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The Transitional-Alkaline Magmatic Series of Moroccan Central High Atlas, (Imilchil, Jbel Hayim and Tamazert Area): Geochemical Signatures and Igneous Phosphate Exploration Implication

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Abstract

The igneous phosphate rocks are mined from alkaline magmatic rocks, like syenite, nephilinic syenite, and apatite carbonatites (e.g., the Kola Peninsula and Kola Peninsula in Russia, the waste rock of the iron mines of Kiruna, Sweden and Arax, in Brazil…). In Morocco, several syenite massifs are recorded from the Precambrian to the Mesozoic and Cenozoic, we respectively cite those of the Reguibat shield, Jbel Boho and Siroua massif in the Central Anti-Atlas, the High Atlas and Middle Atlas . In the Central High Atlas, Jurassic syenites are located in the Imilchil region at the south of Beni Mellal City. Petrographically, these rocks are composed of potassium feldspar, plagioclase, carbonates and traces of silica with secondary minerals mainly iron oxides/hydroxides (magnetite/Ilmenite). Accessory minerals are represented by apatite with trace elements (F, K and P, Ti) and trace Si. From geochemical point of view, the syenites of the Central High Atlas of Imilchil as well as those of Tamazert are characterized by a peralkaline magmatic affinity (strongly potassic alkaline) and set up in an anorogenic geodynamic context, while those of Jbel Hayim were set up in a collisional to post-collisional compressive context related to the closure of the High Atlas basin.

Keywords: Igneous Phosphate, Central High Atlas, Imilchil, Syenite, Jbel Hayim, alkaline magmatism, Apatite.

1. Introduction

Phosphate ore deposits is a matter of attention in many countries worldwide, because these are have a wide spectrum of uses and applications. Phosphates are commonly used in agricultural purposes, as fertilizers, also they are used in many other domains such as metal treatments, plasticizers, oil additives, flotation surfactant, fireworks and many other uses. Three major types of phosphate resources are being mined in the world: 1) Sedimentary phosphate deposits, 2) Igneous phosphate deposits, and 3) Biogenic (or Guano Bird; or Island) deposits. Approximately 75% of the world's phosphate resources are won from sedimentary phosphate rock deposits, 15-20% from igneous and weathered deposits, and only 1-2% from biogenic resources, largely bird and bat guano accumulations.

Alkaline magmatism is relatively rare on the Earth's crust (≈ 1% of magmatic rocks). Despite its scarcity compared to other types of magmas emitted at the Earth's surface, alkaline magmatism is a very important process, in understanding mantle processes and chemical evolution of the mantle. It is widely interpreted as the product of low melting rates at great depths, and it plays a particularly significant role around the existence of mantle plumes ([1]–[4]). It is often emplaced in an extensive geodynamic environment e.g. in the East African Rift in Kenya ([5]) and in the extensive Cambrian system e.g. syenites of Jbel Boho in the Central Anti Atlas, Morocco[6] to the Miocene e.g. nepehilinites of Jbel Saghro [7]. These rocks can also form in geodynamic contexts under compressive regimes (ex. Tamazert alkaline massif in the central High Atlas of Morocco [8]and the Imilchil rifts[9]–[12]. They are also found in the oceanic crust (case of the volcanism of hot spots (e.g.Maio of the Cape Verde Islands [13].

Economically, alkaline felsic intrusions are the subject of several mining explorations worldwide for example: (i) loparite in syenite (e.g. Khibiny and Lovozero deposit in Kola Peninsula, Russia with an estimated 30,000t @ 34 wt.% rare earth oxides (REO)). (ii) the syenite-hosted eudialyte with most of the rare earth elements REE and Nb replacing Ca and Si) in the Ilimaussaq Alkalic Massif in Greenland with resources of about 2 Mt @ 1. 5 wt.% rare earths). (iii) the syenitic and granitic alkaline rare earths deposit of Thor Lake in southwestern Canada, with resources around 65.6 Mt @ 2.53 wt.% in monazite, allanite and carbonate minerals ([14], [15]).

[16] have identified that the negative K, Zr, Hf, and Ti anomalies, incompatible element enrichment, and high Ca/Al and Zr/Yb ratios of intraplate nephelinites and basanites derived from Cenozoic volcanism south of the North China Craton imply that their source underwent carbonatitic-type metasomatism, followed by low melting rates (< 3%).

The igneous phosphate deposits are less abundant and often less rich than the other types (sedimentary deposits and guanos). These deposits were formed by magmatic activity, mainly alkaline, of which syenites, nepheline syenites, carbonatites, ijolites and pyroxenites are frequent ([17], [18])(e.g. Russia, Brazil, South Africa, Canada, Finland and Zimbabwe, Uganda, Malawi, Palabora and Khibiny deposits...) (Fig. 1).

This type of magmatism,particularly the syenite which is exploited in the world for its richness in apatite, which havea good quality of phosphate, many valuable elements and without penalizing elements[18].

Figure 1: Simplified map of the different types of phosphate deposits in the world [19], modified.

Geologically, syenites are the subject of several geochemical, metallogenic and geochronological research works in Morocco. They are found in different areas and have different ages:

(i) In the Saharan domain, the syenites present Archean ages [18],[19]. Recent geochronological works on the Awserd syenites in the west of the Reguibate massif show ages up to 2.46 ± 0.7029 Ga by the $^{87}Sr/^{86}Sr$ method and between 2.46 ± 1.4 Ga and 2.75 Ga by the Nd method ([20],[21]) show that the apatites of the Reguibate shield underwent a warming and a cooling between 159 and 118 Ma.
These facies are composed by three syenitic facies (nepheline syenites, calcic syenites and quartz syenites). Geochemically, they show a highly potassic alkaline affinity; the nepheline syenites are characterized by high K_2O contents >16%, the calcic syenites presents values between 10 to 14 wt.% K_2O [22].

(ii) In the Anti Atlas domain, syenites are identified in several inliers in the adoudouninan formation (e.g. syenites of Jbel Boho in the Central Anti Atlas [6]. These rocks are frequently associated with alkaline magmatism event and emplaced in an extensive geodynamic context of the Cambrian basin (Tata-Taroudant Group) ([24], [22], [25]).

(iii) In the High Atlas, the syenites are represented by ripples set in a compressive geodynamic context. These rocks have a mainly alkaline affinity highly potassic. They are generally associated in the Anti-Atlas with mafic rocks (basalts, gabbros ...) and intermediate rocks (diorite, monzodiorite) ([7], [11], [26],[27]).

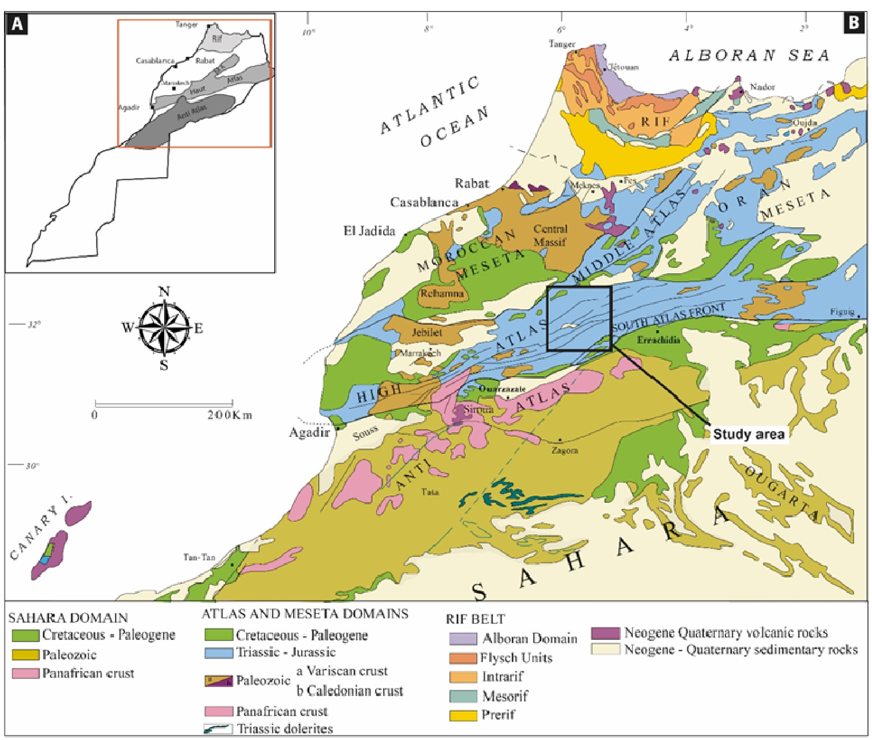
The present paper is devoted to a bibliographic synthesis and an update on the geology, geodynamics, petrochemistry and geology of alkaline magmatic rocks of the Central High Atlas. The objective is to develop another type of phosphate resource in Morocco like igneous resources. We are focusing on the alkaline magmatism of the High Central Atlas of Mesozoic age (High Central Atlas of Imilchil, Tamazert and Jbel Hayim). We base ourselves on a new interpretation of the geochemical and geological data of the alkaline magmatism in the Central High Atlas of Beni Mellal and Imilchil zones.

2. Geological Background of the Central High Atlas

The Moroccan High Atlas is a Cenozoic intracontinental belt that extends from western Morocco to Tunisia ([30], [31]) over awidth of 40 to 100 km and about 700 km in length along a WSW-ENE orientation (Fig. 1). It is limited to the South by the South Atlasic Major Fault (SAMF) and to the North by the Middle Atlas Mountains (Fig. 2). The High Atlas composed by three main units: Eastern , Central and Western High Atlas.

The Central High Atlas terrain is constituted by a thick sedimentary series dated from Triassic to Cretaceous. This geological formation has been deposited in a continental subsidence basin that started by a rifting stage of Permo-Triassic age evolved as a continental platform basin. In the Central High Atlas, the Triassic, essentially formed by clay-sandstone sediments, is overcame by the transgressive Jurassic units formed by fossiliferous limestones and marlstones and by the more regressive Cretaceous, also formed by carbonates with intervals of sandstone-clay with evaporites ([30], [32], [33]). The Central High Atlas contains several major magmatic events: (i) Fissural magmatism, with concordant flows, intercalated in the Triassic sedimentary formations. It reflects the crustal thinning contemporary with the beginning of the opening of the Atlantic Ocean basin. This magmatism corresponds to alkaline basalts that evolved into continental tholeiites ([11], [34]).(ii) Jurassic and Cretaceous magmatism, volcanic and diapiric, which are associated to sediments or which mark the axes of tectonic wrinkles (anticlinal tectonic structures). This magmatism is represented by basic rocks (basalt sills, gabbros), intermediate rocks (diorites and monzodiorites) and by acidic rocks (syenites and trachytes) ([29],[30],[33]). Geochronological dating of these magmatic rocks([36], [37])isattribute toLower Jurassic age to the mafic rocks and Middle Jurassic and Lower Cretaceous to the acidic felsic facies; (iii) The magmatism of alkaline affinity (phonolites, nephelinites), in the form of explosive domes, of Neogene age (Paleogene to Quaternary) well developed in the Middle Atlas to the north and the Siroua massif to the south.

Figure 2: A) Simplified geological domain map of Morocco. B) The location of the study area in the geological map of the northern and central part of Morocco after [38] in [39].



2.1. Geotectonic Setting of the Central High Atlas (Fig. 3)

The tectonic evolution of the High Atlas belt shows multiple deformation stages in a breaking regime without metamorphism ([11], [12]). [40]) have highlighted two stages deformation:

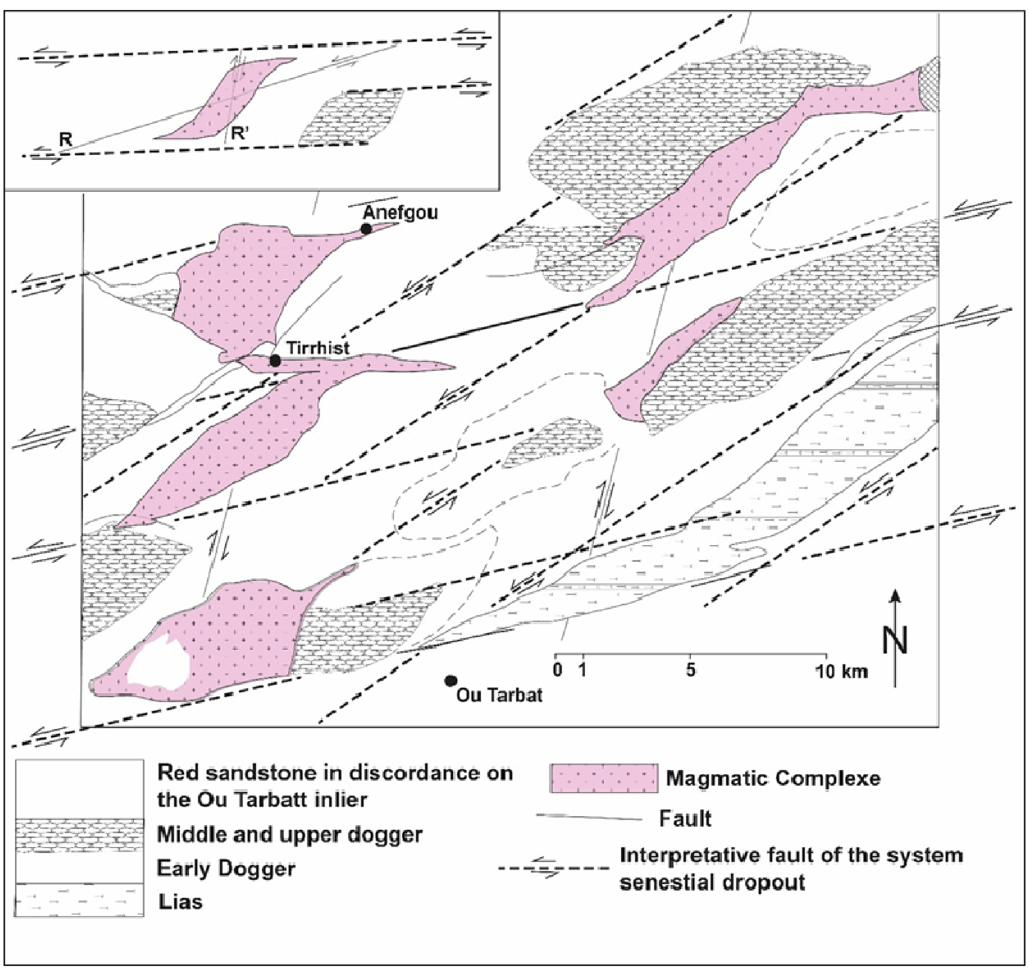
(i) a transtensive sinistral stage responsible for the opening of pull-apart basins accompanied by basic tholeiitic magmatic activity ([30], [31], [41]). This stage is marked by sedimentation of limestones, marly limestones and marls during the Toarciean and Bathonian ([33], [42], [43]).

(ii) a compressive stage in the Oligocene related to the Iberia-Africa collision ([32][44][45]). The majority of deformation is attributed in this stage with a covering sedimentary of approximately 20%.

[12] and [11], they have defined three tectonic stages: (i) an extensive stage in the Jurassic marked by synsedimentary structures frequently oriented E-W and NE, which control the formation of grabens and deposits of Toarcian-Aalenian age; (ii) a compressive stage controlled by faults oriented NS to N10° during the Lower Bajocian and between N160° and NS during the Upper Bajocian-Lower Bathonian. This stage is materialized by the presence of transpressive shears, which controlled the structural evolution of the Imilchil area. (iii) a compressive stage of late Cretaceous age characterized by reverse fault systems N70 to E-W with a senestral fault setting and deep NE-SW to NNE-SSW faults.

Between Stages (ii) and (iii) the Central High Atlas Basin had a period of stress relaxation between the Bathonian and Callovian. This period is characterized by a strong continental sedimentation with basic magmatic activity (basalts, N-S diorite veins) [12].

Figure 3: Simplified structural map of the Central High Atlas from [46].

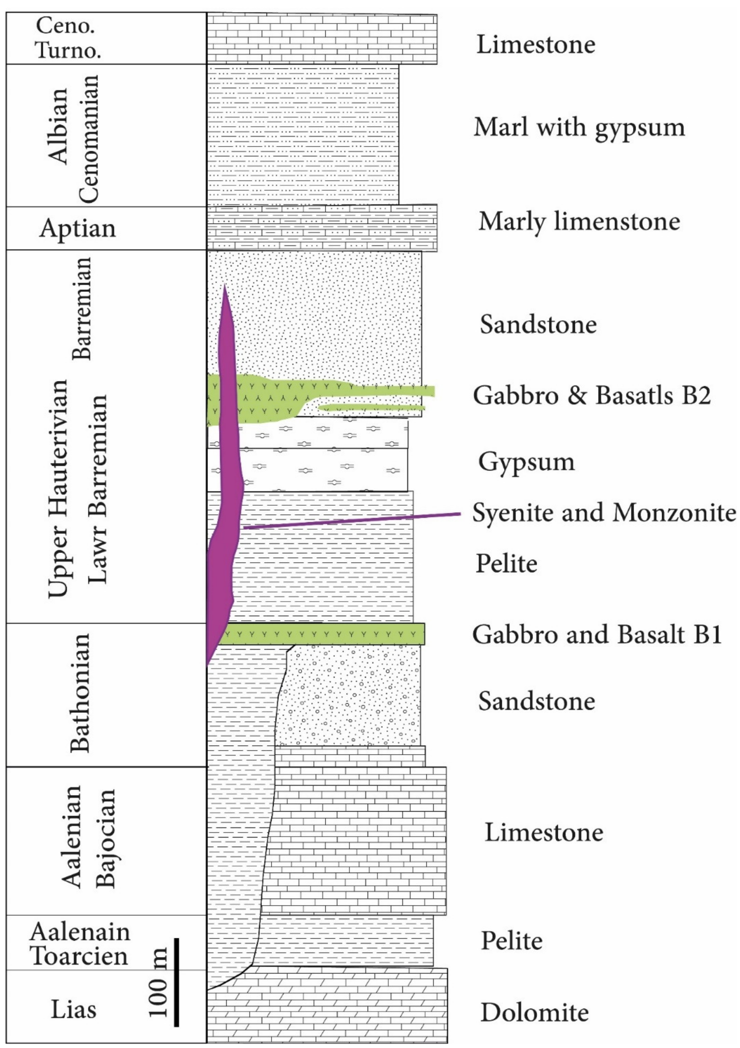


2.2. Litohostratigraphy of the Central High Atlas (Fig. 4)

The study areas are located in the Central High Atlas Range (Fig. 4), it consists of sedimentary formations of Mesozoic age (Fig. 4, 5) ([8],[10]), intruded by alkaline to transitional magmatic rocks [47].

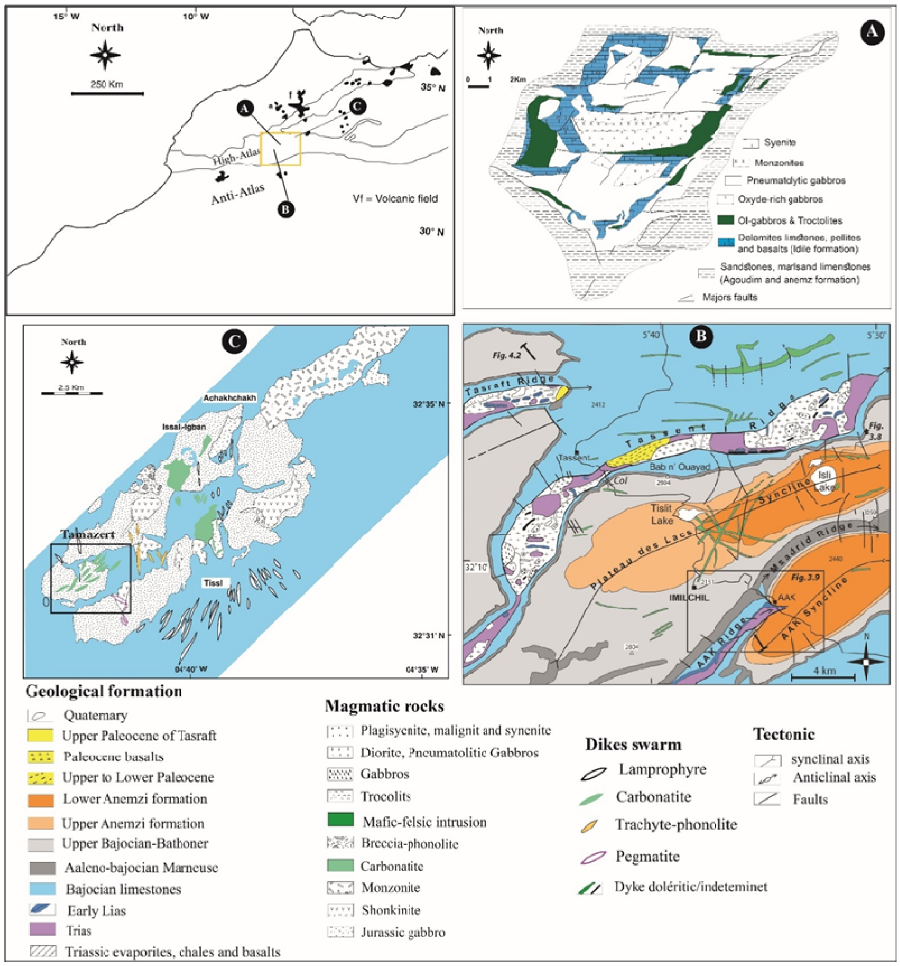
The sedimentary succession is formed at the base by the Tassent formation resting in progressive discordance on the Triassic clays and basalts, it is constituted mainly by alternations of biodetritic limestones and sandstone marls (Fig. 4,5), on which rests the Bab N'Ouyad formation formed essentially by limestones. This formation is unconformity surmounted by the Tislit formation, it is composed by greenish marls with bars of biodetritic limestone, on which rests the series of Imilchil composed by sandstone marls of red and green color with sandstone limestones rich on mudcracks on the top. This formation is surmounted in local angular discordance by the formation of Isli formed by sandstones, limestones siltstones and red clays. The summit part of the sequence is constituted by the Timzought formation which rests in angular unconformity on the Isli formation and which is constituted by sandstones and red clays with sills of reddish basalts. The whole is overlain by white limestones, clays and basal conglomerates of middle Cretaceous age (Fig. 4, 5) [9].

Figure 4: Synthetic stratigraphic log of the Central High Atlas realized in the framework of this study by the compilation of previous works ([40][28][12][11]).



Structurally, the High Atlas area of Imilchil is known by a succession of anticlinal and synclinal folds whose axes are oriented NE-SW to ENE-WSW. These structures correspond globally to a filling of open subsident basins on senestral rifts (Fig. 3). These basins are separated by synsedimentary anticlinal rifts of Jurassic age that show three major orientations (N45, N70 and N120) ([47], [48])).

Figure 5: Location map of the study area. A) Geological map of the main formations of the High Atlas of Jbel Hayim [40]. B) Geological map of the High Atlas of Imilchil [11]. C) Geological map of the main formations of the High Atlas of Tamazert simplified from[8].



3. The Central High Atlas Magmatism of Imilchil

The Mesozoic-Cenozoic sedimentary formations of the Imilchil High Atlas are intruded by several magmatic rocks in the Tassent wrinkles and form the core of the anticlinal rifts globally oriented NE-SW [49], (Fig. 5 and 7). This magmatism is formed by three types of rocks: mafic (basalts, gabbros), intermediate (diorites, monzodiorites) and differentiated (syenites) ([9]–[11]). These intrusions are classified [9] into two facies: (i) a homogeneous facies constituted by a magmatic suite from gabbro to the syenite, (ii) heterogeneous facies constituted by a mixture of felsic and intermediate magmas present in a single massif [9]. These intrusions are deposited on the Precambrian-Paleozoic basement and are bounded by NE-SW faults(Fig. 5B, 7) ([31], [50]).

Figure 6: Synthetic geological section of the Central High Atlas of Imilchil simplified and redesigned after [12]in[10].

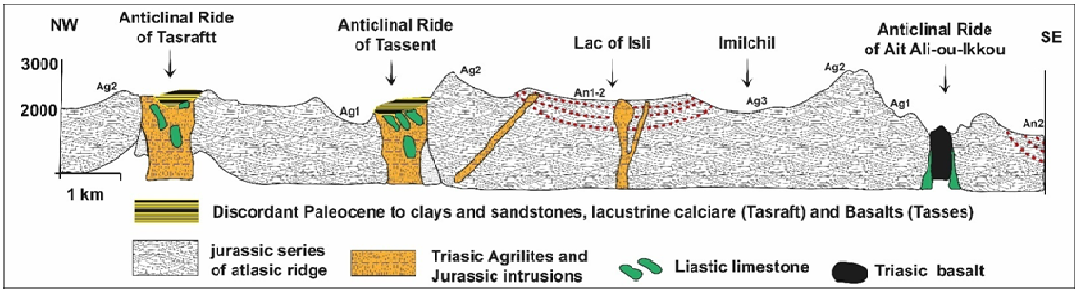
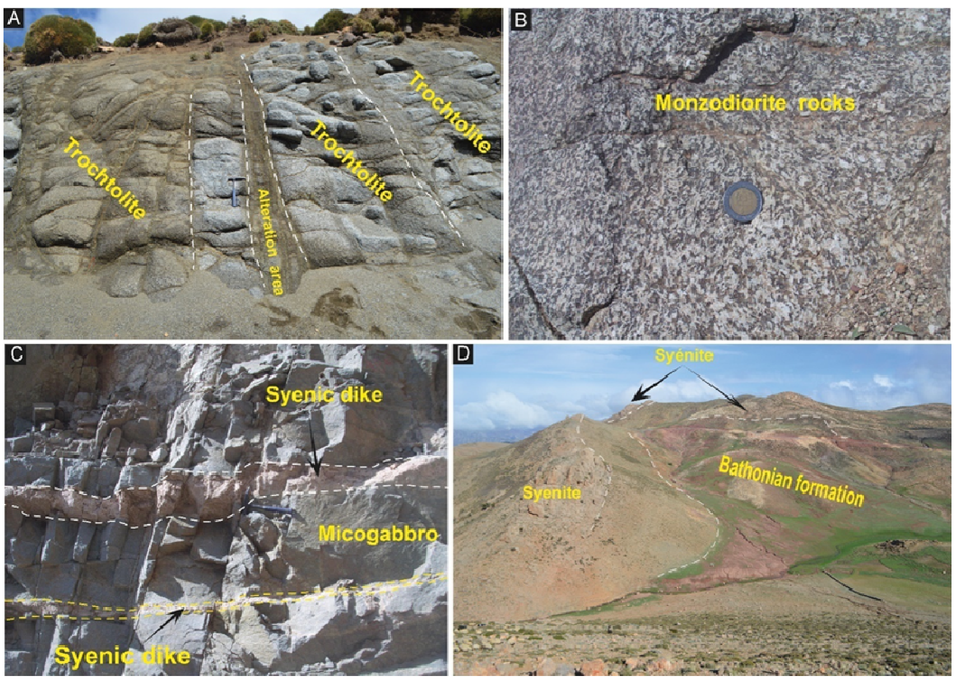


Figure 7: Field photograph of the syenites of Imilchil, High Central Atlas: A) lava flow of the syenites with alteration faults. B) texture of syenites. C) syenite dykes intersect gabbros. D) Contact of syenitic intrusion and triassic formation



3.1. Petrography

The mafic rocks are represented by sills of basalts and olivine gabbros that occupy between 60 and 70% of the magmatic intrusions of the area ([8], [11], [18]). The gabbros and olivine basalts are interbedded in the sedimentary host. The basalts have an intersertal to fluid microlitic texture, the primary mineral paragenesis is comprised by plagioclase that takes up a large percentage of the microlitic phase of the rock. Olivine, which is less abundant, is usually subautomorphic and occurs as phenocrysts [51].

The olivine gabbros show often an orthocumulat texture, the mineralogy is composed by pyroxene, plagioclase and olivine minerals. The secondary minerals are represented by epidote, biotite, chlorite and rarely magnetite and ilmenite [9].

The differentiated magmatic rocks of the High Atlas of Imilchil is composed essentially by the syenites and nephilinite. These rocks cover about 10 to 20 wt.% of all intrusions [18]. The primary mineral paragenetic of theses rocks is generally formed by microcline, hornblende with traces of quartz. Secondary minerals are represented by magnetite and/or ilmenite. Apatite is present as an accessory mineral [9]. Petrographic studies show that the syenites of the High Atlas of Imilchil are composed by four types: syenite with hornblende, syenite without hornblende and rich in interstitial opaque oxides, syenite relatively rich in quartz and syenites with potassium feldspar and rare albitic plagioclases.

3.2. Geochemical Characterization of Magmatic Rocks of the Central High Atlas of Imilchil

3.2.1. Majors Elements

The geochemical characterization based on geochemical analysis performed on magmatic rocks of the High Atlas of Imilchil, shows a magmatic formation with a alkaline affinity ([9], [11], [28])and transitional ([9], [52]. These rocks correspond to anorogenic volcanism that was emplaced in a continental intraplate geodynamic context [9].

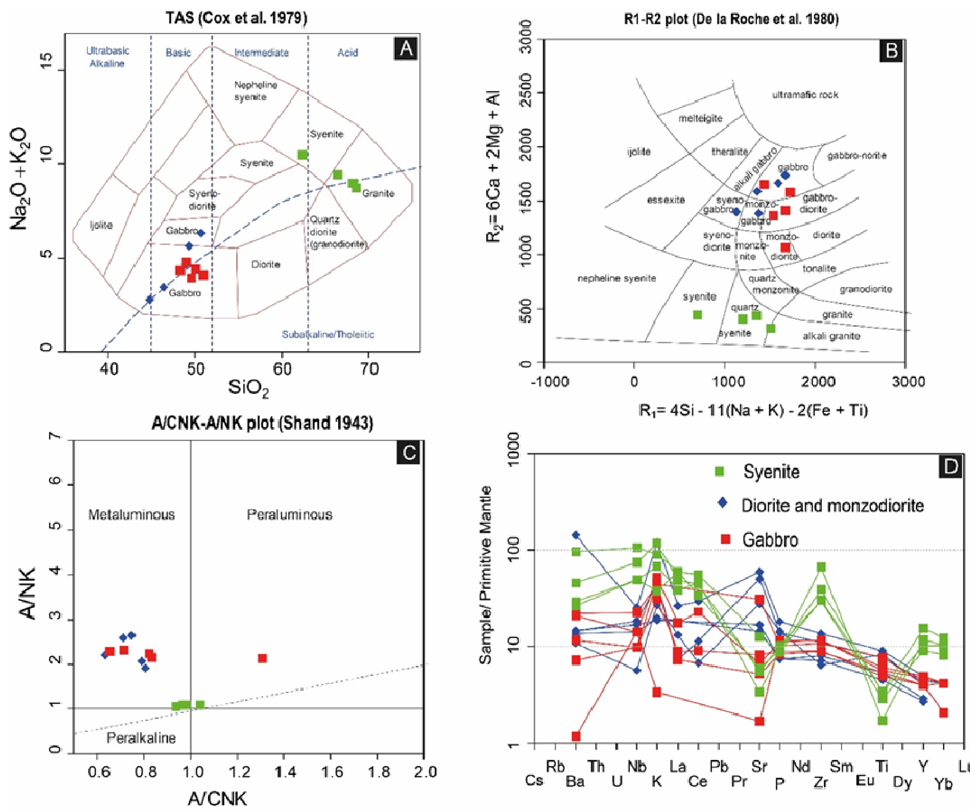
The samples show low values in loss on ignition (<5 wt.%) [9]. This allows us to make a classification based on alkaline elements, in the geochemical characterization. The projection of the samples on this diagram [53](Na_2O + K_2O vs SiO_2) (Fig. 8A) shows that the magmatic series of Imilchil is composed of alkaline basalt, intermediate rocks (diorites) and an felsic rocks formed the syenite. The discrimination of these samples shows a slight magmatic evolution of the mafic and felsic poles (Fig. 8A). This corroborates with the result obtained by using the R1 & R2 of [54] based on major elements (Fig. 8B).

The magmatic rocks of the High Atlas of Imilchil shows a transitional and alkaline magmatic affinity (Fig. 8A and B). The intermediate and basic rocks show a meta-aluminous affinity. The gabbros have relatively high Al_2O_3 contents of (17.7-11.00 wt.%), MgO contents of (17.49-4.53 wt.%), CaO contents of (9.8-6.13 wt.%), and relatively low P_2O_5 contents of (0.39-0.16 wt.%). These rocks also exhibit a trace element ratio (Nb/Y= 0.69) characterized by transitional to alkaline affinity.

The diorites exhibit alkaline metaluminous geochemical affinity with relatively lower concentration of MgO than mafic rocks (gabbro) varying from 10.9 to 5.73 wt.%, CaO varies from (9.76-5.37 wt.%), Fe_2O_3 from (9.77-11.5 wt.%), and relatively high Al2O3 varies from (16.3-11.6 wt.%). (Fig. 8C).

The syenites show a percaline affinity (Fig. 8C) with a trace element ratio (Nb/Y= 0.85) and Al_2O_3 contents varying from (16.6-14.4 wt.%), MgO varies from (0.4-0.08 wt.%) and Fe_2O_3 varies from (7.5-4.4 wt.%) while CaO is from (1-0.3 wt.%).

Figure 8: Classification diagrams of magmatic rocks from Imilchil, Central High Atlas (analysis after [9]: A) Classification diagram of magmatic rocks based on major elements (SiO_2 vs Na_2O+K_2O) the TAS after [53]. B) Diagram R1 & R2 of the plutonic rocks of Imilchil according to [54]. C) Aluminum saturation diagram according to [55]. D) Normalized spectra diagram on the primitive mantle according to [56].



The high CaO/Al_2O_3 ratios of nephelinites and the decline in this ratio toward basanites with increasing SiO_2 is also in agreement with increasing melting degrees of a garnet-bearing source [57].

3.2.2. Traces Elements

The spider diagrams of trace elements normalized to the primitive mantle after [56] show that the basic and intermediate rocks are relatively uniform with sub-parallel spider diagrams and relatively rich in Large Ion Lithophile Elements(LILE) (e.g. Rb, Nb, U, Rb and La) trace elements. These rocks show a positive anomaly in K and Sr (Fig. 10D). However, the syenites show a different trend compared to the mafic and intermediate rocks (gabbro and diorite). They display a positive anomaly in Zr and K and a negative one in Ti (Fig. 8D).

4. Discussion and Conclusion

The Central High Atlas is represented by a magmatic suite extending from the Jurassic to the Upper Cretaceous with a large variety that can be grouped into two major magmatic manifestations: (i) Jurassic age magmatism, e.g. Jbel Hayim diorite 151.3 ± 0.5 Ma to 145.0 ± 0.5 Ma [40] (Terminal Jurassic) ([58]–[63][59]–[64]). This magmatism is the most abundant, characterized by a tholeiitic affinity of sublithospheric origin [8]. It presents in basaltic lava flows (B1), dioritic and doleritic dykes ([9], [11], [28], [65]). This manifestation is established in an extensive geodynamic context in relation with the opening of the Atlantic basin [65]. (ii) alkaline magmatism of Cretaceous age of mantle origin (e.g. Tamazert nephelinites [66], [67]. It is constituted by gabbros, diorites, Monzodiorite, syenites) is identified in the Central High Atlas. It was deposited in sills, flows or dykes form at the level of wrinkles[9], [12], [28], [40], [48])..

4.1. Mafic Magmatism

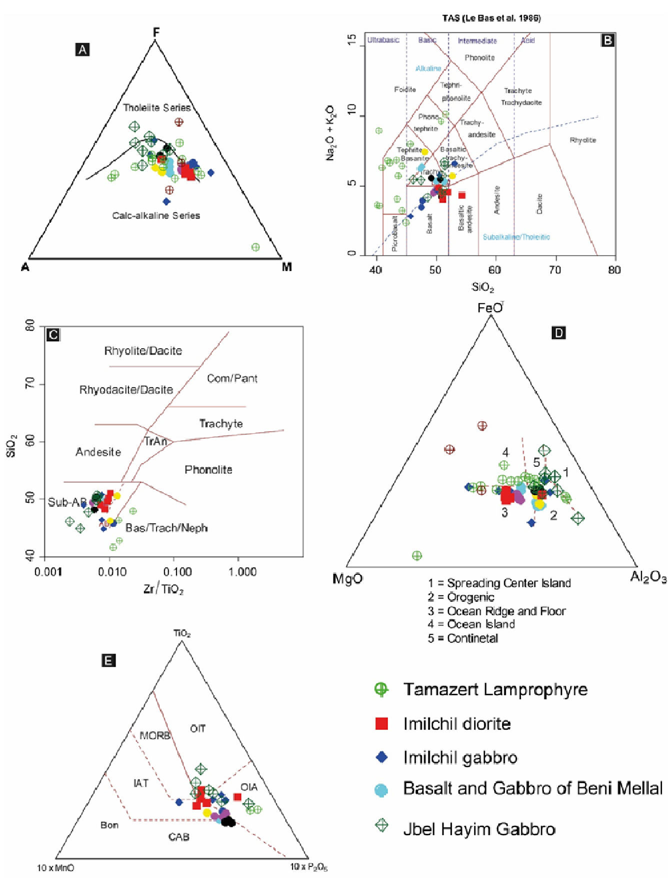
4.1.1. Classification and Affinity

The magmatic activities of the Central High Atlas are marked by mafic rocks with tholeiitic affinity (basalt sills and dykes) from Triassic to the Jurassic (Beni Mellal) ([8], [9], [11], [68]). This magmatism has been considered as an extensive stage related to the opening of the Atlantic basin and is composed of two mafics magmatic suites: carbonatite, lamprophyres and gabbros in the Tamazert High Atlas [8], and basalt, gabbros and monzodiorites in the Beni Mellal and Imilchil High Atlas ([9], [11], [68], [69]).These magmatic rocks are characterized by alkaline/transitional to tholeiitic magmatic affinity (Fig. 9A, B and C) from the Middle Jurassic to the Lower Cretaceous.

4.1.2. Geodynamic Setting

Dissemination of the Jurassic mafic magmatic rocks of Central High Atlas in AFM diagram displaya tholeiitic suite, and represents mainly alkali basalt, basalt andesite, trachyte, tephrites, basanites within (Fig 9A, B, C).They are characterized by intraplaque geodynamic context ([9], [11], [40]). The last discrimination of geochemistry form ([8], [9], [11], [40]) display they are established in transitional stage between orogenic (Lamprophyres of Tamazert, Imlchil Gabbro) to ocean ridge in the last stage of opening of Atlantic basin (Fig 9D and E).

Figure 9: Classified diagram of mafic High Atlas Rocks: A) AFM diagram [70] display the mafic rocks had tholeiitic suite. B) Classified diagram based on major elements [71]show the mafic rocks are composed by basalts, trachybasalt and phonolite with transitional alkali to tholeiitic affinity. C) Classified diagram based on trace elements (Zr/TiO2 vs SiO2) of[72]. D), geotectonic diagram of[73]. E) Geotectonic diagram of [74]. (OIT) Ocean Island Tholeiite, (MORB)Mid-Ocean Ridge Basalt, (IAT) Island Arc Tholeiite, (Bon) boninite(CAB) Calc-alkaline Arc Basalt; (OIA) Ocean Island Alkaline basalts. (data from the Geological analyses of[8], [9], [11], [40]



4.1.3. Cogenetism of Magma Sources

The evolution of trace elements versus Mg (Fig. 10) of the mafic rocks from the Central High Atlas, highlights a minor difference in magmatic activities. It would suggest the presence of two magmatic suites probably related to the opening of the Atlantic basin. The spectra of these rocks show a sub-flat aspect with a low positive Nb anomaly (Fig. 11) probably due to the low rate of crustal contamination during the emplacement of the basic magma.

Figure 10: Evolution of trace elements versus Mg for mafic Central High Atlas rocks

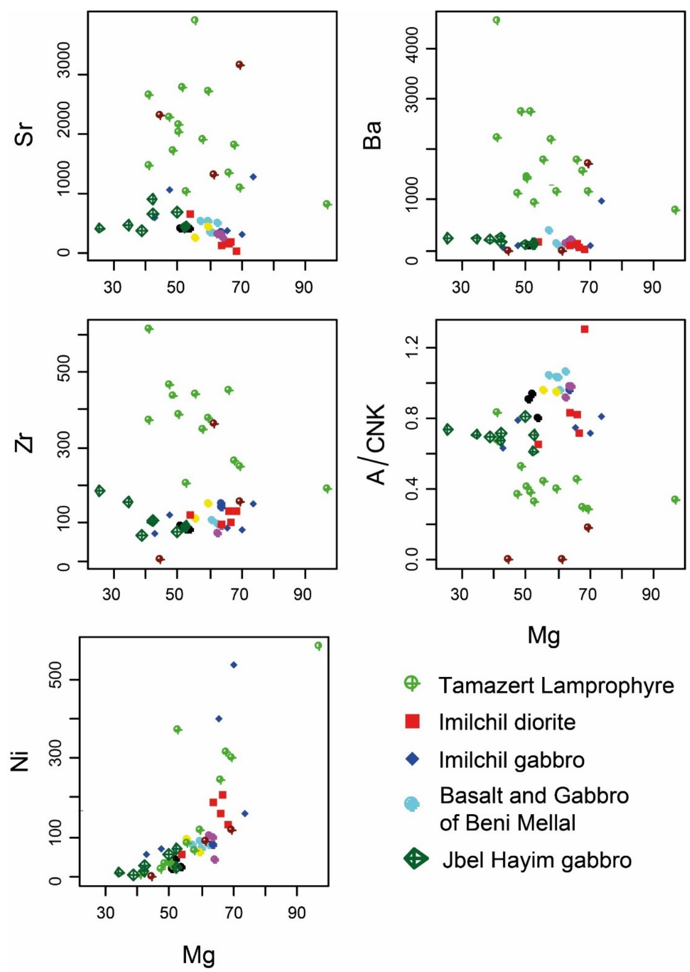
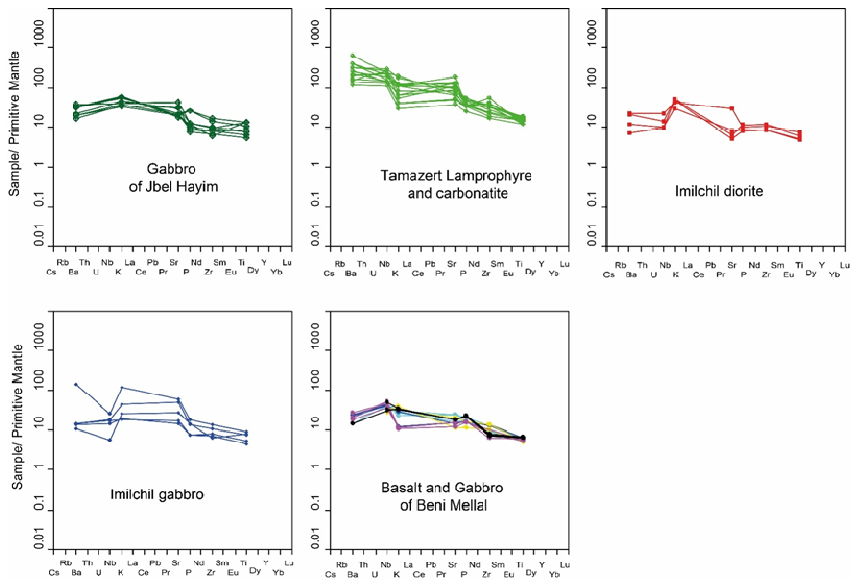


Figure 11: Spider diagrams normalized to the primitive mantle after [75] of mafic Central High Atlas rocks

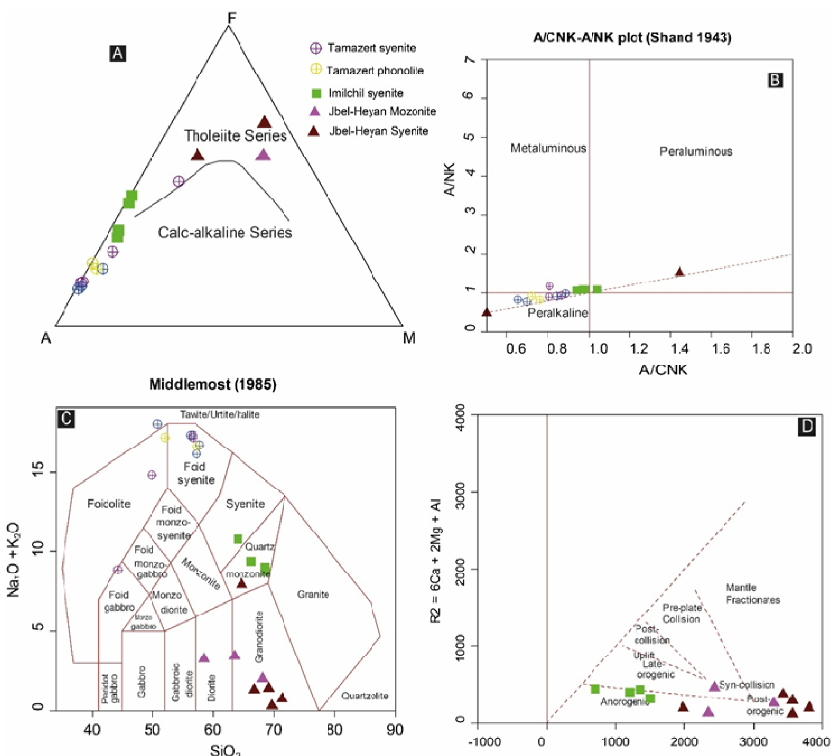


4.2. Felsic Magmatic Rocks (Cretaceous)

4.2.1. Classification and Affinity

The felsic magmatic rocks are represented by syenites and nephelinic syenite of middle Cretaceous age. They are display alkaline to transitionnal peralkaline magmatic affinity (Fig. 12 A, B and C) ([59], [60], [63], [64]).

Figure 12: Classified diagram of mafic High Atlas Rocks: A) AFM diagram[70] display the mafic rocks had tholeiitic suite. B) affinity diagram of[76]show they are peralkaline affinity. C) classification diagram from[71]. D) Tectonic classification diagram the plutonic rocks of Imilchil after[77]



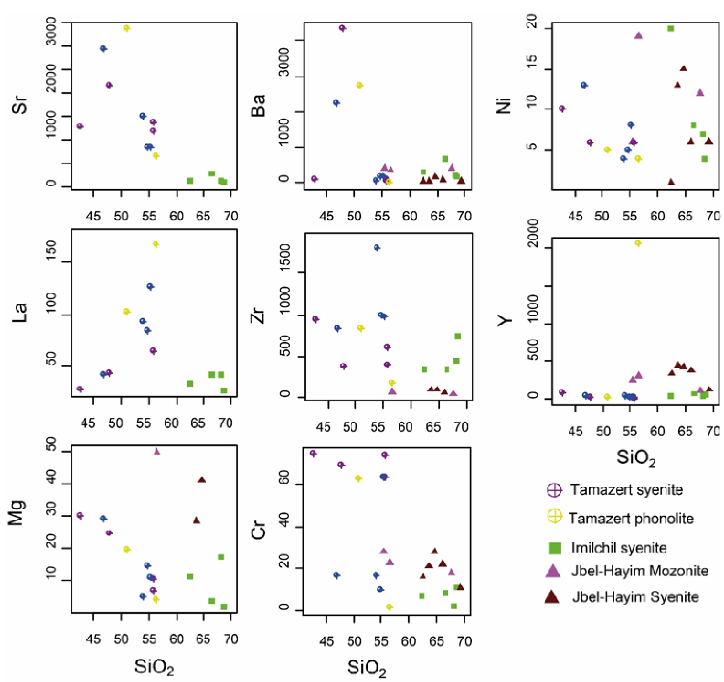
Geodynamically, the felsic Central High Atlas magmatic rocks was established in a syn-orogenic to anorogenic geodynamic context in the Central High Atlas of Imilchil, and post-orogenic towards the northwest (Jbel Hayim Massif) (Fig. 12D). However, they were established in an anorogenic Intraplate context, whereas the diorites and gabbros was established in a post-collisional geotectonic environment (Fig. 12D). These rocks show probably a continuity that highlights an evolution of the geodynamic context.

4.2.2. Fractional Crystallization and Crustal Contamination

According to [78], the mafic rocks of the Central High Atlas have a mantle origin with a slight contamination by the continental crust. The effect of this contamination is indicated by [8] on the magmatic massifs of the High Atlas of Imilchil and especially during the formation of intermediate facies. This formation has been explained by the assimilation phenomenon associed with fractional crystallization [79]. This could explain the presence of heterogeneous monzodiorites and felsic veins at the margins of gabbro intrusions. Furthermore, Sr-Nd isotopic studies by [80]indicate that hydrothermal activity modified the chemical composition of felsic intrusions (syenite and monzonites) by a depletion of K and Rb and an enrichment of Na and Sr. These studies demonstrated that the initial isotopic composition of Sr was modified and presents higher ratios that range between 0.7067 and 0.7075, while Nd is relatively preserved [80].

The intervention of the composition of the crust is also marked by a low anomaly in Nb. This can be observed in the mafic and intermediate rocks by the linear evolution on the correlation diagrams of SiO2 versus trace elements considered immobile or slightly mobile by hydrothermal alteration (Fig. 13). Moreover, the felsic rocks (syenites) do not show any correlation with the rest of the rocks and present an isolated pole on the graphs of SiO_2 evolution versus the major elements. This suggests the presence of at least two magmatic events of different origins. This is well illustrated on the spectra of the normalized diagrams to the primitive mantle by the absence of a parallelism of the spectra of the felsic samples to intermediate and basic poles magmatic rock. Similarly, the anomalies noted on the spider are very different (Fig. 13).

Figure 13: Evolution diagram of SiO2 versus majors' elements of felsic magmatic rocks of the Central High Atlas



4.2.3. Magmatic Source of Felsic Rocks

The mineralogy of Tamazert felsic rocks are includes nepheline, alkali feldspar, aegirine-augite and biotite with accessory amounts of magnetite, ilmenite, sphene, apatite, eudialyte and schorlomite(Ti-rich andradite). The nepheline syenite contains inclusions of ultramafic rocks(mainly pyroxenites) and marble[81], [82].

The primary mineral paragenesis of Imilchil felsic rocks are generally formed of microcline, hornblende with traces of quartz, magnetite and/or ilmenite, with accessory apatite, the syenites of Imilchil are composed of four types: hornblende-rich syenite, hornblende-free syenite rich in interstitial opaque oxides, relatively quartz-rich syenite, and syenites with potassium feldspar and rare albitic plagioclase [9].

Syenites of Imilchil have high silica and high alkali contents ranging from 62.40 to 68.60 wt.% and 8.76 to 10.49 wt.% Na_2O+K_2O, respectively, and 0.30 to 1.00 wt.% CaO. MgO content ranges from 0.08 to 0.47 wt.% ($Mg^{\#}$ = 2.07- 17.46), 0.19 to 0.22 wt.% P_2O_5 and FeO^t content ranges from 3.96 to 6.75 wt.%.

Tamazertsyenitic rocks have a lower alkali (Na_2O+K_2O) of Imilchil syenite varies form (8.53-17.04 wt.%) (Tab 1)) with 42.72 to 55.08 wt.% SiO_2 0.73 to 12.83 wt.%, CaO, 0.12 to 2.50 wt.%, MgO ($Mg^{\#}$= 6.85- 30.36), 0.02 to 0.34 wt.% P_2O_5 and 2.90 to 10.22 wt.% FeO^t(Tab 1).

Therefore, the Jbel Hayim syenites display higher silica concentration witch varies of (62.47-69.30 wt.% SiO_2), intermediate alkali (Na_2O+K_2O) values between 7.19-12.7 wt.%) (Tab. 1) and lower 0.01 to 0.2 wt.% of CaO , and higher values of MgO (3.24 to 5.6 wt.%), P_2O_5 (5,92 to 10.23 wt.%) and FeO^t (5.02 to 17.15 wt.%).

The monzonite of Jbel Hayim characterized by have very lower alkali contents (Na_2O+K_2O) = 2.05 to 3.14 wt.%) (Fig;) than syenites with 55.44 to 67.68 wt.% SiO_2 0.12 to 0.24 wt.% CaO,8.34 wt.% MgO ($Mg^{\#}$= 49.47), 6.14 to 7.14 wt.% P_2O_5 and 14.73 to 15.55 wt.% FeO^t (Tab 1).

Syenites of Imilchil are enriched up to 100*Chondrite higher LILE concentrations than Si-poor Tamazert syenite, with negative anomalies in Nb/Y and Zr/Yb (Zr/Yb = 56.67-147.80, Nb/Y = 0.66-1.30).

The spider diagram normalized of primitive mantel ofImilchil and Tamazerht syenite are sensibly comparable and they are very different from Jbel Hayim syenite. The spider diagramsnormalized of primitive mantel of Imilchil syenite patterns are different from Tamazert syenite patterns with high fractionation of LREE compared to HREE (Fig. 14) La= 26-41 ppm, La_N/Yb_N= 0.75-1.18 for Imilchil syenite and La= 26,7-74 ppm, La_N/Yb_N= 0.44-15.05 for Tamazert syenite.

The Tamazert syenite have high concentrations of Ba contents (54-4353 ppm) and negative anomalies Nb/Y (2.78-6.55) with high concentration of Zr (362-944 ppm). For Imilchil syenite shows also the high values of Zr (330-739 ppm) and high ratio of Nb/Y (0.7-1.22) (Fig. 14).

The Jbel Hayim syenite are enriched also up to 200*Chondrite higher LILE concentrations with negative anomalies of Nb/Y and Zr/Yb (Zr/Yb = 1.35-1.85, Nb/Y = 0.67-0.1) (Fig. 14). they are distinguished from Imilchil and Tamzert syenite by lower values of Zr (52.3-90.3 ppm) and Ba (51-178 ppm) and lower ratio of Zr/Yb (1.35-1.85).

Figure 14: spider diagrams of Central High Atlas felsic rocks (syenites, phonolites and monzonites) normalized to the primitive mantle [75]

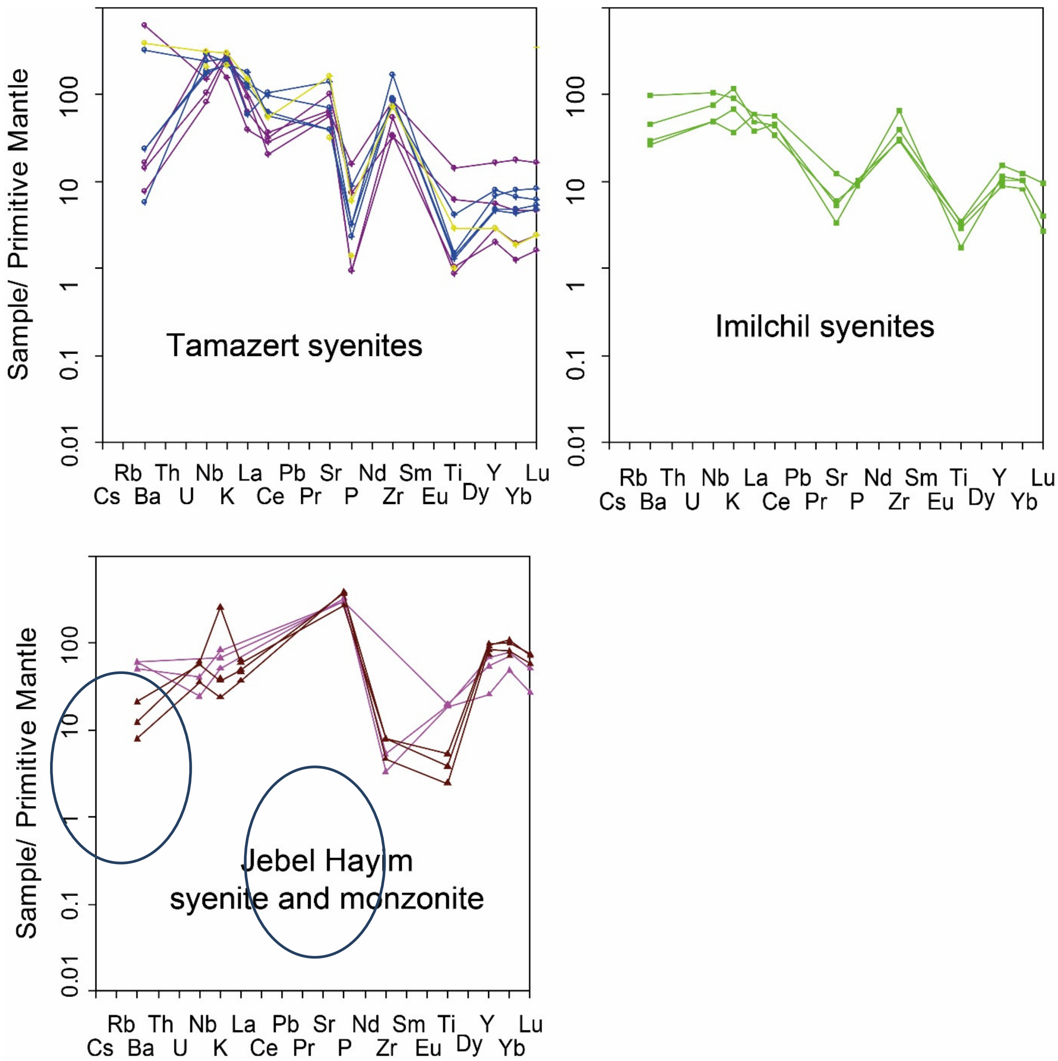
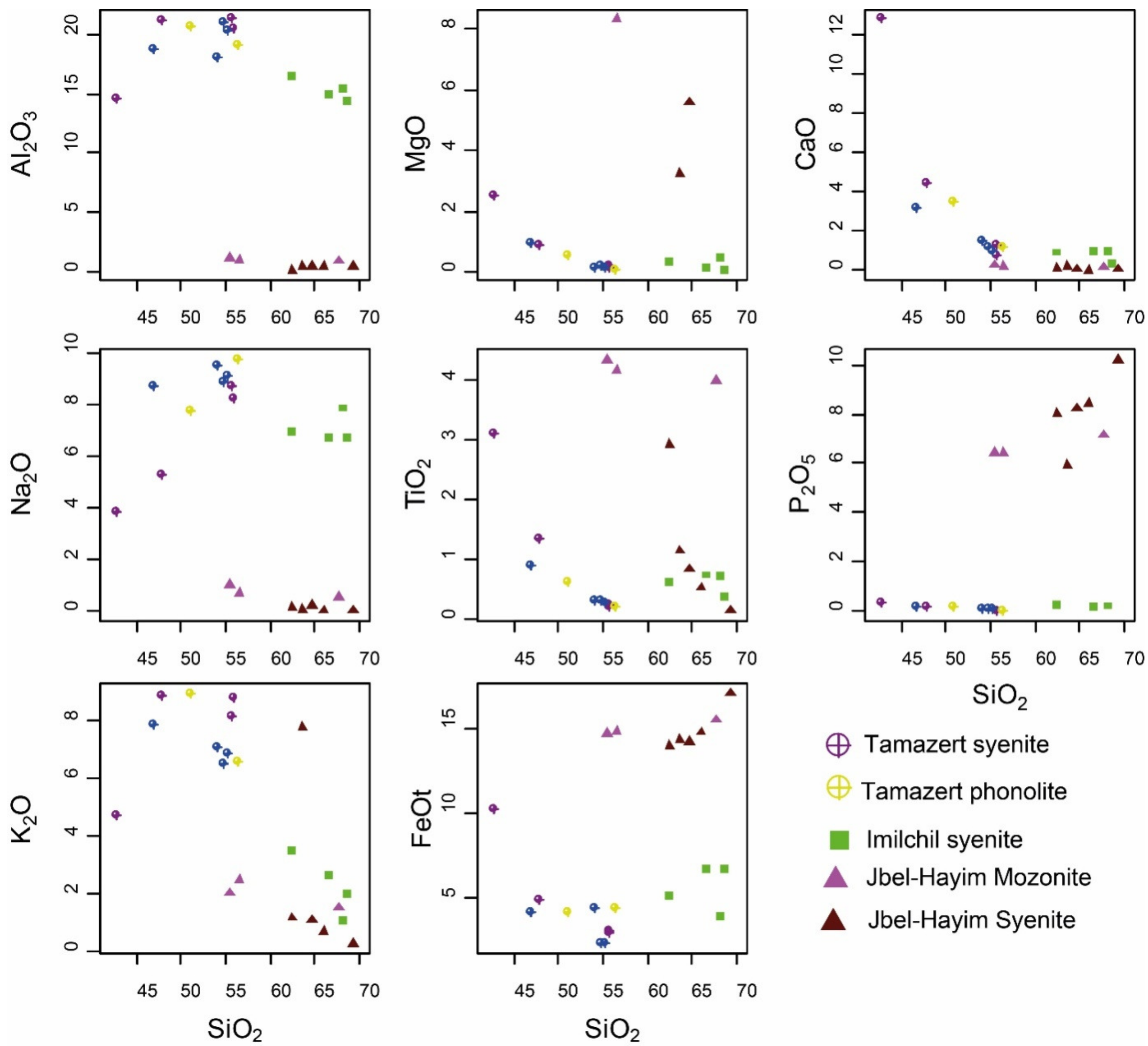


Table 1: Table summarizing the trace elements of Central High Atlas of Central High Atlas of Imilchil, Jbel Hayim and Tamazertsyenitic rocks

Zone/elements	Imilchil		Jbel Hayim		Tamazert	
	Min	Max	Min	Max	Min	Max
SiO_2 (wt.%)	**62.40**	**69.60**	**62.74**	**69.3**	42.72	55.08
Al_2O_3 (wt.%)	**14.4**	**16.6**	0.12	0.48	**14.57**	**21.36**
Alkalin (wt.%)	8.76	10.49	7.19	12.7	8.53	12.04
CaO (wt.%)	0.3	1	0.01	0.2	0.73	12.83
FeO^t(wt.%)	3.96	6	**5.02**	**17**	2.5	10.22
MgO (wt.%)	0.08	0.47	**3.24**	**5.6**	0.12	2.5
P_2O_5 (wt.%)	0.19	0.22	**5.92**	**10.23**	0.02	0.34
TiO_2 (wt.%)	0.37	0.74	0.15	0.91	0.19	3.11

From this correlation it appears that the facies richest in phosphates are those of Jbel Hayim, they are also the richest in SiO_2, MgO, FeO^t and sometimes TiO_2. (Fig. 17), the syenites of Imilchil and Jbel Hayim are comparable in alkali and silica, with however notable differences in Al_2O_3, MgO, FeO^t and P_2O_5.

Figure 15: Evolution of SiO2 versus major elements in felsic rocks of Imilchil-Tamazert and Jbel Hayim



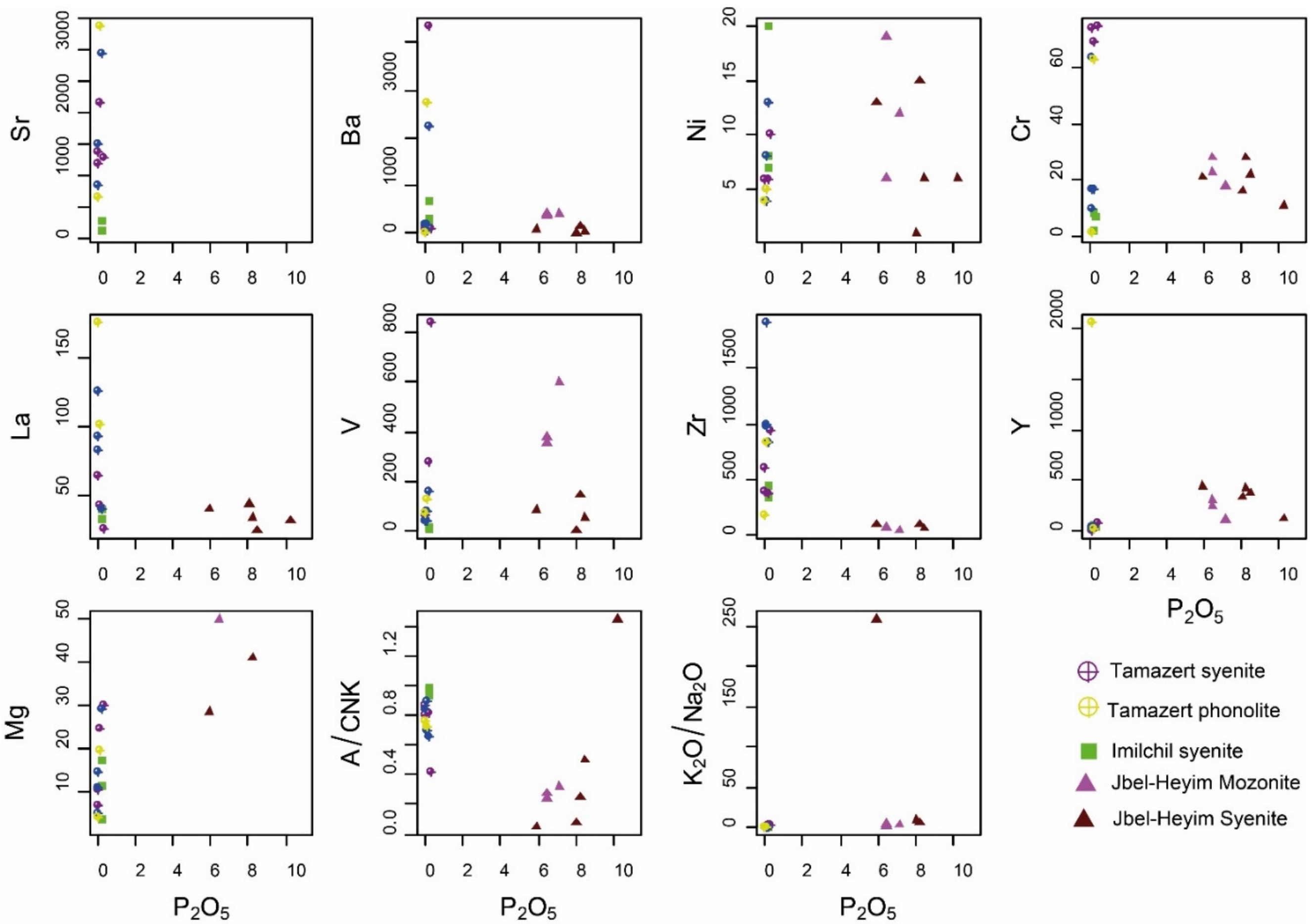
We noted that the Imilchil syenites and Tamazert syenites show a high variability in the concentration of certain elements such as K_2O, CaO, MgO and Al_2O_3 (Fig. 15), Ba and trace elements (Fig. 16). This variability is also apparent for the K/Nb, Ba/La, Ba/Nb and Ba/Rb ratio values (Fig. 16). [83] have indicated that the melting of a carbonate peridotite produces liquids with increasing SiO_2 contents and diminishing TiO_2 concentrations as the melting rate increases. We have indeed noticed on the diagram (TiO_2 vs. SiO_2) that the syenites of Imilchil and Jbel Hayim, show this tendency, and that they would be derived from a slightly higher melting rate than the rocks of Tamazert, which suggests a slight increase in the melting rate with time.

It should be noted that the large variability in K_2O and Ba of the Imilchil and Tamazert Cretaceous syenites for an identical age, would not necessarily be related to assimilation or mantle heterogeneity, but rather to a different melting rate but with a diachrony of emplacement.

The Major and trace diagrams versus P_2O_5, reveal two groups of samples (P_2O_5<1 ; and P_2O_5>6), this is also quite visible in the Major and trace diagrams versus SiO_2. (Fig. 16). One group with the syenite/Monzonite of Jbel Hayim and syenite of Imilchil and one group with the syenite of Tamazert.

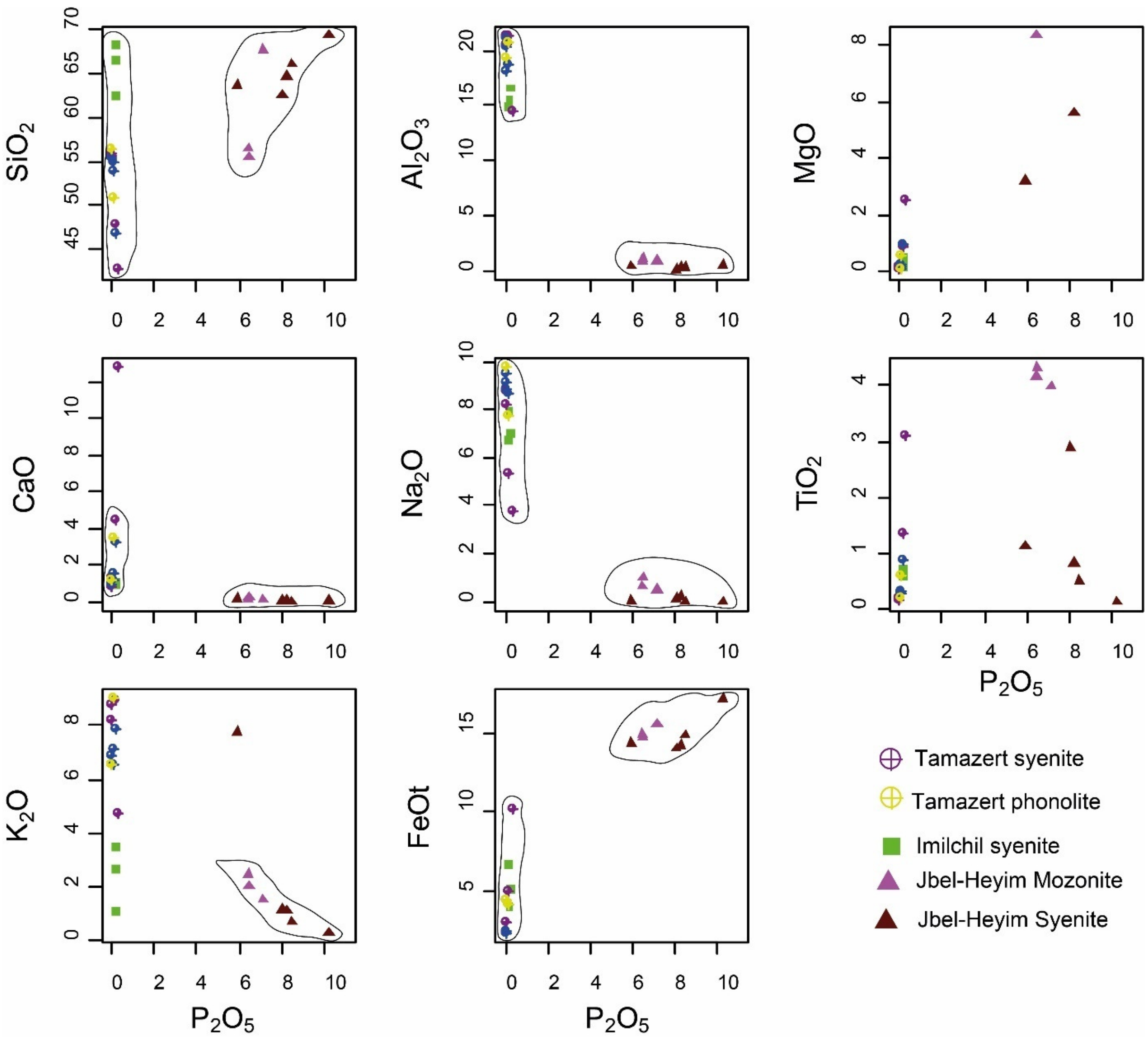
The compatibility of vanadium (V) during mantle melting is a function of oxygen fugacity (fO_2): at high fO_2's, V becomes more incompatible[84], this would explain the variation of vanadium values (Fig. 16).

Figure 16: Evolution of trace elements versus P2O5 in felsic rocks of the Central High Atlas.



The P_2O_5 richness is associated with FeO^t, MgO richness in the Jbel Hayim syenites (Fig. 17), would be related to the collisional to post-collisional geodynamic context, which would be a context where deformation, fluid flow, thermal transport and chemical reactions, and first-order interactions and feedbacks between the mechanisms involved in the mineralization process, are very active, unlike the Tamazert and Imilchil syenites which would have formed earlier in an anorogenic context.

Figure 17: Evolution of P2O5 vs. trace elements in felsic rocks of Imilchil-Tamazert and Jbel Hayim



5. Conclusion

The Central High Atlas (Imilchil, Tamazert and Jbel Hayim) present two main manifestations magmatic events: (i) an early mafic manifestation of Jurassic age with a tholeiitic and transitional affinity. It is constituted by basic rocks of sub-lithospheric origin (basalts), established in extensive intraplate context. (ii) an alkaline event of Cretaceous age characterized by a highly potassic alkaline affinity of mantle origin, and constituted by mafic, intermediate and felsic rocks, established in a post-collisional and anorogenic geotectonic environment. The acidic alkaline suite has two syenite types according to their P_2O_5 richness. (a) Jbel Hayim syenites characterized by phosphate oxide contents exceeding 6 wt.% with the highest FeO^t and MgO contents with the lowest TiO_2 and V concentrations. These manifestations were established in a syn- to post-collisional geodynamic context. (b) Tamzeert and Imilchil syenites show low P_2O_5 contents (less than 1 wt.%) and high Na_2O; Al_2O_3 and K_2O values. These rocks were formed in an anorogenic geotectonic environment, and are part of a magmatic suite with basic (gabbros) and intermediate (diorite and monzodiorites) rocks. The syenites of the Jbel Hayim massif display strong indications of phosphate mineralization (up to 10% P_2O_5), which is expressed as apatite.

Because of their high P_2O_5 content, the syenite and monzonite of Jbel Hayim may be an interesting future source of magmatic phosphate in Morocco. Despite the low grade and tonnage of phosphates in these types of deposits (15-20 wt.%), but they are of great economic interest for "clean" phosphate.

Through this synthesis during this preliminary study on the syenites and monzonites of the Central High Atlas, we retain that the sector in general and Jbel Hayim in particular, would require a more thorough study as to the lithogeochemical characterization and the prospecting and development of apatite resources in these intrusions.

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