GEOCHEMISTRY AND GEOTECTONIC INTERPRETATION OF GRANITOIDS FROM CENTRAL IFORAS (MALI, W. AFRICA)

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ABSTRACT

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Late Proterozoic granitoids from Central Iforas (Mali, W. Africa) show a large range of chemical variations (e.g., $SiO_2 = 52.8 - 75.6\%$) and include diorites, monzotonalites, tonalites, granodiorites and granites. The major and trace element composition of these rocks is comparable to modern calc-alkaline rocks of continental margins which were emplaced far from the trench in an area with thick continental crust. The chemical variations were produced by crustal contamination and by fractional crystallization dominated by hornblende and plagioclase. The granitoids are also similar in composition to Pan-African orogenic volcanic rocks of the Hoggar. Geodynamic interpretations of the "Adrar des Iforas" belt are discussed in the light of these data.

INTRODUCTION

The geodynamic evolution of the Adrar des Iforas, the southwestern part of the Hoggar shield was affected by continent-continent collision during the Pan-African orogeny (~600 Ma ago) (Black et al., 1979). A suture of the collisional orogenic belt is preserved along the eastern border of the West African craton and appears intermittently for a distance of more than 2000 km. It is accompanied by ultramafic bodies and gravimetric anomalies (Bayer and Lesquer, 1978). On the basis of lithostratigraphy and structural evolution, the Adrar des Iforas belt can be divided into 4 domains (Fig. 1): Accretion domain; Main Iforas batholith; Central Iforas; and Eastern Iforas. The geology of the westernmost structural domains (the Accretion and Main batholith domains) fits with the plate tectonic model (Caby et al.,



Fig. 1. Structural domains of the Adrar des Iforas belt: 1 - West African craton; 2 - nappes and ultrabasic bodies; 3 - Accretion domain (Late Proterozoic island arc), 4 - gneisses; 5 - Main Iforas batholiths (a) with extensive remnants of basement and early intrusives (b) volcano-clastic formation and Oumassene andesites (c) Upper Proterozoic shelf formation (d) and Tafeliant Late Proterozoic clastic formation (e); 6 - High-grade Kidal assemblage; 7 - reworked Eburnean granulites; 8 - parautochthonous nappes; and <math>9 - Eastern Iforas domain.

1981), but in the Central Iforas zone the kinematic relationships of the plutonic suites with the subduction and collision are less clear. The latter domain has nappe structures which were formed during an early stage of the tectonometamorphic evolution (Davison, 1980; Boullier, 1982). The zone includes numerous pretectonic to late-tectonic granitoid plutons (Bertrand and Davison, 1981). The Eastern Iforas domain, which is structurally poorly known, forms the southern extension of the eastern Pharusian belt of the Hoggar (Bertrand and Caby, 1978) and is characterized by abundant para-uthochthonous granitoids often associated with migmatites (Gravelle, 1969).

The present study deals mainly with granitoids of the Central Iforas and to a smaller extent with those of the Eastern Iforas. The aim of the paper is to characterize geochemically the Upper Proterozoic granitoids, to compare them with similar rocks of Upper Proterozoic age from East Africa and Saudi Arabia (e.g., Neary et al., 1976; Rogers et al., 1978; Dixon, 1981; Marzouki et al., 1982) and to put some constraints on their petrogenesis.

GEOLOGY AND PETROGRAPHY

The structure of the Central Iforas (Fig. 1) may be summarized by describing the tectonic pile which is the result of an early nappe-forming event defined as D_1 (Boullier et al., 1978). From bottom to top, the structural units are:

(1) the Kidal assemblage (Fig. 1) is composed of high-grade metamorphic rocks of tectonized Eburnean basement (retrogressed granulites), Middle to Upper Proterozoic metasedimentary rocks and pre- to syntectonic granitoid rocks which form up to 60% of the sequence (Boullier, 1982),

(2) the Iforas granulitic unit is made up of granulites of Eburnean age (~2000 Ma old) and is considered to be a nappe (Boullier, 1982). The unit is cross-cut by Proterozoic granitoids (~10-15% of the unit) which are not discussed in the present study; and

(3) the uppermost nappes are composed of Middle to Upper Proterozoic sediments and volcanoclastics metamorphosed under greenschist facies conditions. The sequence was intruded by granitoids (forming $\sim 40\%$ of the unit — Boullier et al., 1978).

A major break occurred in the tectonic evolution of the nappe pile between a D_1 and a D_2 deformation and is probably the result of the main collision with the West African craton (Boullier, 1982). It is shown by an unconformity and the deposition of a clastic formation in which only D_2 has been recognized. Granitoids were emplaced before and after this break (Table I). From Rb/Sr whole-rock dating, the break is ~640 Ma old (Bertrand and Davison, 1981). The D_2 deformation took place between 610 and 580 Ma (Bertrand and Davison, 1981; Liegeois and Black, 1983). In contrast to the Central Iforas, the Late Proterozoic sequence of the Main Iforas batholith domain contains calc-alkaline andesites and dacites which also rest unconformably on top of a tectonized basement (Chikhaoui, 1981). Most of the tectonic evolution of the Eastern Iforas seems related to or postdates D_2 deformation (Caby et al., 1981). Structural settings of Iforas granitoids

Deformations	D ₁	D ₂	D ₃			
Kidal	Al (Meta) D (In Bezzeg)					
assemblage	A'1 MT and GD (Tadait)				
Parautochthonous	A2 (meta) GD an					
nappes	(Ibedouyen)	{	A3 GD and MT (Achamon)			
		{ {	A'3 GD and G			
		unconfo	rmity			
			(Tamaradant)			
			A4 G			
Eastern Iforas						
			(Tamassahart)			

A'3 is emplaced along the boundary between central and eastern domains; A'3 and A4 are both associated with migmatites (Davison, 1980); D - diorite, MT - monzotonalite, GD - granodiorite, G - granite.

On the basis of their relationships with the tectonic events, the granitoids have been subdivided into 6 units (Davison, 1980) (Fig. 2): the A1 and A'1 units (In Bezzeg and Tadait) correspond to D_1 pretectonic intrusives and are emplaced into the Kidal assemblage or its possible southeastern equivalent in Tadait (A'1). The A2 unit (Ibedouyen) postdates D_1 and was deformed and partly recrystallized during the D_2 event. The A3 unit (Achamon) was emplaced syn- to late tectonically with respect to the D_2 deformation. The A'3 unit (Tamaradant) postdates D_2 but is more heterogeneous than A3 and overlaps the Eastern Iforas-Central Iforas boundary; its slight deformation and recrystallization can be attributed to a D_3 event characterized by wrench faulting (Davison, 1980; Boullier, 1982) The A4 unit (Tamassahart) occurs in the Eastern Iforas domain and was emplaced before or during the D_2 deformation.

The mineralogical associations and textures of the Iforas granitoids are closely related to their structural setting and relative chronology:

(1) metadiorites and metatonalites of the A1 unit (samples 1-4 in Table II) have gneissic textures and were recrystallized completely under amphi-

Fig. 2. Distribution of granitoids in Central Iforas: $1 - pretectonic metadiorites and metatonalites (A1); <math>2 - pre D_2$ metagranodiorites and metamonzotonalites (A2); 3 - syn- to post- D_2 granodiorites and monzotonalites (A3); 4 - Eburnean granulites; 5 - older Pan-African granitoids intruding Eburnean granulites; 6 - syntectonic granitoids of the Eastern Iforas domain (A'3 and A4) associated with migmatites; <math>7 - older (not studied) granitoids from Eastern Iforas; 8 - gabbros; and 9 - post-tectonic granites (including alkaline ring complexes). Stars indicate sampling areas.



Unit	A1	_			A '1		A2				
sample	1	2	3	4	5	6	7	8	9	10	11
REE	1	1	1	1	1	1	2	2	2	2	2
SiO,	55.62	59.79	66.58	52.87	60.55	59.84	71.88	61.52	64.04	62.29	63.55
Al,Ô,	17.26	16.91	15.15	18.89	16.72	17.18	14.02	16.28	15.40	16.20	15.30
Fe,O,t	7.46	6.32	3.96	8.37	5.11	5.43	2.02	5.87	5.31	5.92	5.57
MnO	0.12	0.10	0.04	0.14	0.07	0.09	0.05	0.09	0.10	0.12	0.09
MgO	3.74	3.00	1.93	4.69	3.39	3.49	0.48	2.18	1.93	2.15	1.95
CaO	6,37	5.88	4.04	7.20	5.68	5.99	1.73	5.02	4.28	5.01	4.21
Na,O	3.94	3.93	3.85	4.25	4.28	4.45	3.99	4.06	3.87	4.08	3.84
K,Ô	2.01	1.74	1.58	1.82	1.58	1.32	3.88	2.06	2.49	2.17	2.73
TiO,	1.09	0.81	0.64	0.97	0.61	0.60	0.27	0.71	0.64	0.66	0.69
P,O,	0.32	0.31	0.11	0.25	0.12	0.15	0.04	0.13	0.33	0.06	0.13
H ₂ O ⁺	0.88	0.76	0.71	0.92	1.01	0.94	0.60	0.78	0.79	0.86	0.85
Rb (ppm)	66	54	47	52	47	38	89	55	70	62	74
Ba	769	760	791	930	683	572	716	607	691	519	553
Sr	695	656	703	784	724	772	261	429	402	422	336
Zr	169	226	143	220	142	126	96	160	209	157	212
Hf	3.90	5.59	2.81	4.74	3.27	2.63	2.94	3.61	5.46	3.78	5.86
Nb	14	10	9	14	10	9	11	11	12	11	14
Th	1.80	3.56	1.90	1.57	2.49	5.05	5.40	3.30	4.67	5.39	5.90
Sc	16.4	15.1	5.33	23.7	11.8	11.6	4.31	13.2	15.0	15.6	17.9
Ni	29	45	12	26	38	31	10	18	13	10	16
Cr	40	42	34	34	46	48	20	43	30	30	49
v	145	137	70	161	109	100	92	157	112	125	123
La	16.5	20.8	12.1	21.2	15.8	16.0	13.0	15.3	18.9	19.0	18.6
Ce	40.6	39.3	23.8	49.3	32.4	30.3	26.7	33. 9	42.4	42.1	41.2
Sm	5.97	3.88	2.29	6.86	3.29	2.80	2,40	4.0	4.85	4.12	5.47
Eu	1.84	1.15	0.73	1.86	0.93	0.86	0.55	0.93	1.08	1.03	1.08
Tb	0.79	0.55	0.30	0.87	0.38	0.36	0.44	0.61	0.74	0.64	1.16
Yb	2.04	1.35	0.68	2.20	1.10	0.96	1.52	2.43	2.75	2.52	3.70
Lu	0.32	0.20	0.11	0.31	0.18	0.15	0.24	0.38	0.43	0.39	0.55
La/Yb	8.1	15.4	17.8	9.6	14.4	17.8	8.5	6.3	6.9	7.5	5.0

Major and trace element abundances of selected samples from Central Iforas (Mali)

REE - type of REE pattern.

bolite facies conditions. They are composed of medium to coarse-grained quartz, plagioclase, hornblende and biotite.

(2) metatonalites of the A'1 unit (samples 5 and 6) are granulated and partially recrystallized under greenschist facies conditions (probably during the D_2 deformation).

(3) metamonzotonalites and metagranodiorites of the A2 unit (samples 7-11) still contain relicts of their primary magmatic mineralogy. Large hornblende and zoned plagioclase crystals occur in a deformed matrix and were not affected by metamorphic recrystallization which took place under greenschist facies conditions during the D_2 deformation. In contrast, the primary biotite is almost completely replaced by an assemblage of secondary biotite and sphene. The A2 unit is highly heterogeneous and also includes a complex network of deformed aplites and pegmatites.

(4) A3 monzotonalites and granodiorites (samples 12-15) contain euhedral plagioclase with oscillatory zoning, often enclosed together with

TABLE II

A3		0		1.5	A'3	177	A4	10	90	01
12	1.	3	14	15	16	17	18	19	20	21
1	1		1	2			1	1	2	2
62	.10	70.18	73.16	61.91	69.65	73.58	70.73	73.42	75.56	74.46
16	.75	15.34	14.23	15.93	14.91	13.38	14.33	13.71	13.04	13.24
5	.17	2.18	1.38	6.19	2.75	1.40	3.38	2.44	0.80	1.11
0	.10	0.06	0.06	0.11	0.06	0.06	0.10	0.05	0.04	0.04
2	.13	0.61	0.26	2.47	1.20	0.26	0.36	0.36	0.27	0.33
4	.84	2.75	1.93	5.15	2.62	0.93	1.61	1.27	2.08	2.12
3	.96	4.35	4.18	3.73	3.59	3.52	3.77	3.44	4.35	4.05
2	.42	2.44	2.69	2.20	3.59	5.02	4.26	4.67	3.26	3.64
0	.64	0.23	0.15	0.74	0.35	0.16	0.32	0.29	0.22	0.22
0	.18	0.03	0.01	0.08	0.04	0.02	0.01	0.01	0.00	0.00
1	.10	0.83	0.58	0.60	0.73	0.81	0.87	0.58	0.50	0.95
82		78	81	62	146	275	143	131	63	75
872	8	48	1260	689	1192	664	1268	1137	820	908
596	i 4	86	408	421	359	119	230	196	200	209
202	: 1	.48	119	198	194	131	265	197	161	163
4	.52	3.27	2.74	5.07			6.92	5.29	4.31	4.25
15		12	11	11	18	22	53	30	13	13
8	.60	7.92	6.05	4.58			16.8	15.1	7.81	8.23
9	.70	3.13	1,65	16.7			3.97	2.77	5.64	5.97
24		13	13	32	10	10	10	10	10	10
52	1	58	77	88	37	40	25	24	40	42
107		42	26	120	36	10	26	27	15	35
36	.9	21.8	20.6	19.0	53	45	72. 9	56.4	22.8	29.2
70	.2	39.0	36.1	39.8	110	94	137.0	107.0	50.5	56.6
4	.70	2.37	1.88	4.39			6.82	5.08	4.05	4.13
1	26	0.69	0.50	1.0			1.40	1.14	0.61	0.78
0	.61	0.35	0.23	0.67			0.59	0.63	0.63	0.64
1	.70	0.90	0.86	2.32			1.40	1.45	2.61	2.70
0	.26	0.15	0.13	0.36			0.21	0.22	0.42	0.45
21	.7	24.2	23.9	8.2			30.6	38.9	8.7	10.8

1-4: O. Bouressa, metatonalite; 5-6: O. Tadait, metatonalite; 7: Ibedouyen, metagranodiorite; 8-11: Ibedouyen, metamonzotonalite; 12: Achamon, monzotonalite; 13-14: Achamon, granodiorite; 15: Achamon, tonalite with biotite partly recrystallized and relics of clinopyroxene; 16: Tamarandant, granodiorite; 17: Tamarandant, K-feldspar rich granite; 18: Tamassahart, biotite-hornblende granite; 19: Tamassahart, biotite granite; 20-21: Tamassahart, hornblende-clinopyroxene leucocratic granite.

the other minerals within a large anhedral microline (monzonitic texture). Hornblende and biotite are euhedral to subhedral and biotite is frequently chloritized. Quartz forms polycrystalline clusters. The unit also includes syntectonic plutons which have identical composition but show foliation parallel to the pluton margins without any evidence of post-emplacement recrystallization.

(5) the A'3 Tamaradant pluton (Davison, 1980) is composed of granodiorites and granites. Microcline is far more abundant than in the other plutonic units and some samples contain muscovite and garnet (sample 17). Quartz, plagioclase, biotite and hornblende are also present. Incipient granulation and biotite recrystallization are attributed to the D_3 event.

(6) the A4 granites (samples 18-21) show two distinct mineralogical

assemblages corresponding to two distinct parallel linear plutons: the western pluton (A4W) is composed of a biotite granite (samples 18 and 19), rich in allanite, in which microcline is more abundant than plagioclase, while the more leucocratic eastern pluton (A4E) (samples 20 and 21) contains albite, microcline and either colourless hornblende, clinopyroxene and sphene or biotite and blue-green hornblende. Rocks along the margins were foliated during the D₂ deformation and grade to a thin band of migmatite separating the plutons from the surrounding biotite schists.

ANALYTICAL METHODS

Sixty-two representative samples were collected from plutons belonging to the above-defined units. A selection of 21 samples is given in Table II; the other data are available on request. The sample locations are shown in Fig. 2.

The rocks were analyzed for major elements and V, Cr and Ni by plasma spectroscopy following the technique of Govindaraju et al. (1976). Rb, Sr, Ba, La, Ce, Zr and Nb were determined by X-ray fluorescence on powder pellets. Rare earth elements (REE), Sc, Th, and Hf in 20 selected samples were analyzed by instrumental neutron activation. The precision and accuracy of the trace element determinations were given by Dupuy et al. (1979).

MAJOR ELEMENT GEOCHEMISTRY

The analyzed rocks from the Central and Eastern Iforas show large variations of SiO_2 contents ranging from 52.8 to 75.6%, but most rocks have SiO_2 between 60 and 72% (Table II). Although the older granitoids underwent complete metamorphic recrystallization, it does not appear that it has affected the primary geochemical characteristics of the rocks (Davison, 1980). In Figs. 3 and 4 the major element composition of the studied rocks is compared with the following plutonic suites: ancient and modern low K siliceous rock series from the western U.S.A. (Barker et al., 1979), Upper Proterozoic tonalites and trondhjemites from Saudi Arabia (Marzouki et al., 1982), the Cordilleran Tuolumne pluton of Sierra Nevada (Bateman and Chappell, 1979), the island arc-related plutonic suite of the Aleutian islands (Perfit et al., 1980) and the Upper Proterozoic Oumanene formation of Western Iforas (Chikhaoui, 1981). Figure 3 shows that all the rocks are sub-alkaline and can be subdivided into 3 groups according to their contents of SiO_2 and alkalies. This separation also correlates with the age and the structural setting of the rocks. On this graph the 3 groups are aligned obliquely to the classical calc-alkaline trend and especially groups I and II do not show a distinct increase of alkalies toward the more acid rocks.

Group I includes the oldest units (A1 and A'1) and on the Q-F diagram (Fig. 4) of de La Roche (1962) it displays variations (mainly of Q-values)

similar to those of the tonalite—trondhjemite suite of Barker et al. (1979). The slope of its trend differs from that of the Upper Proterozoic tonalite—trondhjemite suite from Saudi Arabia (Marzouki et al., 1982). The K_2O content of the A1 and A'1 rocks ranges from 1.3 to 2.0% and shows very little correlation with SiO₂.

Group II corresponds to granitoids which intruded into the uppermost structural unit of the Central Iforas and includes both pre D_2 and post D_2 intrusives (A2 and A3 units). Its low SiO₂ rocks are very close to Group I. Group III is more heterogeneous and includes rocks of granodioritic to granitic composition. Most of the rocks belong to the A'3 and A4 units but the adamellitic samples of the A2 unit are also included in this group. The A4E granites are enriched in SiO₂ and depleted in alkalies when compared with the A2 and A'3 rocks and display a calc-alkaline trend. Most of the samples of this group have normative corundum.



Fig. 3. SiO₂ versus (Na₂O + K₂O) plot. The 3 defined groups (I, II and III) correlate with the petrography and structure. I: A1 and A'1 pretectonic metadiorites and metatonalites; II: most A2 rocks and all A3 pre- and post- D₂ intrusives from Eastern Iforas. The lines represent: 1 — alkaline-subalkaline boundary of Irvine and Baragar (1971); 2 — Upper Proterozoic tonalites and trondhjemites from Saudi Arabia (Marzouki et al., 1982); 3 – island arc related plutonic suites from Aleutian Islands (Perfit et al., 1980); 4 — Cordilleran Tuolumne pluton from Sierra Nevada (Bateman and Chappell, 1979); and 5 typical calc-alkaline trend of Irvine and Baragar (1971).



Fig. 4. Q-F diagram of de La Roche (1962) revised for average values of plutonic rocks (stars) by Debon and Le Fort (1983): Q = Si/3 - (K + Na + 2/3 Ca); F = K - (Na + Ca). The lines represent: 1 - tonalite-trondhjemite suite (Canyon Creek, Barker et al., 1979); 2, 3 and 4 - same as in Fig. 3; 5 - Oumassene andesitic formation from Western Iforas (Chikhaoui, 1981); 6 - A1 and A'1 pretectonic metadiorites and metatonalites; and 7 - A2 and A3 pre- and post- D₂ intrusives. G - granite, AD - adamelite, GD - granodiorite, TO - tonalite, DQ - quartz diorite, MZDQ - monzodiorite; GO - gabbro.

Overall, the 3 groups have generally calc-alkaline and tonalitic characteristics. The unit with the most distinct calc-alkaline trend is A2 (in groups II and III of Fig. 3). The same pattern is also shown on the AFM diagram (Fig. 5) where the granitoid rocks display a trend typical of calc-alkaline suites which lack Fe enrichment.

TRACE ELEMENTS

In the granitoids of Central Iforas, the Sr content is highest in group I (A1 and A'1; ~700 ppm) and decreases in younger rocks as SiO_2 increases. The rocks of group III (A'3 and A4) have the lowest Sr abundances. Rb displays an increase towards the more differentiated rocks and is strongly correlated with K except in the youngest granites. The corresponding K/Rb ratios usually vary between 200 and 300; this range is typical of granitoids. The Rb/Sr ratio varies between 0.04 and 18, but values >1 are restricted to



Fig. 5. AFM diagram. 1 - amphibolite interfoliated within A1 metatonalites, 2 - reworked gneiss of unknown origin, <math>3 - solid lines define the field of calc-alkaline andesites from Sardinia (Dupuy et al., 1979), 4 - dashed lines outline field of calc-alkaline granitoids from the Querigut Massif (French Pyrenees, Fourcade and Allegre, 1981). Symbols are the same as in Fig. 4.

the A'3 unit and most of the A1 and A'1 units have values <0.1. Some other lithophile elements such as La, Ce, Zr, Hf and Nb vary only slightly with SiO₂. The abundances of Nb are low except in units A'3 (~20 ppm) and A4W (>30 ppm). Zr is also relatively low and correlates with Nb and Hf. Th increases from unit A1 to A4W and its abundances are comparable to those of the Proterozoic plutonic complex of E. Greenland (Tarney and Saunders, 1981). With the exception of group A4W, the Th content is similar to the values from the Proterozoic calc-alkaline volcanic suite from Quarzazate, Hoggar (Dostal et al., 1984).

From the REE contents and chondrite-normalized patterns (Fig. 6) 2 types of rocks may be distinguished. The type 1 pattern displays a distinct light REE (LREE) enrichment and depletion of heavy REE (HREE) with a high La/Yb ratio (8.1 - 38.1). The type 2 pattern has a smaller LREE enrichment and less fractionated HREE with a La/Yb ratio between 5.0 and 10.8. In addition, the rocks having type 2 patterns show negative Eu anom-



Fig. 6. REE patterns of selected Iforas granitoids. Type 1 pattern — solid lines, type 2 pattern — dashed lines: a — oldest units (A1, A'1, A2). b — youngest units (A3, A4). Sample 15 is atypical within the A3 suite (evidence of biotite recrystallization and the lack of characteristic monzonitic texture; it is probably a recrystallized xenolith of A2 origin). The 2 distinct plutons of unit A4 show different REE patterns.

alies in several samples. Such anomalies are generally accompanied by a decrease of Al_2O_3 and Sr, suggesting plagioclase fractionation.

The distinction between these two different types of REE patterns is also illustrated clearly on the graph of SiO_2 versus La/Yb (Fig. 7) which shows that the La/Yb ratios in rocks of both types of REE patterns increase with increasing SiO_2 . On average, the younger rocks (units A3 and A4) have a larger LREE enrichment.

The type 1 pattern includes rocks of units A1, A'1, A4W and most of unit A3. Such patterns are common in granitoids (Buma et al., 1971; Lopez-Escobar et al., 1979), alkaline volcanic rocks (Kay and Gast, 1973) and also characterize some orogenic volcanic zones (Dostal et al., 1977a). They resemble the patterns of Pan-African orogenic andesitic rocks of the Hoggar (Chikhaoui et al., 1980; Chikhaoui, 1981) and some Proterozoic tonalites from Finland (Arth et al., 1978). The patterns of type 2 are typical of calcalkaline volcanics (Thorpe et al., 1976; Dostal et al., 1977b), including some Late Proterozoic volcanics from the Hoggar (Chikhaoui et al., 1980), and are common in granitic rocks (Lopez-Esobar et al., 1979; Perfit et al., 1980; Bellieni et al., 1981). These rocks are poorer in K_2O and richer in CaO in comparison to those with type 1 patterns. All the rocks, including those with low SiO_2 , have low contents of transition elements (Sc, V, Cr and Ni), a feature characteristic of calc-alkaline and alkaline series. These elements decrease systematically while SiO_2 increases. Rocks of comparable SiO_2 contents from different units have similar concentrations of transition elements.



Fig. 7. SiO₂ versus La/Yb plot. The 2 groups which have been distinguished show a good agreement with the structural classification except for sample 15 (A3 in group 2) and for A4 granitoids. Symbols are the same as in Fig. 4.

DISCUSSION

The Iforas granitoids have a calc-alkaline character as shown by the relationship between SiO_2 and alkalies and trends on the AFM diagram. Likewise, the basic and intermediate members of the suites have high Al_2O_3 and K_2O and low TiO_2 . When compared to modern circum-Pacific granodiorites (Taylor, 1969), the studied rocks have similar transition element but higher lithophile element contents. Lithophile element abundances (mostly Rb, Sr, Ba and REE) in the rocks are generally higher than those of intrusive equivalents in typical modern island-arc complexes (Perfit et al., 1980) but are characteristic of Andean-type calc-alkaline suites. The Iforas granitoids show similarities in chemical composition to modern orogenic volcanic rocks even in their trace element abundances and element ratios.

For instance, the Nb/La ratio is relatively low (0.40-0.85) but the Ba/La ratio is high (20-40) and corresponds to values typical of modern orogenic volcanic zones (Kay, 1977). The enrichment of high ionic radii-low field strength elements (LILE) (e.g., Rb, Ba) and the depletion of low ionic radii-high field strength elements (HFSE) (e.g., Zr, Hf, Nb, Ti) which are observed in the studied rocks, are also typical of modern orogenic volcanic rocks (Dixon and Batiza, 1979). In their trace element composition the Central Iforas granitoids are also similar to Tertiary granitoids from central Chile (Lopez-Escobar et al., 1979) or to granitoids of the Sierra Nevada batholith (Dodge, 1972).

The Iforas suites are superficially similar to several Late Proterozoic granitoid complexes from the northern part of the African shield particularly those which Rogers et al. (1978) classified as calc-alkaline plutonic bodies. Although there is only a limited amount of geochemical data on most of these complexes, it appears that compared to calc-alkaline plutons from Saudi Arabia (Marzouki et al., 1982), northeastern Sudan (Neary et al., 1976), Egypt (Dixon, 1979, 1981) and Libya (Ghuma, 1976; Ghuma and Rogers, 1976), the analyzed suites have a similar SiO_2 range but are more potassic, less sodic and contain a larger proportion of granites. For a given SiO_2 content, the rocks are higher in LILE (Ba, Rb, Sr, REE) but have similar HFSE abundances. The granites of units A'3 and A4 show many similarities with LILE-enriched late-orogenic or post-orogenic granitic complexes (Rogers et al., 1978; Engel et al., 1980) such as the Tibisti granites of Libya (Vachette, 1964) and "Younger" granitoids of Sudan (Neary et al., 1976). However, they differ from these complexes by the absence of sodic syenites, riebeckite granites and by a lower content of alkalies. The Iforas granitoids also resemble in their composition contemporaneous Late Proterozoic calc-alkaline volcanic rocks of the Hoggar (Chikhaoui et al., 1980).

Continental margin calc-alkaline rocks have higher REE abundances and more fractionated REE patterns than the island-arc calc-alkaline suites. The patterns of some continental margin intermediate rocks even display fractionation of HREE. The rocks with strongly fractionated REE patterns occur in regions with thick continental crust (Thorpe and Francis, 1979). The REE patterns of Iforas granitoids are similar to those of continental margin volcanic rocks which occur at a large distance from the trench in an area of very thick crust e.g., northern Chile $(Tb_N/Yb_N = 1.3-2.0 \text{ at})$ $SiO_2 = 55.6-64.6\%$ and $K_2O = 1.0-3.0\%$; Thorpe et al., 1976), southcentral Chile $(Tb_N/Yb_N = 1.0-1.9 \text{ at } SiO_2 = 57.8-63.2\%$ and $K_2O =$ 1.65–2.51%; Lopez-Escobar et al., 1977) and Colorado (Tb_N/Yb_N = 1.3-2.0 at SiO₂ = 50.8-63.7% and K₂O = 1.8-3.2%; Zielinski and Lipman, 1976). The REE characteristics and differences between the two types of patterns are comparable to those encountered among shoshonites and/or high-K and esites, and and esites in northern Chile (Thorpe et al., 1976, Thorpe and Francis, 1979) or southern Peru (Dostal et al., 1977a, Dupuy

and Lefevre, 1974). In the latter area some shoshonites (which are related to the subduction zone – Lefevre, 1979) have lower SiO_2 contents than andesites but have higher La/Yb ratios and strongly fractionated HREE.

The data presented may place some constraints on the processes involved in the genesis of the Iforas granitoids. The strong HREE fractionation of several samples with the type 1 pattern may be the result of the presence of refractory garnet during partial melting (Thorpe et al., 1976; Dostal et al., 1977a,b). However, such a REE pattern may also be related to the crystallization of amphibole; the influence of amphibole has frequently been stressed in calc-alkaline magmatism (Allan and Boettcher, 1978). The role of this mineral in the rocks of both REE patterns is corroborated by Fig. 7 where the La/Yb ratio increases with increasing SiO_2 . The simultaneous decrease of Ti and V also suggests the influence of amphibole and/or magnetite. In addition, the increase of K with decreasing Ti negates any significant role of biotite. Plagioclase fractionation in the rocks of the type 2 pattern is obvious from the negative Eu anomaly associated with the decrease of Al and Sr. High FeO_{tot}/MgO ratios and low Sc, Cr and Ni contents in the analyzed mafic rocks also suggest that even these rocks underwent extensive fractional crystallization.

The high and variable contents of lithophile elements, highly variable element ratios and the lack of correlation among these elements indicate that fractional crystallization or variable degrees of partial melting of the same source cannot explain the relationship among the various granitoid bodies on its own. Similar problems are often encountered in the petrogenesis of continental margin volcanic rocks where crustal contamination played an important role. The relatively high initial ${}^{87}Sr/{}^{8\circ}Sr$ ratios (Bertrand and Davison, 1981) may imply the participation of an important crustal component in the genesis of the Central Iforas granitoids. Field evidence for crustal contamination is the close association of granitoids with migmatites. In fact, the samples with the highest initial ${}^{87}Sr/{}^{86}Sr$ ratios also show the strongest field evidence for crustal contamination.

CONCLUSION

Chemical compositions and variation trends of the Iforas granitoids are comparable to those of modern calc-alkaline suites from continental margins. This similarity also applies to REE which display two types of patterns. The suites were probably derived by a combined process of fractional crystallization and crustal contamination. Fractional crystallization included separation of hornblende and plagioclase.

Like recent batholiths in continental margin environments, the Central Iforas granitoids display a large range of compositional variations in which the proportions of differentiated rocks decrease with age. Although these rocks are not geochemically different from equivalents in Andean batholiths, several discrepancies appear when compared with recent orogenic belts and continental margins:

(1) rocks with shoshonitic affinities and/or high-K andesites are generally youngest in recent continental-margin volcanic suites (e.g., McNutt et al., 1975). In the Iforas domains, they seem to be the oldest rock-types in each cycle (Bertrand and Davison, 1981) and show many similarities in major element geochemistry with the tonalite suites of Lower Proterozoic age (Arth et al., 1978);

(2) in Central Iforas, well-developed volcanic series are lacking; most of the supracrustal rocks consist of volcanoclastic greywackes; and

(3) unlike the recent batholiths of the Andean type where little or no tectonic crustal thickening is postulated, the Central Iforas was subjected to large-scale nappe tectonics.

The chemical composition of the studied granitoids is similar to that of Late Proterozoic andesitic rocks from the Pan-African belt farther north (Chikhaoui et al., 1980). The older units (A1, A'1, A2 and A3) resemble in some respects the Pan-African calc-alkaline plutonic suites of Rogers et al. (1978) whereas units A'1 and A4 have some features in common with LILE – enriched, late-orogenic or post-orogenic granitic complexes from other parts of the northern African shield.

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