to have played a direct role in decreasing the $^{18}O$ of the Fe-rich melts. The enrichment of these highly evolved melts with $H_2O$ and $CO_2$ during their ascent through the crust split them into Fe-rich melts and Fe-poor silica melts and lowered their viscosity, which made their eruption easier at about 11 Ma. Our proposed model for the genesis of the of Ain Sedma iron mineralization involves: 1) its formation through the assimilation of altered peridotite. High $CO_2$ and $H_2O$ content fractional crystallization favoured the separation of magnetite droplets and their flotation favoured by gas bubbles before being erupted; 2) the formation of these ores by Fe-rich fluids exsolved after magma solidification that deposited massive magnetite at near magmatic temperatures with increasing oxygen fugacity and decreasing pressure.

**Conclusion.** The textural analysis observed in Ain Sedma ores confirms that these ores are predominantly magmatic in origin. High isotope values of host rock confirm that these rocks are affiliated to S-type granitoids. The high values of $^{18}O$ for both ore and host rock are assigned to a combination of the oceanic sediments melting, crustal contamination, and/or assimilation of the underlaying kinzigites of the basement. The associated altered peridotite of the basement is the most likely source of Fe.

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## Генетичні аспекти залізорудної мінералізації району Айн-Седма, північно-східний Алжир

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**Мета.** Реконструкція геологічної еволюції магнетитових родовищ району Айн-Седма, розташованого на північному сході Алжиру.

**Методика.** Петрографічний аналіз і визначення елементного складу руд здійснювалися за допомогою енергодисперсійної спектроскопії та елементного картування, тоді як ізотопні співвідношення кисню вимірювалися у зразках гірничих порід і високочистих мінеральних фракціях залізної руди з району Айн-Седма.

**Результати.** Петрографічні спостереження виявили масивну текстуру, сферолітові ламелі, скелетні структури, дендритне розгалуження й рідкісні везикулярні кристали. Основними компонентами є оксиди заліза, при цьому кварц є домінуючим породоутворюючим мінералом. Ізотопний аналіз кисню для вміщуючих порід і залізних руд показав значення $\delta^{18}O$ у межах від 19,1 до 22,5 ‰ V-SMOW та від 15,9 до 20,3 ‰ V-SMOW відповідно. Ці результати свідчать про участь компонента, збагаченого елементами $^{18}O$ та Fe, у формуванні вміщуючої (основної) породи й супутньої мінералізації.

**Наукова новизна.** У цьому дослідженні вперше поєднані геохімічні дані й петрографічні спостереження для встановлення генетичних процесів, через які пройшли мінералізація та вміщуюча порода, від початку часткового плавлення до виверження магми.

**Практична значимість.** Це перший геохімічний аналіз, проведений у цьому районі, що зосереджений переважно на генетичній моделі вміщуючої породи та мінералізації, а також на їх взаємозв'язках.

**Ключові слова:** *Айн-Седма, хімічний склад, залізна руда, метаморфічний фундамент, ізотопи кисню, ріоліт*

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