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Geochemical and Tectonic Significance of the Calc-Alkaline Cryogenian Mafic Rocks of the Igherm Inlier (Western Anti-Atlas, Morocco)

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Abstract: In the Igherm inlier (Western Anti-Atlas, Morocco) dolerilic dyke swarms with various directions and gabbroic, intrusive bodies were emplaced during Neoproterosoic times, cutting across either Eburnean micaschists and granites or panafrican limestones and quartzites. The mafic rocks of the lower Cryogenian magmatism from the Igherm inlier (Moroccan Western Anti-Atlas) have calc-alkaline, tholeiitic and alkaline affinities. The calc-alkaline dolerite dykes and gabbros bodies emplaced before the conglomeratic formations of the upper Cryogenian and after the tholeiitic mafic rocks that characterize the pre-Pan-African rifting are similar to rocks from orogenic setting. They are characterized by high LILE, Th, Ce, P, Sm contents and La/Nb ratio and a low HFSE content with negative anomalies in Nb, Zr and Ti. The geodynamic environment of the sedimentary country rocks corresponds to that of a passive margin in a distensive tectonic context. The calc-alkaline affinity of these magmas can be attributed to the influence of a Paleoproterozoic subduction zone that contributed to the enrichment of the subcontinental mantle. During the extensional event of the Pan-African orogenesis, the mantle would have produced tholeiitic, alkaline and/or transitional magmas before melting (caused by adiabatic decompression) reached the enriched subcontinental mantle previously enriched during the Eburnean subduction where it would have generated calc-alkaline magmas.

Key words: Calc-alkaline mafic rocks, lower cryogenian, paleoproterozoic subduction, igherm, Western Anti-Atlas, Morocco

INTRODUCUION

The Proterozoic basement of the Anti-Atlas is divided into 2 domains either side of the WNW-ESE oriented Central Anti-Atlas Fault Zone (CAAFZ) (Fig. 1). The North-eastern domain has been interpreted as a multi-deformed Neoproterozoic Pan-African orogenic segment that encompasses the Siroua, Saghro and Ougnat massifs. However, the Neoproterozoic magmatism of this domain displays a Paleoproterozoic source suggesting an underlying Eburnean basement (Gasquet *et al*., 2005). The South-western domain consists of a Paleoproterozoic and Neoproterozoic basement that was deformed by the Eburnean and Pan-African orogenies and covered by Ediacaran to Paleozoic formations. The Bou Azzer inlier lies between these two domains along the CAAFZ. This inlier consists mostly of a Pan-African ophiolitic complex that has recently been dated at the neighboring Siroua massif at 761±2 Ma (U/Pb on zircons from plagiogranites; Samson *et al*., 2004). The Igherm inlier the focus of the present study belong to the southwestern domain on the northern margin of the West African Craton. No Mesoproterozoic ages have ever been found in the whole Anti-Atlas. The Neoproterozoic of the Anti-Atlas has been divided intotwo supergroups: the Cryogenian Anti-Atlas Supergroup (AASG) and the Ediacaran Ouarzazate Supergroup (OSG) (Thomas *et al*., 2004). The lower Cryogenian formations (Jbel Lkest Group, AASG pro-parte) lie unconformably on the Paleoproterozoic basement (Gasquet *et al*., 2004). The bottom part of the AASG (limestones and quartzites) consists of epicontinental platform sediments whereas the upper

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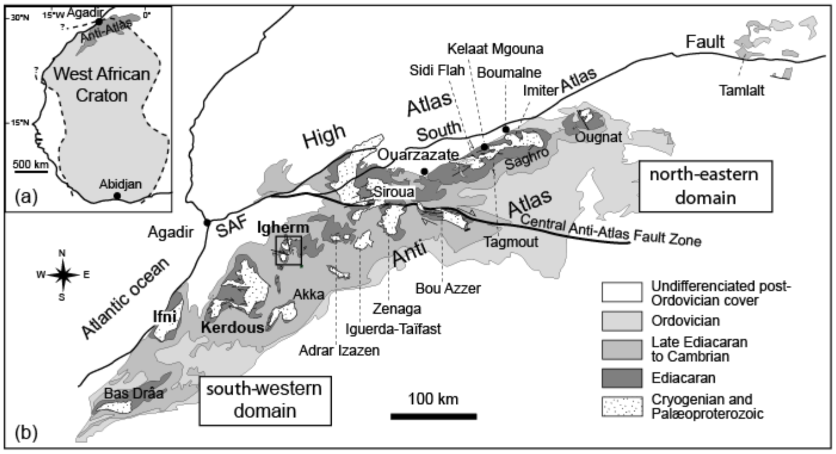

Fig. 1: Geological sketch map of the Anti-Atlas belt in Southern Morocco and location of the Igherm inlier (bold square) SAF: South Atlas Fault

members (schists and stratified quartzites) are characteristic of an ocean basin environment. Mafic rocks have been described within all the Cryogenian sedimentary sequences of the AASG (Gasquet *et al*., 2004).

The upper Cryogenian which records the late Pan-African event is composed mostly of molassic conglomerates with rhyolites, ignimbrites and acid tufs at the base.

The Ediacaran OSG formations consist of conglomerates overlain by purple-blue pelites, preceded by andesitic flows in the northeastern part of the Igherm inlier and more generally across the Anti-Atlas by extremely thick (up to 2000 m in the Ouarzazate area) piles of felsic volcanic rocks (notably rhyolites).

The Paleoproterozoic of the Anti-Atlas consists of micaschists and calc-alkaline granites deformed during the Eburnean (Gasquet *et al*., 2005). Syn-orogenic granitoids developed after 2050 Ma, associated with calc-alkaline and peraluminous magmas derived from a mafic source (with a small Archaean crustal component) in a plate-convergence back-arc setting (Gasquet *et al*., 2004, 2005, 2008).

According to Benziane, the Paleoproterozoic in the Anti-Atlas is characterized by two distinguishable magmatic events both related to a subduction setting: the first at 2110-2080 Ma (trondhjemitic magmatism) and the second at 2050-2030 Ma (calc-alkaline magmatism).

Mafic magmatism in the Anti-Atlas is represented by at least four generations of dykes: Tholeiitic dykes of Paleoproterozoic age. Dykes in the Tagragra de Tata have been dated at 2040±6 Ma using the SHRIMP U/Pb method on zircons (Walsh *et al*., 2002) and a microgranite from the Tafeltast inlier which is cartographically and structurally associated to the mafic dykes in this inlier and to those in the Tagragra d'Akka inlier has been dated at 1760±3 Ma (Gasquet *et al*., 2004). Cryogenian dykes with tholeiitic and alkaline affinities, coeval with the opening of back-arc oceanic basin in the central Anti-Atlas (Clauer *et al*., 1982).

U/Pb ages of 761±2 Ma have been obtained using zircons from plagiogranites associated with the Siroua ophiolites (Samson *et al*., 2004). Dacite dykes in the Tafeltast and Tagragra d'Akka inliers, dated at 600±5 Ma using the SHRIMP U/Pb method (Gasquet *et al*., 2004). Late Pan-African mafic dykes including those that crosscut the Taourgha granite, dated at 575±4 Ma (U/Pb ages) using samples from the Bas Draa inlier.

GEOLOGICAL SETTING OF THE CAL-ALKALINE MAFIC ROCKS OF THE IGHERM INLIER

The calc-alkaline mafic rocks of the Igherm inlier outcrop in the form of numerous dolerite dykes that trend NW-SE to N-S and that range from several meters to several tens of meters in length and from 0.5-1.5 m in width together with 100 m scale mafic bodies that do not show any magmatic fabric at outcrop. They intrude the schist-greywackes and granites of the Paleoproterozoic basement and into lower Cryogenian limestones and quartzites. They precede the upper Cryogenian conglomeratic formations.

The limestones in direct contact with the mafic bodies have been metamorphosed to greenschist facies whereas the quartzites have centimeter-scale borders with a horny aspect and a very fine grain. The Paleoproterozoic and

Cryogenian formations and the mafic rocks are affected by the regional NE-SW trending Pan-African schistosity. Relative chronology shows that the calc-alkaline dykes intrude both the calc-alkaline mafic bodies (present study) and the dykes with tholeiitic affinities. On the other hand, no relationship has been observed at outcrop between the mafic dykes, mafic bodies and alkaline dykes.

The latter, like the calc-alkaline dykes, intrude the Paleoproterozoic basement and the tholeiitic mafic bodies and have not been observed in lower Cryogenian quartzites.

PETROGRAPHY

The calc-alkaline mafic dykes are recognizable on the field by their grey color and their fine grained texture and mm sized phenocrysts with respect of the tholeiitic and alkaline dykes which are green or red colored and show a medium or coarse grained texture. However, no distinction is possible on the field between the different mafic bodies. The albite, chlorite, actinote, epidote, leucoxene and quartz paragenesis shows that the calc-alkaline mafic rocks have undergone secondary metamorphism in the greenschist facies. The fluidal and porphyritic microlitic textures found along the edges of the dykes or bodies gives way to a fine intersertal texture in their centers. The groundmass is cryptocrystalline and rich in calcite, chlorite and quartz.

These rocks contain particularly large quantities of plagioclase which can account for as much as 45-50% of the total volume of the rock. Chlorite and iron oxide pseudomorphs have the characteristic shapes of amphibole and olivine. Micro-phenocrysts of plagioclase have been transformed into calcite and albite (An05). Subeuhedral oxide and sulphide minerals are found in both the plagioclase and the chlorite pseudomorphs of ferro-magnesian minerals.

The primary mineral paragenesis of the gabbro bodies consists of plagioclase, uralitized pyroxene, opaque minerals and rare quartz-albite micropegmatite. The texture is generally intersertal along the borders of the mafic bodies becoming ophitic to sub-ophitic or phaneritic in the centers.

GEOCHEMICAL CHARACTERIZATION

About 30 samples of the least altered rocks were analyzed by the Rock and Mineral Analysis Department at CRPG-CNRS (Nancy) using ICP-AES and ICP-MS (Table 1) and following the procedures described by

Table 1: Representative major (wt.%) and trace (ppm) element analyses of the calc-alkaline mafic rocks from Igherm inlier. Analytical methods: Major element concentrations were determined by ICP-AES, and trace elements by ICP-MS at CRPG-CNRS (Nancy, France). Analytical uncertainties are estimated at 2% for major elements and at 5 or 10% for trace-element concentrations (except REE) higher or <20 ppm, respectively. Precision for REE is estimated at 5% when chondrite-normalized concentrations are >10 and at 10% when they are lower. LOI: Loss on Ignition, nd: not determined, <D.L.: below Detection Limit

Ech.	ITH 3b	ITH 3c	TAS 1b	TAS 3	TAS 4	TAS 5	TAS 7b	TAS 8	ISS 2c	TAS 16	ISS2	TAL 2	TNW 2	TAS 03	TAS 08	AS 16b
SiO_2	52.62	52.19	50.28	47.20	47.57	50.12	51.71	48.00	51.37	46.40	52.40	52.33	49.10	47.79	47.92	46.84
Al_2O_3	14.85	14.87	15.36	20.64	19.03	16.10	15.51	17.10	16.23	17.10	14.61	15.29	16.39	20.86	17.21	17.47
TiO_2	1.01	1.02	0.76	1.12	1.41	0.86	0.91	1.38	0.88	1.12	0.68	1.16	0.90	1.14	1.40	1.20
Fe_2O_{3t}	11.25	11.15	9.80	9.91	9.07	10.96	9.35	12.81	9.16	12.91	10.16	12.20	9.95	10.01	12.94	13.14
MnO	0.17	0.17	0.15	0.17	0.15	0.17	0.16	0.22	0.16	0.26	0.17	0.16	0.19	0.18	0.21	0.25
MgO	6.05	6.05	5.87	4.72	4.16	5.05	5.41	6.05	6.19	6.83	6.75	5.16	5.58	4.76	6.04	6.85
CaO	7.16	7.41	9.41	7.33	9.46	9.28	7.37	7.20	7.59	7.63	8.66	6.77	7.98	7.44	7.35	7.91
Na_2O	3.40	3.27	4.48	3.72	3.06	2.95	5.25	2.95	3.06	2.91	2.61	2.31	3.21	3.60	2.85	2.87
K_2O	0.60	0.62	0.34	1.20	1.56	0.30	0.52	0.83	1.88	0.56	0.91	0.96	2.93	1.21	0.83	0.60
P_2O_5	0.14	0.15	0.20	0.30	0.39	0.22	0.34	0.34	0.28	0.29	0.20	0.16	0.26	0.24	0.28	0.21
P.F	2.55	2.98	3.16	2.67	2.95	3.81	2.62	2.76	2.75	2.61	2.66	3.34	3.46	2.70	2.89	2.60
Total	99.80	99.88	99.81	98.98	98.81	99.82	99.15	99.64	99.55	98.62	99.81	99.84	99.95	99.93	99.92	99.94
ppm																
Ba	227.00	228.00	120.00	519.00	497.00	135.00	180.00	457.00	1400.00	323.00	200.00	245.00	380.00	496.00	418.00	345.00
Be	1.20	1.07	1.00	0.80	1.00	1.29	1.00	1.10	1.00	1.20	1.60	0.81	0.83	1.08	0.52	1.03
Co	30.00	69.00	36.00	42.00	38.00	44.00	47.00	46.00	28.00	660.00	54.00	48.00	35.00	46.00	53.00	63.00
Cr	66.00	62.00	105.00	27.00	31.00	62.00	59.00	73.00	144.00	120.00	98.00	7.00	172.00	23.00	62.00	114.00
Ga	16.00	19.00	5.00	9.00	5.00	5.00	20.00	5.00	26.00	18.00	23.00	nd	19.00	23.00	20.00	23.00
Cu	51.00	44.00	8.00	6.00	9.00	8.00	7.00	11.00	31.00	8.00	7.00	0.30	2.00	3.00	5.00	5.00
Ni	56.00	57.00	27.00	50.00	52.00	19.00	26.00	53.00	64.00	68.00	30.00	18.00	64.00	52.00	48.00	60.00
Nb	7.00	6.40	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	6.80	4.50	5.40	5.40	4.90
Rb	20.00	20.00	13.00	42.00	57.00	12.00	15.00	26.00	74.00	19.00	19.00	20.00	126.00	44.00	26.00	17.00
Sc	33.00	33.00	39.00	17.00	21.00	38.00	26.00	23.00	22.00	25.00	41.00	23.00	nd	14.00	22.00	24.00
Sr	253.00	257.00	232.00	595.00	508.00	338.00	227.00	482.00	168.00	595.00	248.00	220.00	103.00	576.00	441.00	613.00
V	236.00	242.00	181.00	144.00	163.00	225.00	184.00	171.00	167.00	179.00	232.00	286.00	157	141.00	170.00	184.00
Zn	112.00	127.00	83.00	84.00	80.00	95.00	110.00	66.00	140.00	121.00	130.00	101.00	155.00	95.00	122.00	151.00
Zr	96.00	101.00	75.00	82.00	89.00	85.00	123.00	90.00	106.00	71.00	66.00	114.00	117.00	88.00	87.00	79.00
Th	1.80	2.95	5.00	5.00	5.00	5.00	9.00	7.00	7.00	5.00	6.00	nd	2.62	1.27	1.13	1.09

Table 1: Continue

Ech.	ITH 3b	ITH 3c	TAS 1b	TAS 3	TAS 4	TAS 5	TAS 7b	TAS 8	ISS 2c	TAS 16	ISS2	TAL 2	TNW 2	TAS 03	TAS 08	AS 16b
Ta	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Y	20.99	20.42	16.62	16.41	20.26	19.90	18.63	20.75	35.34	29.99	30.40	24.20	21.30	16.24	19.40	16.59
U	1.00	0.55	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	1.88	0.17	0.14	0.16
La	25.65	13.34	12.96	14.65	16.38	13.64	13.06	15.49	17.27	27.77	23.04	13.70	18.55	14.77	14.22	12.81
Ce	54.15	29.31	27.30	30.55	36.72	29.08	37.45	34.36	42.66	61.42	48.94	29.71	38.51	31.21	31.55	28.84
Nd	32.30	15.57	13.86	17.17	21.26	14.69	28.71	19.76	27.97	34.57	24.25	15.84	21.33	17.15	17.99	16.42
Sm	7.67	3.55	3.01	3.60	4.66	3.25	6.90	4.41	6.33	7.49	5.25	3.85	4.38	3.58	3.92	3.36
Eu	2.32	1.18	0.91	1.51	1.69	1.03	1.39	1.63	1.96	3.16	1.82	1.13	1.00	1.49	1.43	1.31
Gd	7.04	3.46	2.66	2.99	3.65	2.75	4.53	3.77	6.27	6.97	5.09	3.68	3.92	3.28	3.94	3.21
Dy	5.62	3.42	2.85	2.95	3.64	3.16	3.55	3.55	6.99	6.22	5.74	3.96	3.46	2.80	2.98	2.68
Er	2.84	1.97	1.71	1.58	1.86	1.99	1.94	1.96	4.02	3.44	3.72	2.22	2.07	1.47	1.63	1.55
Yb	2.82	1.98	1.85	1.49	1.83	2.26	2.20	1.85	4.18	3.28	4.27	2.30	2.12	1.53	1.82	1.58
Lu	0.50	0.31	0.28	0.23	0.28	0.35	0.33	0.29	0.66	0.50	0.68	0.36	0.33	0.24	0.28	0.26
∑REE	140.90	74.10	67.40	76.70	92.00	72.20	100.10	87.10	118.30	154.80	122.80	76.80	95.70	77.50	79.80	72.00
(La/Yb) N	6.15	4.56	4.73	6.64	6.05	4.08	4.01	5.66	2.79	5.72	3.65	4.02	5.91	6.53	5.29	5.47
(La/Sm) N	2.10	2.36	2.71	2.56	2.21	2.64	1.19	2.21	1.72	2.33	2.76	2.24	2.66	2.59	2.28	2.40
(Gd/Yb) N	10.85	7.61	6.25	8.72	8.67	5.29	8.95	8.86	6.52	9.24	5.18	6.96	8.04	9.33	9.44	8.80
La/Nb	3.66	2.10	2.59	2.93	3.28	2.73	2.61	3.10	3.45	5.55	4.61	2.03	4.11	2.72	2.64	2.62
Ti/V	25.68	25.28	25.19	46.67	51.90	22.93	29.67	48.42	31.62	37.54	17.59	24.34	34.39	48.41	49.51	39.20
Y/Nb	3.00	3.21	3.32	3.28	4.05	3.98	3.73	4.15	7.07	6.00	6.08	3.58	4.72	2.99	3.60	3.39

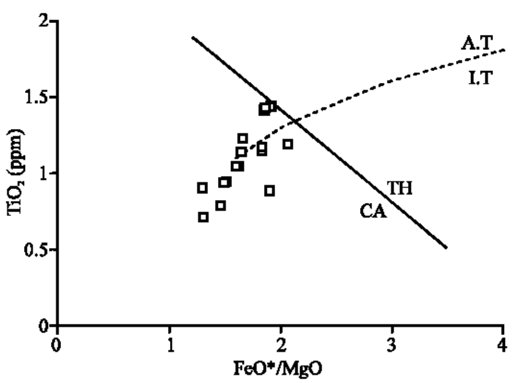

Fig. 2: TiO_2 vs FeO*/MgO from Miyashiro and Shido (1975) of the calc-alkaline mafic rocks from Igherm inlier. TH (Tholeitic), CA (Calc-Alkaline). The boundaries between the A.T (Anisotitanous) and I.T (Isotitanous) domains are redrawn from Bebien Carignan *et al*. (2001). Samples with high contents of secondary magnetite, iron oxides, quartz and calcite were excluded from the analysis. Analyses of major, incompatible trace elements and rare earth elements which are considered to show very little mobility during alteration processes (Pearce and Cann, 1973; Floyd and Winchester, 1975; Tarney *et al*., 1979) revealed high Al_2O_3 contents (14.10-20.64%) and low concentrations of $(Fe_2O_3)t$ (7.00-12.94%), TiO_2 (0.68-1.60%), Zr (66-257 ppm), Nb (4.9-9.57 ppm), Y (9.7-30.4 ppm) and V (105-2242 ppm) compared to the high La/Nb ratios (2.09-5.55). The low V contents and their progressive decrease with respect to FeO*/MgO, together with the absence of iron enrichment (Miyashiro, 1974; Miyashiro and Shido, 1975) indicate a calc-alkaline character (Fig. 2). The very low variations

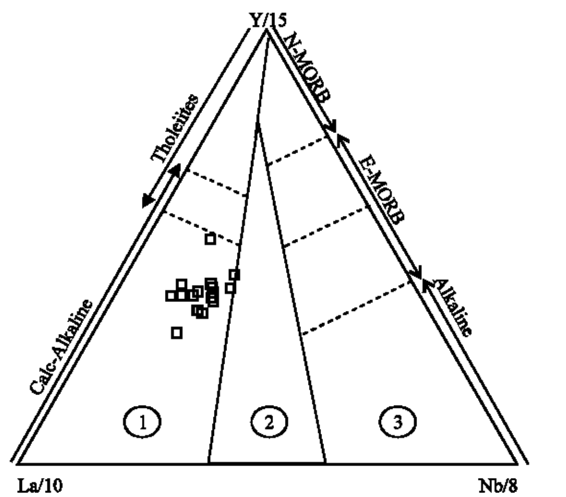

Fig. 3: Y/15-La/10-Nb/8 diagram of the calc-alkaline mafic rocks from Igherm inlier. 1: orogenic domain, 2: late to post orogenic intra-continental domain, 3: non-orogenic domain

in TiO_2 (0.68-1.60%) with respect to FeO*/MgO (1.07-2.13) reflect an isotitanium character that is typical of orogenic zones (Fig. 2) as indicated in Y/15-La/10-Nb/8 diagram (Fig. 3). The Ti/V ratios (17.58-61.94) of these dolerites and gabbros belong within the field of mid-ocean ridge or back-arc basalts in Shervais (1982)'s Ti/1000-V diagram. However, they demonstrate a clear calc-alkaline affinity (Fig. 4).

When normalized to the chondrite of Evensen *et al*. (1978), their REE patterns show $(La/Sm)_N$, $(La/Yb)_N$ and $(Gd/Yb)_N$ ratios of between 1.19 and 3.42, 2.79 and 20.52 and 0.96 and 4.20, respectively which indicate high enrichment in LREEs and a slight fractionation of the HREEs (Fig. 5). The weak positive

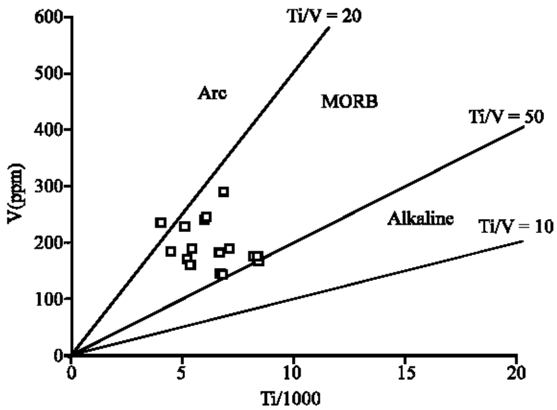

Fig. 4: V vs Ti/1000 diagram (Shervais, 1982) of the calc-alkaline mafic rocks from Igherm inlier

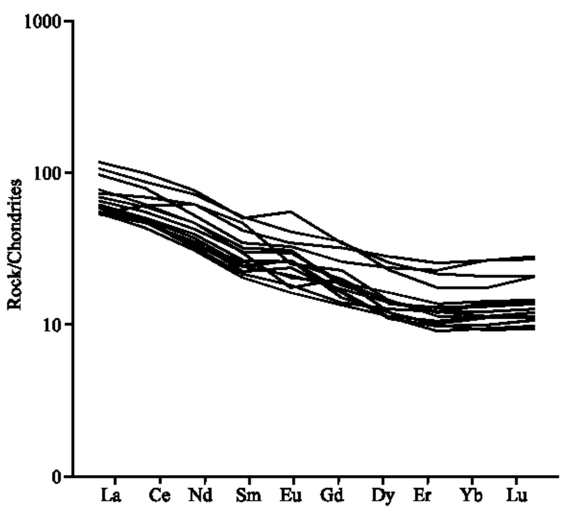

Fig. 5: Chondrite-normalized REE patterns (Evensen *et al*., 1978) of the calc-alkaline mafic rocks from Igherm inlier

Eu anomaly can be related to the relative richness of these rocks in plagioclase due to the original magma composition.

DISCUSSION

The presence in the WAA Cryogenian sedimentary formations of a calc-alkaline mafic magmatism nearly coeval with tholeiitic and alkaline magmas poses the problem of the source of the magmas and the geodynamic setting of their emplacement.

This problem was addressed by looking at the nature of the sedimentary rocks and by investigating the geochemistry of the magmatic rocks. The Pan-African geodynamic setting of the Anti-Atlas was then identified by comparing it with geodynamic settings described in other parts of the world. The lower Cryogenian sedimentary environment in which the WAA calc-alkaline magmatism was emplaced evolved from an epicontinental platform (limestones and quartzites) to an ocean basin (schists and stratified quartzites).

This environment may correspond to pre-Pan-African rifting at the same time that a Pan-African back-arc oceanic basin was opening in the central Anti-Atlas (200 km East of Igherm) as indicated by the Bou Azzer and Siroua ophiolites.

The Cryogenian calc-alkaline mafic rocks of the Igherm inlier show enrichment in elements with large-ion lithophile elements (Sr, K, Rb, Ba, Th), depletion of elements with high field strength elements and rare earth elements and selective enrichment in Th, Ce, P and Sm which is characteristic of calc-alkaline orogenic basalts (Fig. 6). More or less pronounced negative anomalies for Nb, Zr and Ti and La/Nb ratios of >1.6 (2.09-5.55) are classically considered to indicate ocean subduction (Pearce, 1982) rather than a crustal influence (Thompson *et al*., 1984). These geochemical characteristics correspond to magmas that are emplaced above or near a subduction zone or in continental domains during the first stages of rift or back-arc basin opening (Pearce, 1982).

In these zones, calc-alkaline orogenic rocks are generated by dehydratation of the subducted plate (Gill, 1981; Pearce, 1983; Defant and Drummond, 1990) which leads to enrichment in the most soluble elements (silicon and incompatible LILE elements) in the overlying mantle wedge.

Consequently, this wedge may be subjected to a higher rate of partial fusion (Gallagher and Hawkesworth, 1992) and thus generate mafic magmas of the calc-alkaline association (Pearce, 1983).

In these hydrous conditions, the decoupling mechanism for incompatible HFSE (depleted) and LILE (enriched) elements may be accentuated by the presence of minor phases such as ilmenite, titanite, rutile and zircon which become stable in the residue (Kay, 1978; Yogodzinski *et al*., 1994; Saunders *et al*., 1980; Thompson *et al*., 1984).

The calc-alkaline rocks of the Igherm inlier show similar Nb and Ti anomalies to the basalts in the Karoo province of South Africa and the Ferrar province of Australia (Fig. 7); anomalies that have been attributed to contamination of the mantle source by fluids from subducted crust (Hergt *et al*., 1991). The WAA calc-alkaline rocks are also comparable (Fig. 6) with the

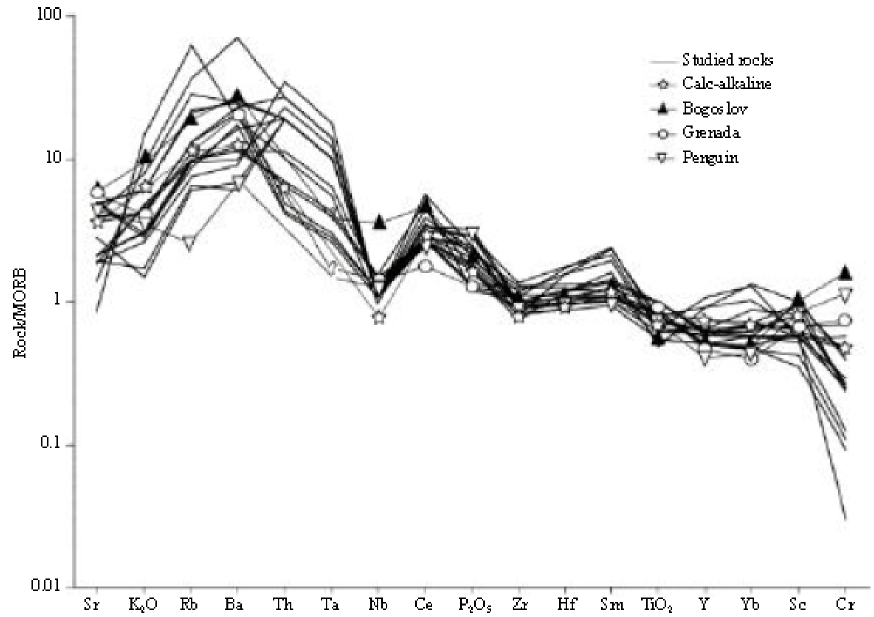

Fig. 6: MORB-normalized diagram (Pearce, 1982) of the calc-alkaline mafic rocks from Igherm inlier compared to calc-alkaline and transitional basalts from the volcanic arcs of Grenada (Antilles), Bogoslov (Aleutian Islands) and Penguin (Antarctic) (Pearce, 1982, 1983)

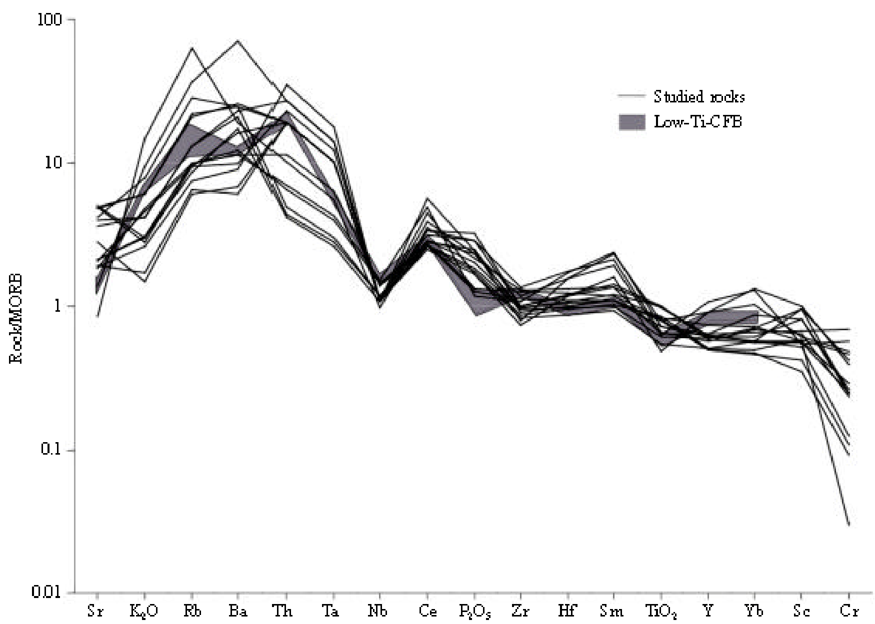

Fig. 7: MORB-normalized diagram (Pearce, 1982) of the calc-alkaline mafic rocks from Igherm inlier compared to low-Ti continental flow basalts (low Ti-CFB) from Australia after Hergt *et al.* (1991)

calc-alkaline basalts of the transitional volcanic arcs of the West Indies, the Aleutians and Antarctica (Pearce, 1982) and they show similarities with the Eocene and Miocene basalts of the North-west USA and Southern Canada where a close association between the calc-alkaline magmatism and extension has been demonstrated (Noblet, 1981; Hooper *et al.*, 1995; Morris *et al.*, 2000) (Fig. 8). In this latter setting, the sub-continental mantle, enriched by prior subduction episodes may provide a source for the calc-alkaline magmas without active subduction

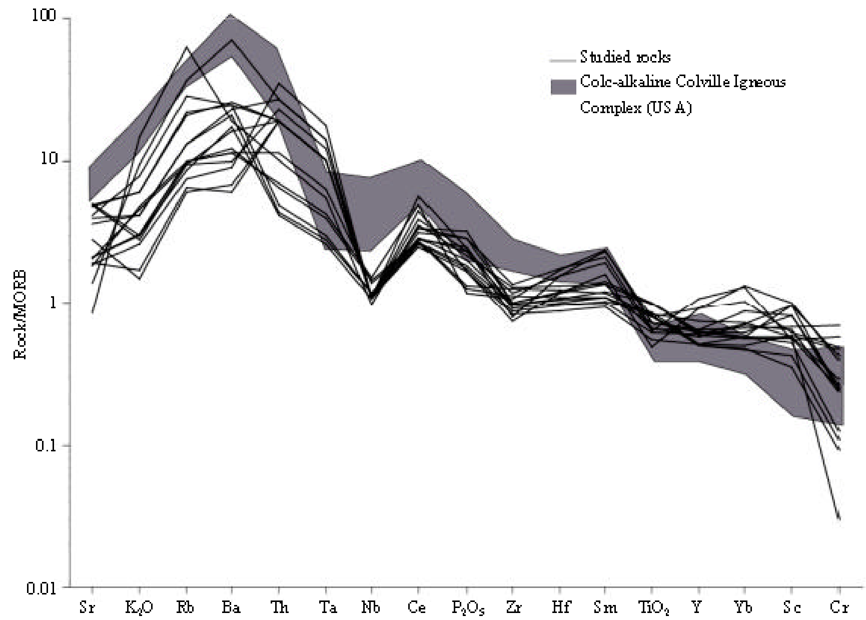

Fig. 8: MORB-normalized spiderdiagrams of the calc-alkaline mafic rocks from Igherm inlier (Pearce, 1982) compared to the mafic calc-alkaline magmatism from the Colville Igneous Complex (NE Washington State, USA) after Morris *et al.* (2000)

(Ewart *et al.*, 1992; Hooper *et al.*, 1995). In the case of the Colville Igneous Complex (NE Washington state, USA), the calc-alkaline magmatic rocks show an affinity with the geochemical signatures of orogenic magmas from subduction zones (Morris *et al.*, 2000) such as the calc-alkaline rocks of the WAA (Fig. 8). Morris *et al.* (2000) conclude that these calc-alkaline rocks result from a regional extension that caused decompression melting of the continental crust and intrusion of mantle materials. In this case, the calc-alkaline geochemical signature of the magmas would be completely inherited from earlier Proterozoic subduction(s).

However, if geochemical characteristics point to the composition of the source of the granitoids and not to their geotectonic setting, conditions of partial melting have to be met for the considered source to generate magmas (Liegeois *et al.*, 1998) and this depends from the geotectonic setting. The calc-alkaline rocks of the Igherm inlier are emplaced in the same geological setting (intruded the lower Cryogenian series as bodies or dykes) and thus appears as nearly coeval with the tholeiitic and alkaline mafic rocks. Associations of alkaline and calc-alkaline rocks have frequently been described in the Basin and Range province of North America where they are considered to mark extension phases (Fitton *et al.*, 1988; Kempton *et al.*, 1991; Bradshaw *et al.*, 1993; Hooper *et al.*, 1995; Hawkesworth *et al.*, 1995). Evolution from calc-alkaline to alkaline magmatism in an extensional setting is linked to a change in the source of the magma from a lithospheric source (calc-alkaline magmas) to an asthenospheric source (alkaline magmas) as the asthenosphere rises (Hooper *et al.*, 1995).

There are 2 possible explanations for the coexistence between calc-alkaline and tholeiitic-alkaline rocks in the WAA. The first possibility is emplacement in a distal position during a transition period between the oceanization phase and the subduction phase as described for the Pan-African orogeny in the central Anti-Atlas. In this case, the chemical compositions of the magmatisms would be influenced by the oceanization (tholeiitic, alkaline and/or transitional) and by the subduction (calc-alkaline). The second possibility is decompression melting of lithospheric sub-continental mantle enriched by a probable Paleoproterozoic subduction in the WAA (Gasquet *et al.*, 2004, 2005). The only epsilon Nd data from literature ($-11 < \epsilon Nd < -7$; Gasquet *et al.*, 2005) for the Neoproterozoic High-K calc-alkaline magmatism seem to be in accordance with a mantle metasomatized by a Paleoproterozoic subduction. On a regional scale, calc-alkaline mafic rocks are poorly documented in the AA excepted in the WAA where some dolerite dykes that intrude the neighboring Bas Draa and Tagragra d'Akka inliers have similar geochemical characteristics and in the Siroua Massif of the central Anti-Atlas where dolerite dykes partly derive from a crustal component related to an old subduction. However, this orogenic-like type mafic magmatism is distributed irregularly both across the Western Anti-Atlas (Bas Draa, Igherm, Kerdous, Ifni and Tagragra d'Akka) and across each and there is no obvious argument indicating an association with a subduction zone.

This suggests that the magma probably formed in a tectonic, magmatic and sedimentary setting undergoing extension and by the decompression melting of a lithospheric sub-continental mantle enriched by an earlier subduction (Paleoproterozoic). Such a Paleoproterozoic subduction is also suggested by the association of calc-alkaline and peraluminous magmas found in the WAA (Gasquet *et al*., 2004, 2005). The tholeiitic, transitional and alkaline rocks would then be the expression of the earliest magmatic activity of this Cryogenian extension which took place before the melting reached the lower layers of the lithospheric enriched mantle.

CONCLUSION

The petrographical and geochemical study revealed the presence of Cryogenian calc-alkaline mafic rocks and of them isotitanium characteristics in the Igherm inlier. These rocks were emplaced before the conglomeratic formations of the upper Cryogenian and after the tholeiitic mafic rocks that characterize the pre-Pan-African rifting.

Although, mafic rocks with tholeiitic or alkaline affinities and with anorogenic and intra-plate characteristics can be interpreted as the expression of an extensional setting marking the pre-Pan-African rifting in these inliers, the occurrence of calc-alkaline magmas in an extensional regime is more problematical.

However, the calc-alkaline magmas can be attributed to the influence of a Paleoproterozoic subduction zone that contributed to the enrichment of the sub-continental mantle. During the extensional period of the Pan-African orogenesis, the mantle would have produced tholeiitic, alkaline and/or transitional magmas before melting (caused by adiabatic decompression) reached the enriched sub-continental mantle where it would have generated calc-alkaline magmas.

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