

Geochemistry of Precambrian ophiolites from Bou Azzer, Morocco

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Abstract. The Upper Proterozoic ophiolite complex of Bou Azzer, Morocco, includes ultramafic rocks, cumulate gabbros, sheeted dykes, pillow lavas and diorite-quartz diorite intrusions and an overlying volcano-sedimentary sequence. The gabbroic cumulates, basaltic flows and dykes have compositions similar to recent ocean-floor rocks (N- and/or T-type). Among other features, they have comparable light REE-depleted patterns and relations of Ti–Zr and La–Nb. Although fractional crystallization played an important role in the evolution of these rocks, the large variations in their chemical compositions require generation from a heterogeneous upper mantle source and/or by a dynamic partial melting process. Diorites, quartz diorites and the volcanic rocks of the overlying sequence are calc-alkaline, genetically unrelated to the tholeiitic suite and indicative of an island arc setting. A possible tectonic model for the ophiolite complex is a marginal basin just behind a still active island arc.

Introduction

Since the pioneering study of Miyashiro (1973) on the Troodos ophiolites which suggested that some ophiolite complexes were not formed at mid-ocean spreading centres, numerous papers (e.g. Church and Coish 1976; Sun and Nesbitt 1978; Upadhyay and Neale 1979; Coish et al. 1982) have examined the problem of the tectonic settings of ophiolites. Some ophiolites are considered to have been formed at mid-ocean ridges while others were probably formed at the base of an island arc or in a back-arc basin. Although there are numerous studies on Phanerozoic ophiolites, there are only few data on ophiolites of Proterozoic age. More information on the Proterozoic ophiolites is needed particularly since it has been suggested that there have been important changes in the conditions of crustal evolution since the Upper Proterozoic (Wynne-Edwards 1976). Such studies could also evaluate whether geodynamic models and magmatic processes suggested for Phanerozoic ophiolites can be applied to those of Proterozoic time. The purpose of this paper is to present the geochemical characteristics of the Proterozoic Bou-Azzer ophiolites, Morocco (the first complete ophiolite complex described in the Proterozoic-Leblanc 1972; Church and Young 1974; Church 1980), to evaluate processes that formed this complex and to discuss the tectonic regime of the ophiolites.

Geological setting

The Bou Azzer ophiolite complex (Leblanc 1972, 1975, 1976, 1981), which outcrops about 300 km east of Agadir, forms a belt about 60 km long and 5 km wide (Fig. 1). It is located in the central part of the Anti-Atlas along the contact between two major structural units: the West African craton to the southwest dated at 2,000 M.y. (Charlot 1978) and the Pan-African orogenic belt to the northeast. The Bou Azzer massif which is unconformably overlain by Infra-Cambrian and Paleozoic sediments, is composed of ultrabasic to acid plutonic and volcanic rocks which were metamorphosed under greenschist facies during the major Pan-African deformation around 685 M.y. ago (Clauer 1976). The Bou Azzer complex comprises from bottom to top (Leblanc 1975, 1981; Church 1980): a) ~2,000 m of serpentinitized mantle peridotite, b) ~500 m of ultrabasic and basic layered cumulates (layered gabbros), c) ~500 m of submarine basaltic pillow lavas, d) large stocks of diorites and quartz diorites, e) ~1,500 m of volcanosedimentary series.

The serpentinitized peridotite (mainly dunite and harzburgite) is the dominant rock type in the complex. The layered cumulates are locally discordant upon a pre-existing foliation in the serpentinitized tectonite peridotite. The ultrabasic cumulates occur together with gabbros in the lower part of the sequence and exhibit dm scale layering. Gabbro is the most abundant rock type toward the top. The layered gabbros contain sills and dykes mainly of dolerite; the dykes become more abundant toward the top of the sequence.

The basaltic lavas overlie the layered cumulates with either a gradational contact through massive microgabbro or a sharp contact marked by magmatic breccia with leucocratic matrix. The upper part of this sequence contains pillow lavas and hyaloclastites. The basaltic lavas are cut by numerous dykes, mainly of dolerite, which occasionally form sheeted dyke complexes at their base. Diorite forms large laccoliths between the layered cumulates and the overlying lavas; they are sometimes several km long. The diorites display generally diffuse interfingering with the layered gabbro and intrusive contact with the lavas. Another generation of diorite has intruded into the upper part of the Bou Azzer complex during the major Pan-African deformation. The volcano-sedimentary series which overlies the complex is mainly composed of graywackes, tuffs associated with limestones, and jaspilites. It also contains spilitic and keratophyric lavas. This sequence seems to be unrelated to ophiolites (W.R. Church 1983, written communication).

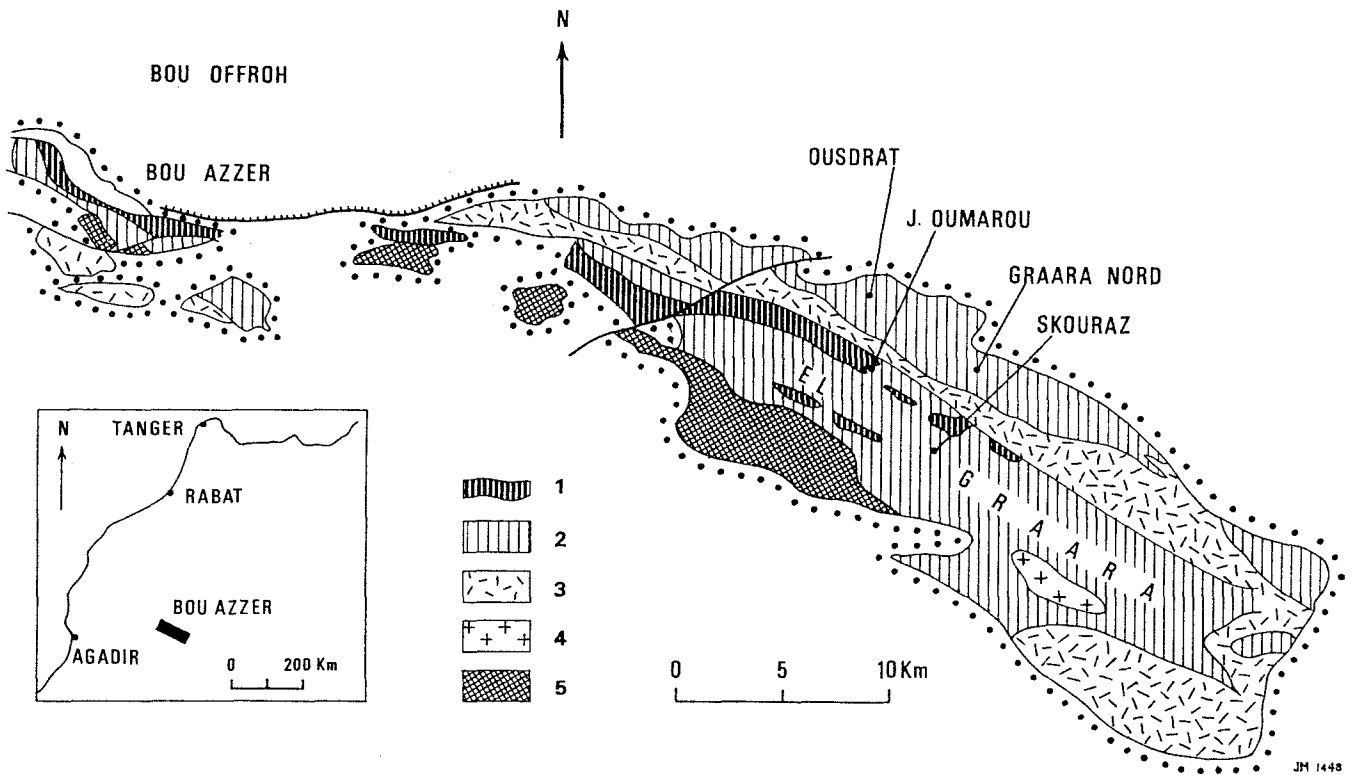


Fig. 1. Generalized geological map of the Bou Azzer area. The insert shows the location of the area in north-west Africa. Legend: 1, serpentinites, 2, effusive and intrusive ophiolitic rocks, 3, Post-tectonic Tiddiline formation (615 M.y. old), 4, Late Pan-African granites, 5, Eburnean gneisses and amphibolites; dots, Infra-Cambrian cover (580 M.y. old)

The Bou Azzer ophiolite complex probably represents a piece of oceanic crust (about 788 M.y. old – Clauer 1976) obducted onto the northern margin of the West African craton during the major Pan-African deformation event dated at about 685 M.y., (Leblanc 1975, 1976, 1981). However, it is possible that the ophiolite obduction and Pan-African deformation events may be older (>700 M.y., Jeannette and Tisserant 1977).

Petrography

The petrography of the ophiolite complex has been described elsewhere (Leblanc 1975). Briefly, the rocks are strongly altered and are composed mainly of secondary minerals typical of greenschist facies (albite, actinolite, chlorite, serpentine, epidote, calcite, quartz). However, relict magmatic minerals and textures are preserved in places and can be used along with the pseudomorphs to characterize the original petrography of the rocks.

The cumulate sequence is dominated in the lower part by alternating dunites, wehrlites and gabbros composed of cumulate olivine, plagioclase, clinopyroxene and subordinate orthopyroxene. In the rest of the sequence layered gabbros are by far the most abundant rock type. They are mostly plagioclase-pyroxene (both augite and hypersthene) cumulates with variable amounts of titanomagnetite. Microgabbros and doleritic dykes are frequently composed of pyroxene and plagioclase with the dykes having still well preserved ophitic texture. The basaltic lavas vary texturally from pilotaxitic to intersertal and subophitic with the primary magmatic assemblage dominated by pyroxene, plagioclase and possibly also olivine.

Diorites, quartz diorites and related rock types are composed mainly of variable amounts of plagioclase, hornblende, biotite, pyroxene, quartz and Fe—Ti oxide minerals and usually display hypidiomorphic granular textures. Spilites and keratophyres have been very strongly altered and the primary magmatic minerals and textures were not preserved.

Analytical notes

Major element and Rb, Sr, Li, V, Cr, Co, Ni, Cu and Zn concentrations were determined by the atomic absorption technique. Ba, Zr and Nb were analyzed by X-ray fluorescence whereas rare earth elements (REE), Sc, Th and Hf were determined by instrumental neutron activation analysis. The precision of trace element data is generally better than 10% with the exception of Tb for which the precision is about 15%. The accuracy of the trace element determinations has been reported by Dupuy et al. (1979).

Geochemistry

The analyzed rocks include a wide variety of rocks ranging from ultrabasic cumulates to keratophyric lavas. The suite displays large variations in composition with SiO_2 ranging from 43 to 86% and $\text{FeO}_{\text{tot}}/\text{MgO}$ from 0.15 to 5.7 (Tables 1–3). On the AFM diagram (Fig. 2), the Bou Azzer complex shows an evolutionary trend similar to that of the Troodos ophiolites (Thayer 1967). When observed in detail, two distinct trends may be recognized: a) a tholeiitic trend of basic non-cumulate rocks (microgabbros, dolerites, pillow lavas)

Table 1. Composition of representative samples of the tholeiitic sequence: layered cumulates – massive microgabbros – mafic dykes – mafic lavas

Sample	Cumulates									Non-cumulative rocks							
	311	1207	1206	1204	A4	1205	712	1203	1201	575	1200	569	1199	A8	1179	1403	743
SiO ₂ (%)	49.90	47.10	43.26	46.51	47.01	45.56	48.26	51.60	48.40	49.31	50.50	47.00	55.00	51.81	50.90	48.10	42.44
TiO ₂	0.06	0.22	0.07	0.12	0.28	0.11	0.09	0.27	0.20	0.51	0.81	0.58	0.58	0.60	1.34	1.37	2.10
Al ₂ O ₃	1.28	7.20	12.90	17.30	8.95	16.80	20.30	15.60	17.72	16.00	14.10	16.30	14.10	15.26	13.20	14.80	17.20
FeO*	3.56	7.26	3.96	5.31	9.15	5.16	4.03	6.10	6.53	8.26	8.53	8.69	8.15	8.78	9.31	10.17	12.47
MnO	0.11	0.10	0.18	0.14	0.02	0.16	0.11	0.15	0.16	0.17	0.19	0.18	0.21	0.19	0.18	0.20	0.27
MgO	23.86	23.20	12.00	11.40	18.98	10.76	6.68	9.23	8.21	8.60	8.80	8.65	7.64	7.14	7.16	6.87	5.28
CaO	16.58	7.76	22.75	11.87	10.57	14.77	14.57	10.53	9.96	9.59	8.95	10.22	7.86	8.47	11.68	10.38	11.77
Na ₂ O	0.09	0.19	0.04	1.87	0.46	1.23	2.09	2.95	2.36	3.18	3.32	2.70	3.93	3.90	2.55	3.61	2.53
K ₂ O	0.01	0.03	0.01	0.16	0.04	0.13	0.34	0.22	0.83	0.28	0.33	0.48	0.12	0.32	0.09	0.41	0.41
P ₂ O ₅	0.03	0.00	0.01	0.01	0.11	0.01	0.04	0.14	0.03	0.09	0.06	0.09	0.04	0.10	0.16	0.23	0.26
LOI	3.87	5.56	3.50	3.69	3.55	4.05	3.45	2.56	4.18	2.24	2.26	3.95	0.92	2.23	2.16	1.82	2.96
FeO*/MgO	0.15	0.31	0.33	0.47	0.48	0.48	0.60	0.66	0.80	0.96	0.97	1.00	1.07	1.23	1.30	1.48	2.36
Th(ppm)	0.09	0.06	0.16	0.13	0.37	0.15	0.25	0.25	0.29	0.06	0.44	0.33	0.08	0.20	0.24	0.67	0.40
Zr	3		4	20	10	3	18	17	23	22	42	24	27	43	85		130
Hf	0.03	0.10	0.04	0.08	0.23	0.07	0.14	0.39	0.43	0.55	1.07	0.79	0.70	0.91	2.07	2.49	2.87
Nb	3		3	4	4	4	4	4	4	5	6	5	5	6	8		13
La		0.48		0.39	0.66	0.44	0.89	0.98	1.29	1.03	1.57	1.10	0.97	1.80	2.79	5.77	8.35
Ce		0.38		0.29	1.75	0.70	0.96	2.28	3.36	2.52	5.12	2.57	2.69	4.56	9.23	15.7	21.3
Nd		0.62		0.49	1.48	0.57	0.75	1.69	2.08	2.10	4.39	2.12	2.49	3.69	7.89	12.2	14.1
Sm		0.26		0.24	0.52	0.25	0.28	0.61	0.56	0.91	1.61	1.20	1.06	1.28	2.74	3.71	4.20
Eu		0.10		0.12	0.20	0.15	0.13	0.25	0.25	0.39	0.60	0.47	0.43	0.55	0.97	1.38	1.57
Tb		0.08		0.07	0.14	0.07	0.07	0.16	0.14	0.35	0.47	0.36	0.40	0.45	0.82	0.88	0.94
Yb		0.52		0.29	0.66	0.31	0.26	0.73	0.64	1.51	1.81	1.57	1.69	1.81	2.98	2.92	2.55
Lu		0.11		0.06	0.13	0.06	0.05	0.14	0.13	0.25	0.31	0.23	0.28	0.31	0.49	0.47	0.42
Li	2	23	27	36	27	40	25	17	36	17	13	18	7	14	14	24	25
Rb	1	1	2	4	1	4	5	5	22	5	7	6	1	4	1	5	9
Sr	11	5	45	291	36	107	291	113	182	149	148	52	120	225	73	393	551
Ba			24	78		128	105	161	617	123	100	108	71	19			115
Sc										36.7			35.3	38.7	36.7	44.5	39.0
V	86	171	108	121	145	103	88	150	153	235	228	234	230	258	283	274	340
Cr	3,210	1,600	355	356	665	435	150	315	82	255	308	313	260	127	337	187	174
Co	36	58	43	53	86	54	55	57	50	60	61	58	72	36	52	40	52
Ni	750	350	103	120	750	240	70	127	69	103	114	108	84	233	126	224	69
Cu	9	239	136	34	965	220	124	46	69	10	71	22	48	70	10	29	7
Zn	72	350	119	49	78	73	53	86	100	86	95	99	156	89	71	95	129

FeO* = Total iron as FeO; clinopyroxenolite: 311; plagioclase pyroxenolite: 1207, A4; layered gabbro: 1206, 1204, 1205, 1203, 1201, 712; massive gabbro: 569, 1200; dolerite: 575, 1199, A8, 1403, 743; basalt pillow-lava: 1179. Locations (Fig. 1): Bou Offroh – 311; J. Oumarou – 1199, 1200, 1201, 1203, 1204, 1205, 1206, 1207, A4, A8; Graara Nord – 1179; Graara – 569, 575, 712, 743, 1403

and b) a calc-alkaline trend of the diorites. On this graph, cumulates are displaced toward the Mg apex while keratophyres cluster toward the alkali apex. The two trends shown on the AFM diagram are confirmed when plotting elements such as Fe, Ti, Mn and V against a differentiation index (Fig. 3). Compared to rocks with tholeiitic affinities, the diorites are characterized by a large SiO₂ range, higher K₂O, Al₂O₃ and P₂O₅ and lower MgO and TiO₂. Their composition is typical of high alumina basalts and andesites.

The abundances of REE normalized to chondrites are plotted on Fig. 4. There are several types of patterns. The rocks with tholeiitic affinities are depleted in light REE (LREE) and have a variable but low Ce/Yb ratio [(Ce/Yb)_N = 1.9–0.3]. Their REE content and patterns are typical of mid-ocean ridge basalts (MORB) and are encountered in most ophiolite complexes (Kay and Senechal 1976; Venturelli et al. 1979; Stern 1979; Dupuy et al. 1981). The diorites are enriched in LREE and display slight heavy REE (HREE) fractionation. Their (Ce/Yb)_N ratios vary between

8.5 and 1.8. The slope of their REE patterns is typical of continental margin andesites (Dostal et al. 1977, 1982; Lopez-Escobar et al. 1977). Cumulate rocks have the lowest REE contents and can be subdivided according to REE pattern and content into two groups: a) plagioclase cumulates which are characterized by positive Eu anomalies associated with high Al₂O₃ content and b) pyroxene cumulates which are strongly depleted in LREE. The pyroxene cumulates have a low (Ce/Yb)_N ratio accompanied by low Al₂O₃ and high Cr contents. Other samples classified as cumulates (Table 1) are intermediate between these two groups and may contain intercumulus liquid (e.g. sample 1201).

With one exception (Sample 734), spilites display the same REE pattern as diorites marked by an enrichment of LREE and slightly fractionated HREE. Although these rocks are strongly altered, their calc-alkaline affinities are suggested by the large range of SiO₂, high Al₂O₃ and low TiO₂, Ni and Cr contents. Keratophyres have high SiO₂ content and are depleted in K₂O. On the K₂O vs SiO₂ diagram, they plot into the field of oceanic plagiogranites.

Table 2. Composition of representative volcanic rocks of the upper volcano-sedimentary series

Sample	Spilites			Keratophyres			
	734	1184	736	1167	1166	1452	1451
SiO ₂ (%)	56.70	63.30	53.40	50.53	72.70	78.22	86.42
TiO ₂	1.11	0.47	0.57	0.74	0.42	0.36	0.20
Al ₂ O ₃	16.35	14.80	16.00	16.58	12.40	11.95	7.14
FeO*	7.93	6.15	10.31	10.94	3.17	0.89	1.18
MnO	0.16	0.18	0.21	0.15	0.07	0.03	0.04
MgO	5.46	3.78	5.67	4.20	0.56	0.52	0.33
CaO	1.01	2.28	5.03	4.17	2.10	0.38	0.15
Na ₂ O	5.64	5.22	3.19	6.19	5.06	6.10	3.42
K ₂ O	0.30	0.26	0.22	0.12	0.83	0.32	0.17
P ₂ O ₅	0.25	0.13	0.20	0.12	0.08	0.14	0.07
LOI	3.87	2.63	3.73	3.90	1.82	0.71	0.43
FeO*/MgO	1.45	1.63	1.82	2.60	5.66	1.71	3.58
Th (ppm)	1.44	1.04	0.77	0.76	1.23	0.60	0.47
Zr	130	94	40	20	113	67	67
Hf	3.19	1.86	0.76	0.53	2.96	1.99	2.06
Nb	9	6	5	5	7	5	5
La	3.81	5.85	5.10	3.87	6.08	3.27	1.78
Ce	6.60	15.2	12.0	8.82	15.5	7.14	5.24
Nd	4.98	8.81	7.93	5.20	10.74	4.20	3.70
Sm	1.59	2.19	1.72	1.40	3.01	1.18	1.04
Eu	0.64	0.64	0.62	0.51	0.83	0.31	0.27
Tb	0.61	0.39	0.34	0.28	0.76	0.30	0.27
Yb	2.58	1.52	0.99	0.82	3.57	1.35	1.56
Lu	0.43	0.25	0.17	0.13	0.61	0.25	0.29
Li	56	30	41	42	7	11	14
Rb	2	5	4	2	15	7	2
Sr	39	259	306	70	106	49	32
Ba	58	76	81	70	171		
Sc	21.3	24.3	38.8	33.3	8.9	3.6	4.0
V	120	170	380	253	30	13	2
Cr	87	26	23	101	7		
Co	62	66	69	47	62	3	2
Ni	68	12	24	50	6		
Cu	3	10	8	8	6	4	13
Zn	107	72	100	63	60	39	55

FeO* = Total iron as FeO. Locations (Fig. 1): Skouraz - 734, 736, 1184; Ousdrat: 1167, 1451, 1452; Graara Nord: 1166

Overall, these rocks are depleted in most lithophile elements including REE. Their REE pattern is relatively flat marked by a negative Eu anomaly. They are similar to trondhjemitic rocks from the Sparta ophiolite complex, Oregon, which are considered to have been formed in an island arc environment (Phelps and Ave-Lallemant 1980).

Discussion

Interpretation of the presented geochemical data requires an evaluation of the extent to which secondary processes may have modified the original composition of these rocks. Most of the rocks were affected by greenschist facies metamorphism and sea floor alteration and thus the concentration of some elements may have changed from their original values. In fact it appears that some elements such as K, Li, Rb, Sr which display large scatter and anomalous values in several samples (e.g. enrichment of Li in cumulate rocks, depletion and Sr and Cu in spilites, low and variable K/Rb ratios) were indeed mobilized. The other elements were probably not affected by secondary processes. They display

Table 3. Composition of representative diorites, quartz diorites and related rocks

Sample	1460	1273	701	285	A2	1172
SiO ₂ (%)	55.08	51.68	53.23	60.63	56.81	56.00
TiO ₂	0.24	0.80	0.66	0.66	0.56	0.60
Al ₂ O ₃	7.02	16.89	14.90	17.20	19.70	19.55
FeO*	13.19	7.79	7.60	5.57	4.46	4.46
MnO	0.28	0.28	0.17	0.05	0.11	0.11
MgO	15.30	7.58	6.43	3.67	2.16	1.85
CaO	3.33	5.59	8.09	2.55	7.03	7.47
Na ₂ O	0.10	3.40	3.04	3.23	4.32	3.89
K ₂ O	0.04	1.14	1.92	2.36	1.32	1.51
P ₂ O ₅	0.15	0.14	0.37	0.27	0.21	0.23
LOI	4.60	2.83	2.63	3.33	2.71	2.80
FeO*/MgO	0.86	1.02	1.18	1.52	2.06	2.41
Th (ppm)	1.8	0.41	3.9	1.0	1.5	1.9
Zr	41	64	142	119	89	115
Hf	1.35	1.48	2.96	2.89	3.65	3.55
Nb	4	5	9	9	7	9
La	4.75	5.25	21.4	9.94	10.2	12.0
Ce	13.4	12.1	51.8	23.0	24.4	26.9
Nd	9.54	8.25	33.0	15.7	16.1	18.1
Sm	2.33	2.12	6.15	2.82	3.50	3.67
Eu	0.32	0.77	1.76	0.96	1.18	1.21
Tb	0.42	0.47	0.57	0.51	0.57	0.55
Yb	1.70	1.25	1.38	1.61	1.94	1.91
Lu	0.31	0.22	0.23	0.27	0.34	0.34
Li	80	72	13	52	24	17
Rb	1	29	40	68	26	33
Sr	7	220	525	231	451	462
Ba	4	383	486	274	434	392
Sc	24.7	23.2	25.9	26.5	12.2	13.7
V	80	168	256	111	91	92
Cr	433	310	145	22	114	7
Co	71	57	44	41	12	30
Ni	345	136	49	14		7
Cu	161	55	15	6	39	13
Zn	170	200	80	33	79	54

FeO* = Total iron as FeO; hornblende cumulate: 1460. Locations (Fig. 1): Ousdrat - 1273, 1460; Graara - 701; J. Oumarou - A2, 285, 1172

interelement correlations and variations typical of magmatic rocks. Nevertheless, caution should be exercised when these elements are used to interpret the magmatic evolution of the suite.

Tholeiitic rocks

Most of these rocks have chondrite-normalized patterns with relative depletion of LREE. This LREE depletion is probably a primary magmatic feature of the rocks, especially as low temperature alteration usually leads to enrichment of LREE (Frey et al. 1974; Hellman et al. 1979). Furthermore, MORB geochemical characteristics of these rocks suggested by their REE patterns are consistent with the relationship of La-Nb and Ti-Zr (Fig. 5).

In the tholeiitic sequence, elements such as LREE, Hf, P, Ti and V increase while Ni and Cr decrease with the increase of the FeO_{tot}/MgO ratio suggesting that the rocks underwent fractional crystallization. Although this process has certainly played a role in the evolution of these rocks it cannot explain all the observed geochemical variations.

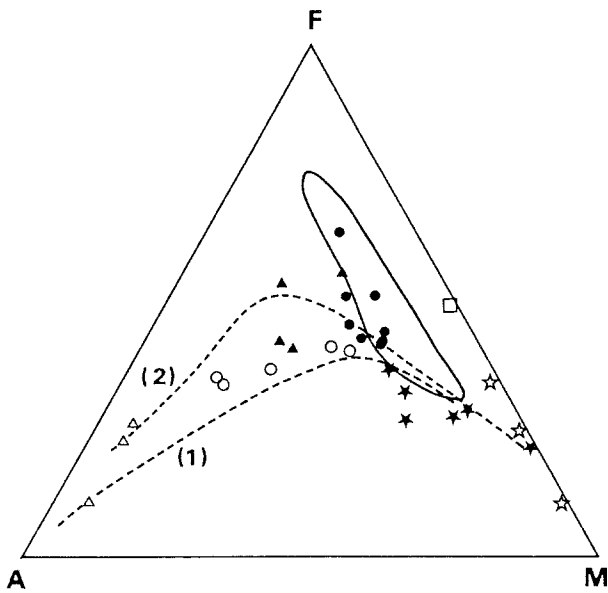


Fig. 2. AFM diagram for rocks of the Bou Azzer ophiolite complex. Layered cumulates: ☆, pyroxenite, ★, gabbro, tholeiitic suite: ●, massive gabbro; dolerite dykes and sills and basaltic lavas; upper volcano-sedimentary series: ▲, spilite, ▲, keratophyre; diorites and related rocks: □, hornblende cumulate, ○, diorite and quartz diorite. Solid line delineates the field of MORB from the North Atlantic (Wood et al. 1979). Dashed lines: 1-calc-alkaline trend (Hess 1960), 2, Troodos trend (Thayer 1967)

For example, to generate the REE pattern of sample 743 from a parent having the composition of sample A8 requires fractionation of clinopyroxene and plagioclase in the proportions 1:1 and a large degree of solidification ($F \sim 60\%$). However, such a high F is not readily consistent with their contents of major and transition elements. Likewise, a variable degree of partial melting from the same upper mantle source cannot generate such large variations in Ce/Yb ratios in lavas with similar abundances of major and transition elements. This argument has been discussed in more detail for comparable rocks by Strong and Dostal (1980) and Bertrand et al. (1982). A heterogeneous upper mantle source and/or a dynamic partial melting model (Langmuir et al. 1977) with minor subsequent modification of the melt by fractional crystallization seems to best explain the large variations of incompatible elements in this suite. Such a model has frequently been postulated for mid-ocean ridge basalts (e.g. Langmuir et al. 1977; Wood 1979) and ophiolites (Strong and Dostal 1980; Furnes et al. 1982; Coish et al. 1982).

Cumulate

Due to secondary processes, several samples display in addition to their Li and Rb enrichment, a preferential La increase accompanied by a marked Ce anomaly in their chondrite-normalized REE patterns. Similar changes of the REE patterns have been described for the pillow lavas of Troodos (Robertson and Fleet 1976). Nevertheless, the magmatic geochemical characteristics of the cumulate rocks are still well-preserved.

The cumulates appear to be related to the tholeiitic sequence because the ratios of several incompatible elements such as La/Nb or Zr/Nb are comparable in the two types

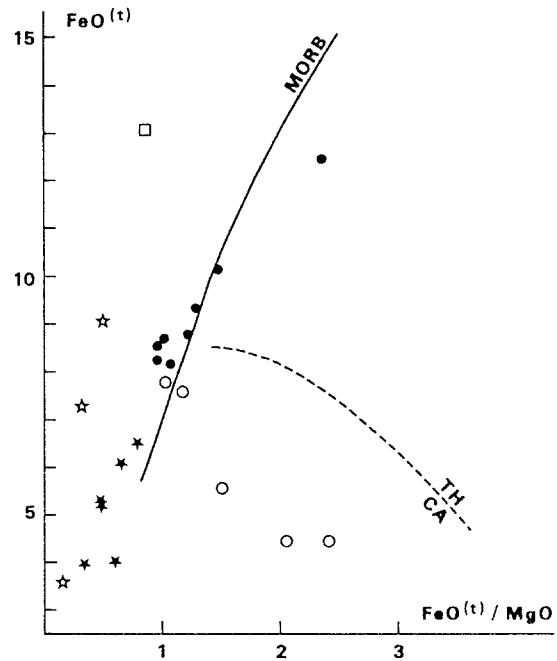


Fig. 3. FeO_{tot} vs $\text{FeO}_{\text{tot}}/\text{MgO}$ diagram for ophiolitic rocks of the Bou Azzer complex (except for keratophyres). Dashed line separates tholeiitic (TH) and calc-alkaline (CA) fields (Miyashiro 1973) solid line represents a fractionation trend for MORB (Saunders et al. 1979, Upadhyay and Neale 1979). Symbols are the same as in Fig. 2

of rocks and also both plot on the same variation trends in differentiation diagrams (e.g. FeO_{tot} vs $\text{FeO}_{\text{tot}}/\text{MgO}$ or TiO_2 vs Zr). One exception is a hornblende cumulate (sample 1460, Table 3) which occurs within the diorite intrusion. This rock differs markedly from the other studied cumulates by its chemical composition including a REE pattern which is characterized by a negative Eu anomaly and LREE enrichment and is probably related to the calc-alkaline series.

Diorites

Among the analyzed rocks, diorites have the highest LREE contents. They also have distinctly fractionated REE patterns with strong LREE enrichment (Fig. 4) similar to those of calc-alkaline rocks. As most samples have major element compositions typical of high aluminium basalts or andesites it may be reasonably assumed that the enrichment in LREE is a primary feature and not related to secondary processes. There are several other features indicating that these rocks have a calc-alkaline rather than tholeiitic character. On the TiO_2 vs Zr graph of Pearce and Cann (1973) diorites fall into the calc-alkaline field (Fig. 5); they are relatively enriched in large-ion-lithophile elements (LIL) including La and Ce but depleted in high-field-strength elements (HFS) resulting in high LIL/HFS element ratios (e.g. La/Nb) which are characteristic of orogenic magmatic suites.

Quartz diorites and diorites associated with ophiolite complexes have been interpreted either as residual liquids produced by fractional crystallization of oceanic tholeiitic magma (Coleman and Donato 1979; Kay and Senechal 1976) or as partial melts of tholeiitic basalts (Phelps 1979). However, none of these models can account for the geochemical characteristics of the studied diorites. In fact, it is unlikely that the diorites with their calc-alkaline character

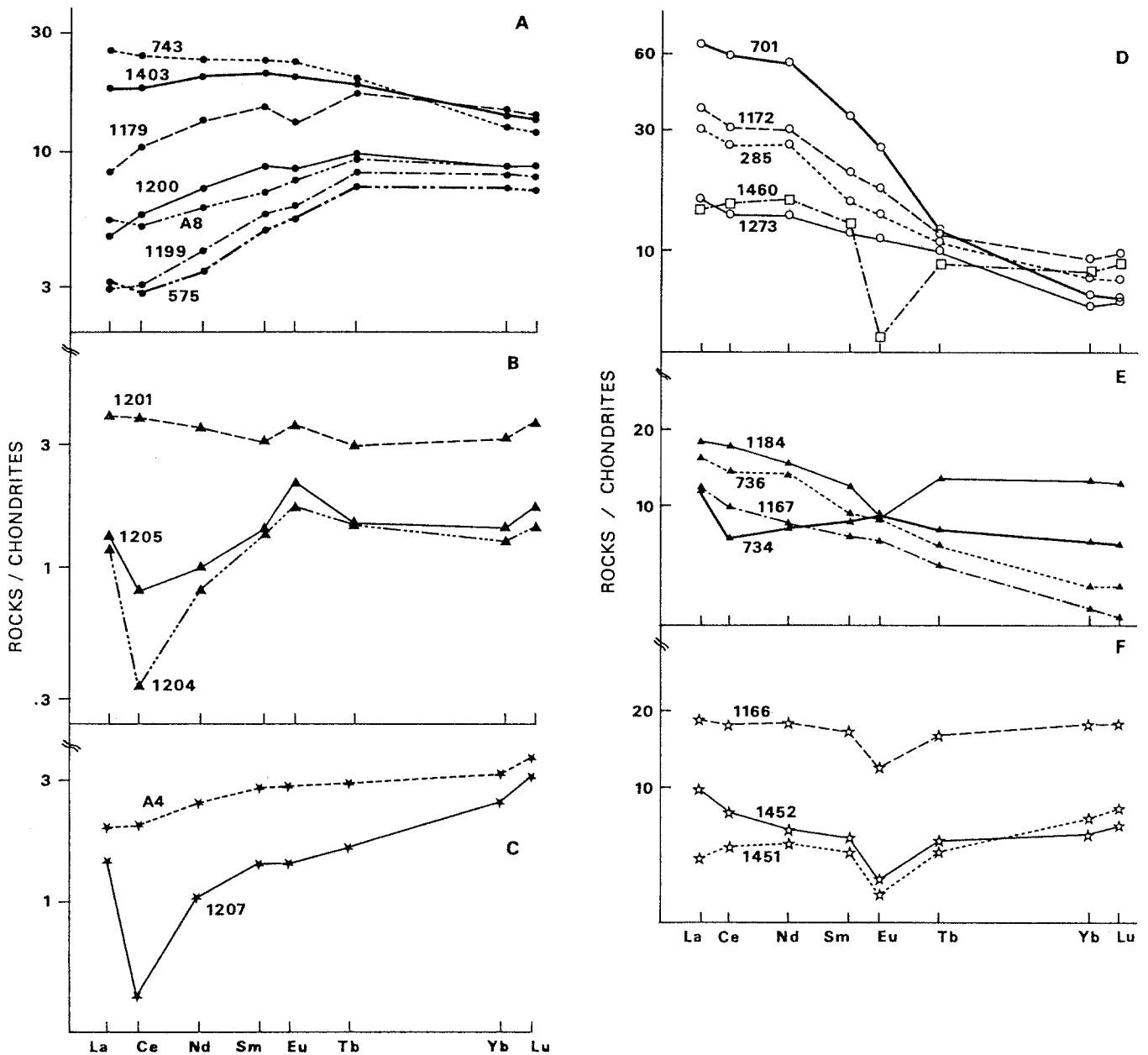


Fig. 4. REE patterns normalized to chondrites (Frey et al. 1968). A: non-cumulates of tholeiitic suite; B: gabbroic cumulates of tholeiitic suite; C: pyroxenites; D: diorites and quartz diorites; E: spilites; F: keratophyres

are genetically related to the tholeiitic sequence and probably, as in the Sparta ophiolite complex, Oregon (Phelps and Ave-Lallemant 1980) represent a later separate magmatic event.

Spilites and keratophyres

These rocks have been strongly affected by secondary processes. In spilites, Ca, Sr and Cu tend to be depleted while Na and Li are enriched. However, their REE contents and patterns are very similar to those of diorites and quartz diorites. The exception is sample 734 which is the most altered. Like diorites, the spilites show calc-alkaline affinities indicated by low contents of Ti and other HFS elements associated with a high La/Nb ratio.

Although the three keratophyre samples analyzed have subparallel REE patterns, two samples (1451 and 1452)

have very low REE contents. Such a depletion may result either from a dilution effect during silicification of the rocks (Dostal and Strong 1983) or from hydrothermal leaching (Furnes et al. 1982). Among the keratophyres, sample 1166 is the only one which retained its magmatic features. Its major element composition and REE content and pattern are very similar to the Sparta trondhjemites (Phelps and Ave-Lallemant 1980).

Conclusion

The geochemical data presented in this paper indicate that the Bou Azzer ophiolite complex is composed of two distinct magmatic sequences: tholeiitic and calc-alkaline. The tholeiitic series includes microgabbros, diabases and pillow lavas. The cumulates are probably genetically related to this suite. The geochemical characteristics of the tholeiitic

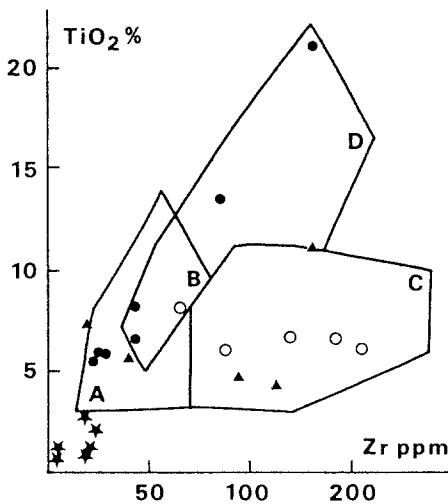


Fig. 5. TiO_2 vs Zr diagram of Pearce and Cann (1973) for the ophiolite rocks of the Bou Azzer complex with outlined fields for MORB (B and D) calc-alkaline basalts (C) and low potassium tholeiites (A and B). Symbols as for Fig. 2

suite correspond to the N and/or T type of MORB (Sun et al. 1979). Although the rocks of the tholeiitic sequence were generated from an upper mantle source, the large variations in REE accompanied by relatively small differences in major and some trace elements indicate derivation from a heterogeneous source and/or by a dynamic melting process. The absence of ferrogabbros among the cumulates suggests the limited extent of the fractional crystallization process. This may be indicative of an open magma chamber periodically replenished with new batches of undifferentiated parental magma (O'Hara 1977; Church and Riccio 1977; Stern 1979).

The calc-alkaline sequence mainly includes diorites and quartz diorites. The trace elements data shows that the calc-alkaline rocks are not genetically related to the tholeiitic sequence. The intrusive field relationship of the diorites at Ousdrat and Bou Azzer is compatible with their emplacement after the ophiolite obduction event. The intrusive diorites are very similar to those encountered in the Sparta ophiolites (Phelps 1979). The Bou Azzer complex is also overlain by a sedimentary series which is intercalated with spilite and keratophyre having calc-alkaline affinities. Church (1980), on the basis of limited data, concluded that the Bou Azzer complex includes both ocean-floor basalts and calc-alkaline rocks. In fact, the occurrence of a calc-alkaline sequence which is not uncommon in ophiolites has frequently been interpreted as indicative of an island arc environment (Upadhyay and Neale 1979).

All these features (tholeiitic magmatism, early intrusive calc-alkaline series overlain by a thick volcano-sedimentary sequence) are consistent with a tectonic model where the Bou Azzer complex was formed in a marginal basin just behind a still active island arc. A similar model has been proposed for the Mesozoic ophiolites of southern Chile (Dalziel et al. 1974).

Regarding the geotectonic evolution of the Bou Azzer complex, the following conclusions can be proposed: The early intrusion of a significant volume of diorites and quartz diorites suggest an early stage of the opening of the oceanic basin which was therefore of rather limited size. This is supported by the volcano-sedimentary sequence overlaying

both the ophiolite complex and the margin of West African craton. The ocean basin was subsequently closed during the main phase of the Pan-African orogeny (~685 M.y. ago) while the calc-alkaline magmatism continued (i.e. emplacement of syn-tectonic diorite and quartz diorite).

The overall similarities of the tectonic evolution of the Bou Azzer ophiolites to the Proterozoic oceanic crust of the Burin Group, eastern Newfoundland, are consistent with the suggestion of Strong et al. (1978) that the Proterozoic oceanic crust in the Eastern Newfoundland can be correlated with the crust along the margins of the West African craton. In addition, the similarity of the Bou Azzer ophiolite complex to Phanerozoic tholeiitic and calc-alkaline rocks also confirms the observations that Proterozoic magmatic processes are comparable to those of the Phanerozoic and that there has been no significant change in the composition of upper mantle since that time. It may be significant that the ophiolites of Bou Azzer, like most other Proterozoic ophiolites (e.g. Baker 1973; Baker et al. 1976; Thorpe 1978; Strong et al. 1978; Strong 1979) can represent remnants of a back-arc oceanic crust obducted onto the continent.

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