A New Banded Iron Formations Deposit Discovery in the Eastern Anti Atlas of Morocco

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Abstract— **The Moroccan structural domain of the Anti Atlas presents a deformed part of West African Craton (WAC). In this area, the succession of epeirogenic cycles has generated the development of different mineralization kind's in several geodynamic contexts (Fe, Co, Ag, Au, Pb,…). During Ordovician, the Tafilalt basin characterizes an implementation of Iron mineralization which manifests as Banded Iron Formation (BIF) where the setting marks a significant geodynamic and tectonic activity in a delta and shallow sea environment. To that aim, our interests are based on the classification of iron mineralization using petrographic and metallogenic studies and the determination of an appropriated iron mineral implementation geodynamic model.**

Keywords— **BIF, Exploitable Deposits, Ordovician, Tafilalt Basin, Anti Atlas, Morocco and Gondwana**

I. INTRODUCTION

Iron is assigned to the transition metals, existed as a pure form or an alloy with other elements. Generally, it is exposed in earth as hematite (Fe_2O_3) and magnetite (Fe_3O_4).

In Morocco, the Iron mineralization exists in the Archean dorsal of Aghalas at the Precambrian buttonholes of the Anti Atlas as itabritique form. However, it is pyrometasomatic at the Hercynian granite of Azgour especially in Cambro-Ordovician metamorphic series of Toulkine, and also in tertiary intrusion of Ouixane. The mineralization kind iron replacement or substitution occurs in the Carboniferous outcrops of Khenifra and the Paleozoic limestones of Agadir ou Azizen. Whatever the spectacular Iron mineralization is mainly sedimentary and presented as oolitic form, covering the western and eastern part of the Anti Atlas [1].

Because of the specific character belonging to the eastern Anti Atlas standpoint establishment of Archean, Precambrian and Paleozoic mineralization, The present paper focus on the one hand, the study of scientific references describing iron mineral occurrences especially in the Tafilalt Ordovician basin which is described as oolitic Iron related to the Cambro-Ordovician sedimentation [2]-[10]. On the other hand the results are based on the verification of these indices which involved a field exploration study of iron mineralization development in the Tafilalt Ordovician Basin at the Moroccan Anti Atlas domain.

The interpretations describe the mineralization through the petrographic analysis and metallogeny study, completed by rocks geochemical results. However the first conclusion indicates that it is not just a mining indices but a real potential Iron deposit.

The deposit is formed in a specific geological context described for the first time in Morocco. The establishment of a geodynamic model characterizing the development of iron mineralization in Tafilalt basin, allows us to integrate this deposit in the BIF classification, established by Klein (2005) [11] and completed by Anbar and al (2007) [12].

II. GEOLOGICAL BACKGROUND

A. Generalities

The Moroccan Anti-Atlas is a Precambrian and Paleozoic belts oriented NE-SW [13]. The eastern zone is characterized by Saghro and Ougnat Precambrian outcrops [14] (Fig. 1).

The Paleozoic thickness arranges from 6 to 8km, and forms the bedrock cover, which is folded and metamorphosed. The whole is sealed by bulge anticline of Upper Cretaceous – Neogene deposits [15].

The sedimentary sequence is characterized by a detrital style whichever emerged until Late Ordovician (Fig. 2). Already it indicates a shallow sea environment (Delta), and qualifies the area as intercontinental basin [16].

On regional scale there is a series of Precambrian domes (Saghro and Ougnate) and Palaeozoic basins (Maidar, Tafilalt) which plunge down to the east of Ougartian belts NW-SE.

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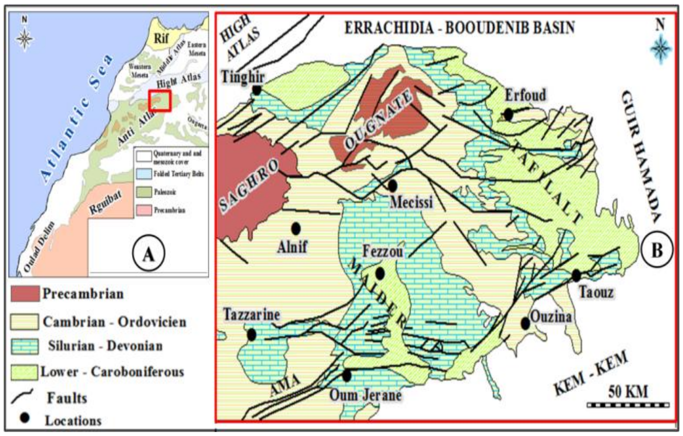

Fig. 1: (A) The Morocco Structural domains (B) Simplified geological map of the eastern Anti Atlas with position of Precambrian and Paleozoic outcrops

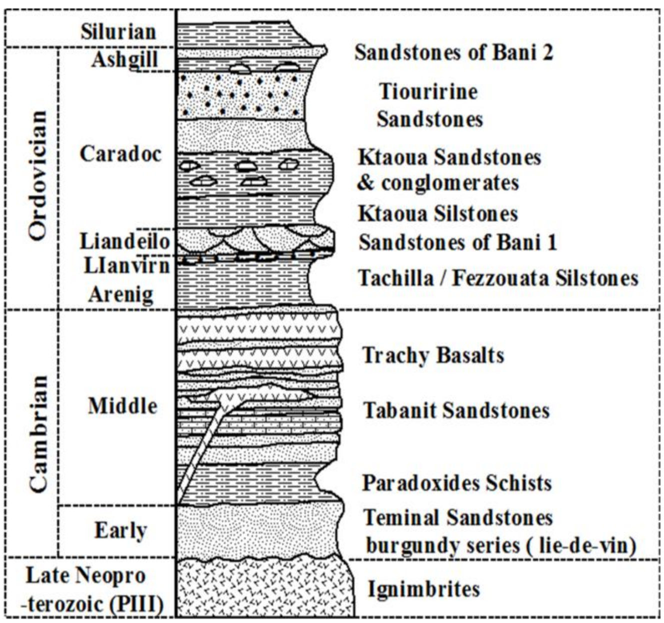

Fig. 2: the eastern Anti-Atlas Paleozoic formations and Stratigraphic column [2], [3]

The Panafrican basement outcrops at eastern Anti Atlas in the form of buttonholes (Boutonnières), represented by Saghro and Ougnate. This is crystalline bedrock which shows that the consolidation dates from the Panafrican orogeny. While the Major Anti Atlas Accident corresponds the West African Carton (WAC) old border [17]-[20], [15].

The Anti Atlas bedrock's is complex and divided into three units [21], [22]: (a) an Eburnean Paleo-Proterozoic units characterized by granitic intrusions within metamorphic series, marking the Saharan area which is part of the WAC; (b) the super group of the Anti Atlas with volcano-sedimentary, intrusives and ophiolite rocks, corresponding to the Panafrican accretion which represents Bouazzer suture (Neo Proterozoic). Finally, (c) the super group of Ouarzazate composed of volcanic and detrital rocks [23] marking a finished to post collision context. The Panafrican orogeny is expressed by the Major Accident of Anti Atlas and follows Tibesti lineament [24], while the northern limit of the WAC is collateral to the Southern Atlas Fault (SAF) [18], this structure nowadays is described as a southern limit of an aulacogene lower Neoproterozoic basin [19], [17], [20].

The eastern Anti Atlas Paleozoic sedimentary series (Fig. 2) characterize a thickness of 6km in the west, which decrease to 4km into the east and northwest of Saghro and Ougnate [25]-[28]. The detrital sedimentation dominates during the Paleozoic, and comes more carbonated in Silurian and Devonian [2]-[8], [29], [30].

The Cambrian: Starts by basal conglomerates forming Ouarzazate super group. The lower limestone, wine lees, and upper limestones series, are attributed to the Adoudounian. They are followed by pink sandstone deposits [31], [32]. Note that in eastern Anti Atlas there is no series of Adoudounian and lower Cambrian pink limestone.

The Ordovician: Its base consists on shale topped by Bani1quartzite bar [3], [32], [33], [34]. Its characterized also by the appearance of a second quartzite bar, marking the Bani 2, the latter is based on shale that assigns the middle Ordovician and it's includes microconglomerats. The eroded surfaces indicate a glacial paleo-environment [35], [28], [36], [37].

The Silurian: the carbonate character starts by filing a thick series of black shale [38]. At the end of Silurian, the first limestone bars appear and dominate the Devonian [16].

The Devonian: It is characterized by a bluish-gray limestone bars development. The stratigraphy shows homogeneous or mixed sequences of sandy limestones, and well stratified argillites. The sedimentary trend becomes more carbonated in a reef platform environment [29], [30], [31].

The Carboniferous: the sedimentary trend becomes increasingly detrital, due to shale deposits followed by sandstone benches. The Carboniferous characterizes a delta environment with an abundance marker of bioturbation and channels figure [16].

The Neoproterozoic – Cambrian rifting is responsible of the establishment and the appearance of weak areas expressed as normal faults, reactivated during the Variscan inversion. The Anti Atlas - Ougarta interference allows a structural differentiation of this part from the rest of eastern Anti-Atlas belts, through metacratonic bedrock.

The deformation marks a "thick skin" structures [16], [15] whereas the contact bedrock- coverage is continuous. The faults are rooted deep and expressed on surface by overlapped folded structures characterizing a ramp and bearing. The deposits of northern part of the Anti atlas are less thick compared to those of central portion, and indicates Upper Ordovician EW sillon (Caradoc). However the isopachs rotation marks a NW-SE sillon, parallel to Ougnate Ouzina-ride [15], [39].

B. Zone Study

The Tafilalt Paleozoic basin is located between the southern edge of Precambrian mountains at eastern part of Anti Atlas (Saghro and Ougnate) and the Cretaceous plateau of Errachidia-Boudnib-basin to the north and to the west (Fig. 3).

In this area the alternations of tinny sandstones and bioturbated argillites characterize the Upper Ordovician and indicate an offshore basin, subjected to occasional tidal influence [36], [37], [40].

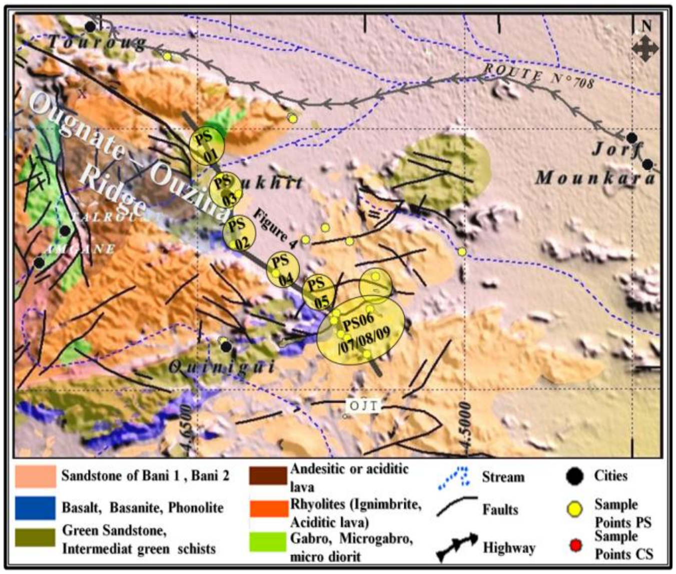

Fig. 3: Geological map of the Paleozoic outcrops in Tafilalt Basin – eastern Anti Atlas (Saoud et al, 2015)

The pro-delta sandstones interfere in regressive sequences of clays with a spreading as a form of slope [34], [40]. The Cambro-Ordovician outcrops extend around Precambrian rocks. Especially along "Ougnate-Ouzina" ride which is oriented NW-SE and parallel to the Upper Ordovician isopachs (Caradoc-Ashgill).

The southern boundary of these structures is distinguished by Oumjrane-Taouz fault (OJT) which presents a west extension of the Major Accident of Anti-Atlas (MAA). The Carboniferous outcrops of Tinghir-Tissdafine define the northern boundary of the area, and they are attributed to the southern maseta zone (ZSM) [5], [41], [6].

The middle Cambrian magmatic activity is expressed by dykes and basic silts which shows an environment of a diving magmatic province [30][42]. The complete stratigraphic series (south-east of Ougnate) (Fig. 2) shows that the Neoproterozoic crystalline bedrock is topped by the lower Cambrian basis, which illustrates a thin series of wine lees followed by terminal sandstones [3]. The Middle Cambrian characterize a detrital diet of tinny sandstones, however the southeast of Ougnate marks a clastic deposits and mafic alkaline volcanism. The Cambro-Ordovician transition is distinguished by the development of a gully discordance which defines the Upper Cambrian gap, and also by an alkaline volcanism in form of silts and dykes. The Ordovician assigns siliciclastic sedimentation dominance: a thickening of series towards east-west direction parallel to Ougnate-Saghro axis [2] which is an anti Atlas direction marking the lower Ordovician.

The Upper Ordovician isopachs indicates SE-NW direction which is parallel to "Ougnate-Ouzina" axis [15], [39] and follows an Ougartian direction. The Bani1 and Bani 2 Ordovician bars present the major geomorphologic peaks of the Anti Atlas [36], [3]. However our study focus the indices of iron mineralization associated to these two sandstone masses, as well as other iron indices located in this area and cited by several authors [37], [42], [15], [15], [39].

III. INDICES CHECKING AND FIELD EXPLORATION

The mineralization indices are in the form of oolitic iron or iron oxides. The verification of these clues comprises the follow of sandstone bars (Bani1, Bani2) along a NNW-SSE transect and perpendicular to the Cambro-Ordovician structures. The targeted transect starts from the Precambrian massif of Ougnate, through Oukhit, arrives to the Upper Ordovician outcrops of Bani 2 (southeast of Ougnate) (Fig. 4).

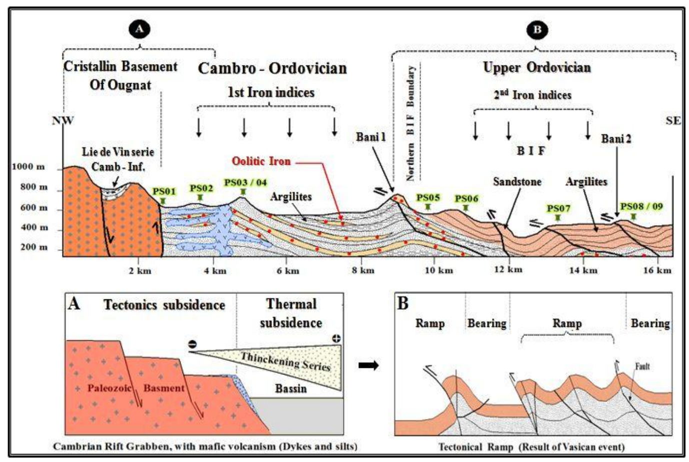

Fig. 4: Structural cross-section of the studied transects, with position sample groups (PS) (Cambrian-Ordovician series). (A) Simplified sketch of tectonic subsidence, (B) Simplified sketch of thermal subsidence in the Tafilalt basin whith illustration of tectonic ramps

The goal is obtain a clear vision about the Iron indices content. For this reason, two kinds of sampling was conducted, where the first is subjected to the petrographic and metallongenic study, using thin sections and polished surfaces interpretations for mineralogical description (PS groups), while the second was for geochemical analysis (SC groups) and it's made to highlight the tenors.

A. Petrographic and metallogenic analyzes

Made on dozens selective sample, through thin sections and polished surfaces confectioned at the laboratory of georesources and environment (LGE). The taken samples follow the Cambro-Ordovician series (Fig. 4) [40].

The mineralization detected along NNW-SSE transect shows a spatiotemporal distribution of iron clues which originates from a basaltic intrusion, and marks the Middle Cambrian green sandstones. This basaltic intrusion presents a nourishing iron source (Fig. 5). The mineralization is very local and principally in oolitic form, and the iron oxides (Fe_2O_3, Fe_3O_4) are precipitated around the ooltic substances (Groups PS01, PS02, PS03 and).

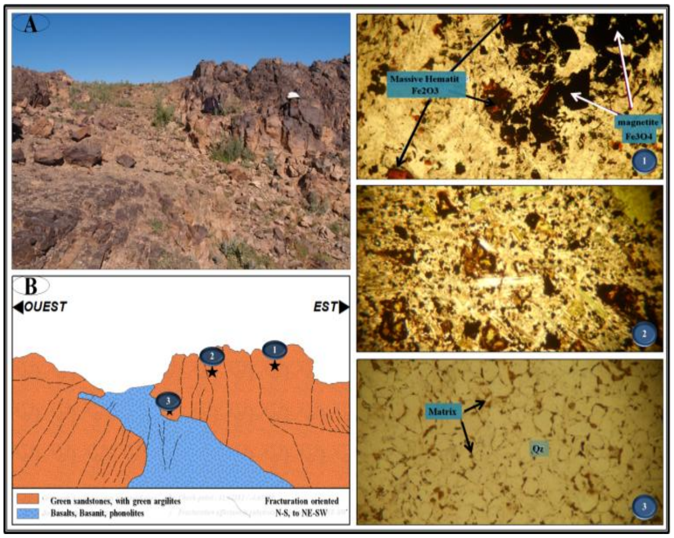

Fig. 5: A) green sandstones magmatic intrusion of Middle Cambrian, fractured NS to NE-SW. B) cross section E-W of A. 1) And 2) oolitic iron mineralization in the): thin sections of samples 1 and 2, 3) poor mineralization in sample 3 (Group PS01)

Climbing in the Cambro-Ordovician series, a second mineralization is occurred in the Bani 1 which characterizes the lower Ordovician (Fig. 6).

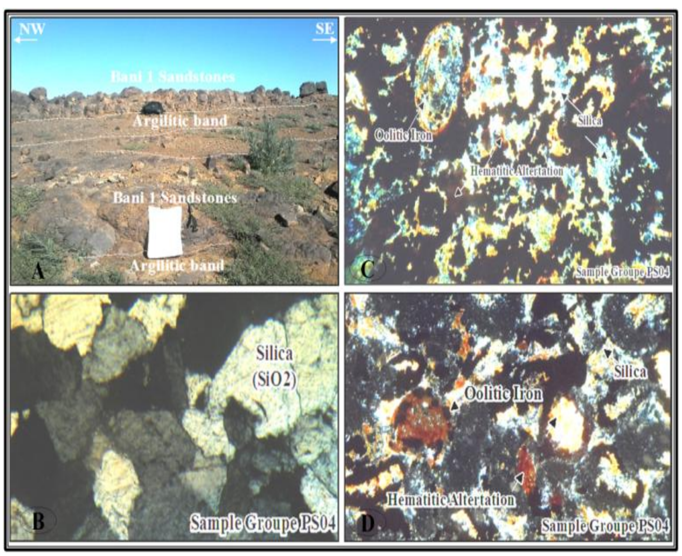

Fig. 6: A) the Bani 1bar showing intercalated sandstone-argillite beds, and sample locations B, C, and D, and their petrographic thin sections

However the iron is manifested in the form of a poor hematite alteration's which occupies generally the matrix (samples Group PS04). The Ktaoua Group characterizes the Caradoc, and presents an intense oolitic mineralization shape. The hematite is the abundant mineral and the magnetite occupies some levels of the sandstone bar.

The Upper Ordovician illustrates a largest extension of iron mineralization, where an alternation of mineralized sandy beds and sterile clay benches defines the Bani 2 bar (samples group PS05, PS06, PS07, PS08, PS09, PS10) (Fig. 7).

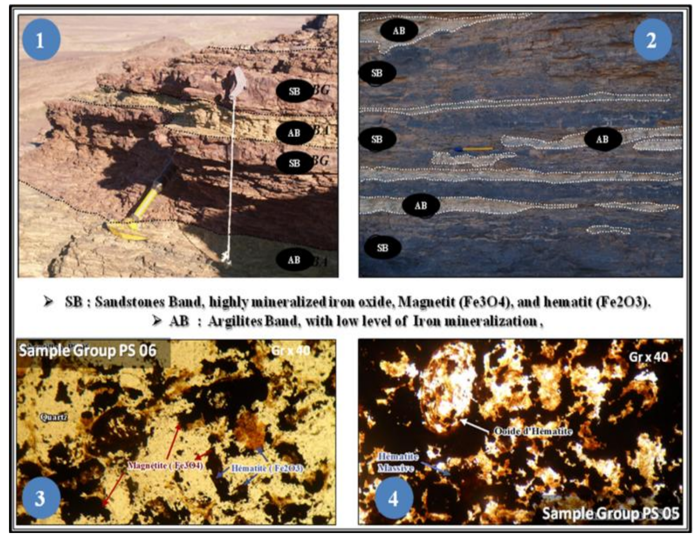

Fig. 7: (1) intercalation of sandstone and argillites benches of Upper Ordovician (group PS06); (2) intercalated sandstones and argillites benches (group PS05, Upper Ordovician), (3) representative petrographic thin section of PS06, 4) representative petrographic thin section of PS05

B. *Geochemical Analyzes*

The major elements chemical analyzes of (Fe), (Cu), (Mn) and (Pb) are made in stone powder obtained from crushed sample rocks. The powder is subjected to X-Ray-Fluorescence analyzes, which present a preferment method in order of result precision. All analyzes are done thanks to the laboratory of Transfer Technology and Innovation City of Fez University. The results are presented in Table 1.

Table 1: geochemical analyzes Results, with sample locations and their description

Sampl N°	Long (d'd)	Lat (d'd)	Fe (%)	Mn (ppm)	Pb (ppm)	Description d'échantillon
SC01	31.3679	-4.558	**45.5**	3380	55.3	Channel sampling of 1m long, with observation of high hemtitic alteration.
SC02	31.3679	-4.557	**49.6**	1130	11.7	Sandstone benches of 5 to 50cm thickness. 140N 10SW.
SC03	31.3679	-4.557	**40.0**	622	19.0	1m Channel sampling with existence of a quartz vein which is parallel to the S1, the hickness is about 10cm, layer oriented N200.
SC04	31.3679	-4.558	**45.7**	373	11.8	High alteration on hematit and magnetit. The mineralization occupies generally the porosity.
SC05	31.3658	-4.561	**30.2**	815	39.4	benche, locally limonitic
SC06	31.3658	-4.561	**31.1**	1220	55.2	hematitic altération
SC07	31.3729	-4.562	**44.3**	395	19.1	Sandstone bench with high alteration on hematit.
SC08	31.3729	-4.562	**40.3**	2130	32.4	Sandstone benche with presence of limonite in the fractures N150.
SC09	31.3734	-4.562	**35**	1780	29.1	3m channel in sandstone benche with hematitic alteration.
SC10	31.368	-4.558	**45.5**	3380	55.3	Collected sample from surface (3 x 3m), with manifestation of iron mineralization.

Field observations and geochemical analyzes of the post Cambrian series, indicate a high concentration of iron mineralization in the Upper Ordovician Bani 2sandstones, characterizing the Ashgill. The iron is concentrated in the banded sandstone phases and absent in the argillites. The obtained geochemical analyzes results confirm an iron content varied between 31.1% and 49.6% (Fe) with an average of 40.18% (Fe) for the entire deposit.

The present study indicates firstly that it is no mining indices but an exploitable deposit where the nature of banded iron classifies it as BIF. The ore is siliciclastic sedimentary rock (as kind sandstone) containing alternated laminated and banded Benches of sterile clays and ferruginous minerals (Fig. 8). The Ferruginous benches corresponds to the late Ordovician deposited sandstones, in a context characterized by the dominance of glacial environment [43], [44], [2], [9].

Indeed the eastern Anti Atlas under polar conditions was characterized by a thick ice cap formation. The Upper Ordovician sedimentary sequences show a succession of tinny sandstone bars alternating with clays. These sequences are characteristic of a middle estuary leading to the slope environment [34].

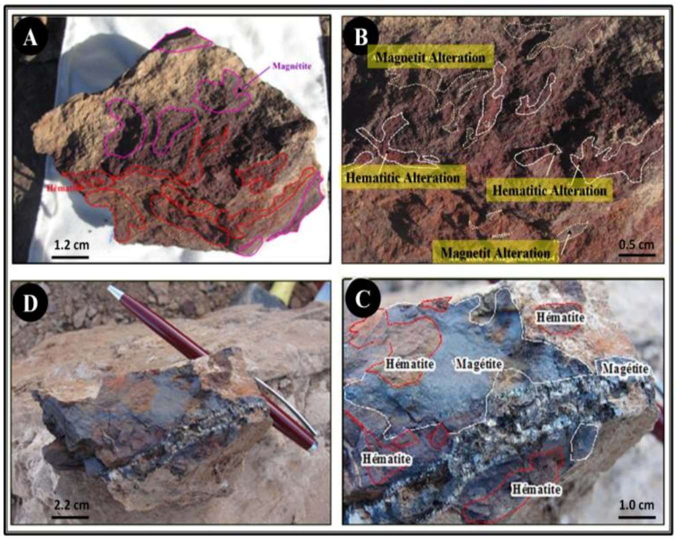

Fig. 8: The detected iron mineralization in the sandstones of Upper Ordovician, A, B) strong alteration on Hematite (Fe_2O_3); C, D) strong alteration on magnetite (Fe_3O_4)

The iron oxides is distributed along a representative Bani 2elementary sequences, and shows a succession of argillites (10 to 20cm thickness) on the basis, and a greater sandstone beds (1-2 m) presenting the top of 2nd order sequence's. Nevertheless the iron content exceed of each sequences is an average of 40% (Fe). Almost the iron tenors peaks are characterized at the level the sandstone beds, while they are basically missed in the clay beds (Fig. 9).

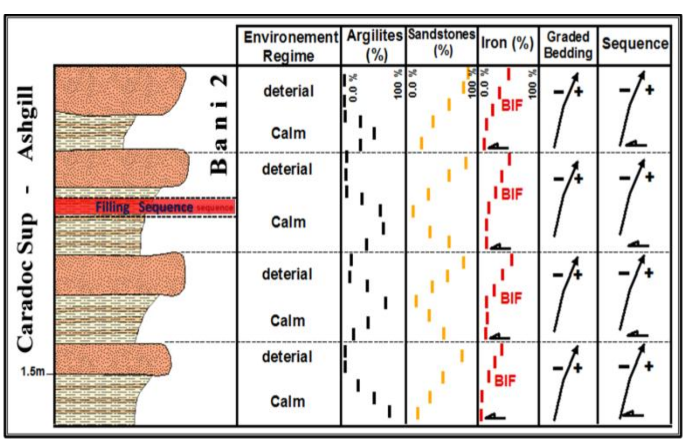

Fig. 9: Iron content Distribution in function of sandstones and clay fraction percentages along the elementary sequence

The mineralization evolution is assigned by a siliciclastic detrital phase contribution. This sediment supply is towards the platform or even the slope.

However, iron nourishment is ensured by alteration and erosion of the WAC, which outcrops in the north west of the studied area, as Saghro and Ougnate enliers, and in the south as the Saharan shield (Fig. 10) [9], [34].

IV. GEODYNAMIC DEPOSIT SYSTEM OF IRON MINERALIZATION IN THE ORDOVICIAN BASIN OF TAFILALT

Along the eastern part of the Anti Atlas, the upper Ordovician Paleogeographic reconstruction, shows an affiliation to shallow platform environment with a wide geographic spread, named the Gondwanian platform [45]-[48].

Extensive tectonic is manifested as a rifting accompanied by magmatic and volcanic intrusives which affects and outcrops in the region. The landmass movement of the Gondwana to south dating late Ordovician leads to a vast ice sheet formation [9], [34]. However the bioturbated argillites deposits of the Upper Ordovician characterize an offshore field, with occasionally wave's influences.

Note the presence of estuarine sequences and a prodelta structure topped by a tinny to mean sandstones that determines the slope. The siliciclastic sediments assign the eroded crystalline bedrock, which belong to the panafrican basement. Whatever the latter is highlighted and expressed the result of epeirogenic movements [2], [3].

The iron banded formations (BIF) are hosted during Ashgill in the sandstones of Bani 2, and attributed to the upper Ordovician [40]. The ore concentration is highly related to the dynamics of this basin, where the clay phase marks a quiet environment poor on mineralization, while the detrital sandstones triggers the iron mineralization processes.

The Cambrian rifting contributes to the creation of space, and thermal subsidence accompanied by tectonic movements, where the Ougnat-Ouzina bedrock provides a rich iron detrital supply [2], [15], [39]. However the upper Ordovician glaciations events marks the eastern Anti Atlas [43], [9], and presents the key factor of the Tafilalt BIF training.

The shallow platform environment supersaturated on reduced iron is separated by the ice cap from the atmosphere. The water column features more or less a low eustatic level. While the sediment supply originated from the Panafrican and or Gondwanian basement, is mainly controlled by erosion and glacial transportation (Fig. 10). The Ashgill deglaciation event allows the melting snow on the continent, causing high grade erosion, accompanied by an increasing of sea level and an important marine medium oxygenation.

Whatever contributes to release the oxygen and establishes a combination with reduced iron and give birth to the iron oxides complex. The high density provides to the iron oxides its precipitation in the sandstones of Bani 2 (Fig. 11) and giving rise to a BIF (Fig. 12).

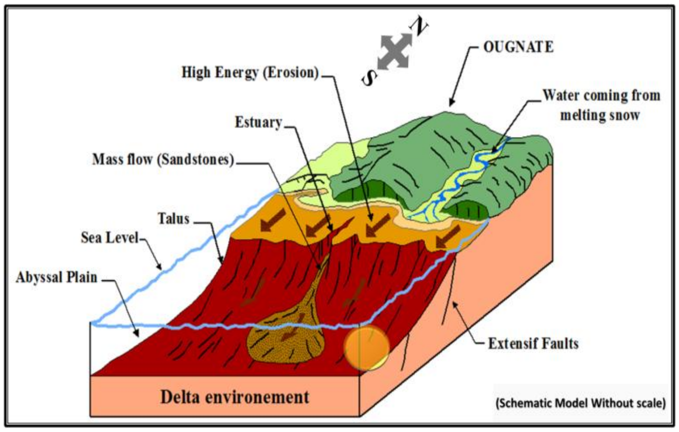

Fig. 10: Schematic model of the erosion process, sedimentation and transportation resulting from melting snow in Tafilalt basin upper Ordovician (Asghill)

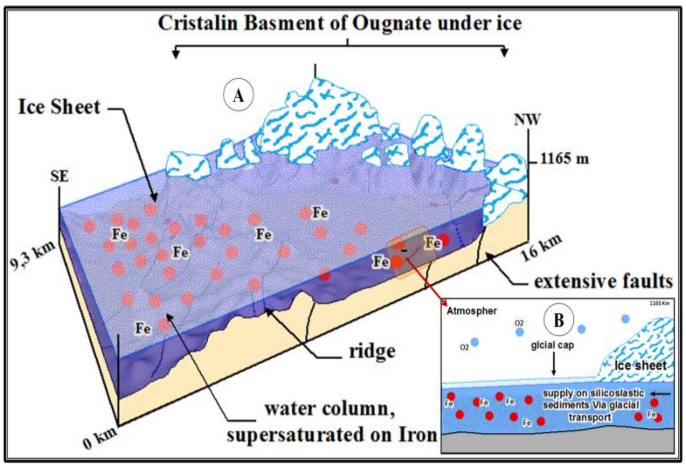

Fig. 10: (A) Geodynamic model of Tafilalt basin with the super saturated sea environment on reduced iron (Fe), with appearance of the ice cap during Caradoc, (B) explanatory sketch of rich reduced iron sediments supply

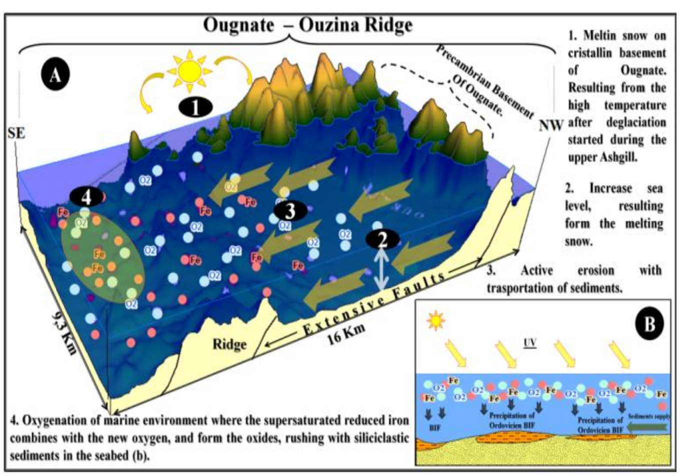

Fig. 11: A) Geodynamics model of Tafilalt BIFs implementation processing, triggered by deglaciation phenomenon dating the Upper Ashgill. B) Explanatory sketch of the Oxygen intervention in the iron oxides formation process, and their precipitation in a delta environment

According to the BIF spatiotemporal classification made by Klein (2005) [11] and Anbar et al (2007) [12], notes that the majority of banded iron formations are between 3.5 and 2.2 Ga and therefore related to Precambrian events.

This new discovery of BIF especially at Tafilalt basin allows to the observation and the study of this Paleozoic timescale, and especially the Ordovician Period in the Moroccan structural domain of the Anti Atlas. The BIF present a local character and linked to specific geodynamic phenomenon resulting against Gondwana transition from a polar ice situation to platform location (Fig. 12).

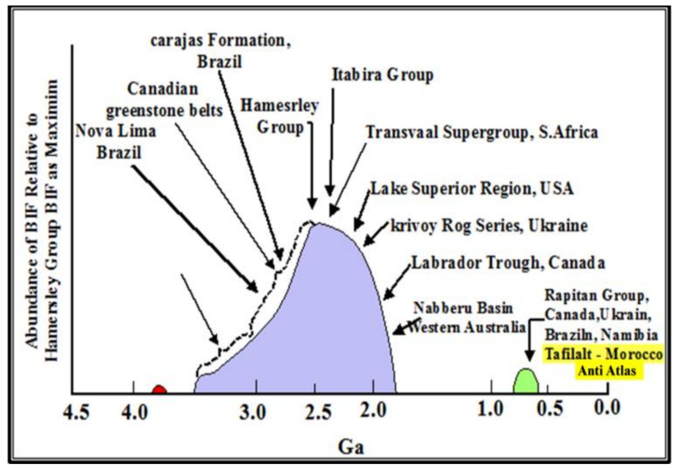

Fig. 12: spatiotemporal classification of BIFs across the globe (Trendall 2002; Klein 2005, Anbar et al., 2007), with the addition of Tafilalt BIF (Anti Atlas) as Rapitan group

V. CONCLUSION

The geodynamic model related to the Tafilalt BIF characterizes an evolution of iron mineralization in a specific context, mainly characterizing marine offshore field, with occasionally wave's influences. The interpretations describe the mineralization through the petrographic analysis and metallogeny study, completed by rocks geochemical results. However the results show that is not just a mining indices but a real potential Iron deposit. The Banded Iron Formations of Tafilalt Bassin in the Anti Atlas domain are formed in a specific geological context described for the first time in Morocco. The discovered BIFs are actually an exploitable deposit, since the content levels exceed 40% (Fe). This syn-sedimentary deposit is associated to the detrital siliciclastic phase which dates the Ashgill. It corresponds to a BIFs deposit as a kind of Rapitan, and formed during Upper Ordovician where the glaciations event was the triggered engine of iron mineralization implementation.

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