

Xenocrysts in Eocene camptonites from Taourirt, northern Morocco

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Abstract

A study of xenocrystic material included in 57 Ma igneous rocks that outcrop in the Taourirt area of north-east Morocco has been made. The mineralogy of the host rocks is essentially clinopyroxene, rare olivine, titanomagnetite and either kaersutite or biotite. Feldspars (plagioclase and alkali feldspar) and nepheline are usually altered. Accessories may include haüyne, perovskite and ferriannite-rich annite. The complex xenocrystic assemblage includes various types of clinopyroxene, amphiboles, micas of differing compositions and various types of spinel. These inclusions did not dissolve in the melt and, as a consequence, the residual (alkali-rich) mineralogical assemblage is not modified. Their abundance is such that they may not significantly affect the major element compositions, but they may strongly influence the levels of certain trace elements such as Cr and Ni.

KEYWORDS: xenocrysts, Eocene camptonites, Taourirt, Morocco, clinopyroxene, amphibole, mica.

Introduction

INTRUSIVE rocks in the Taourirt area of north-east Morocco (Agard, 1950; Giret, 1985) outcrop as dykes and sills with an average thickness of around 3 m. Some breccia pipes are also present. Even though they form numerous outcrops shown on the map published by Agard (Fig. 1), the quantities of magma brought to the surface are small. The stratigraphic age of these rocks has been established as post-Cretaceous to Tortonian (Giret, 1985) and confirmed by K/Ar measurements (Charlot *et al.*, 1964) which give an age of 57 Ma for the eruptive rocks.

The present study has been limited to occurrences around the Ferme Dubois locality, an area limited by $x = 715$ to 725 and $y = 425$ to 435 on the detailed map of Morocco (Fig. 1).

The Moroccan basic rocks were initially described by Duparc (1925) under new names, aiounites and mestigmerites and briefly examined later by Jeremine (1948). Aiounites, corresponding to the ferromagnesian-rich facies, were defined as containing essential augite, biotite and opaques in a poorly defined groundmass. Mestigmerites, the ferromagnesian-poor rocks, were defined by the presence of essential 'acmitic augite' and nepheline with accessory apatite and sphene.

The texture of these rocks varies greatly from

almost aphanitic to largely porphyric and these variations may be observed within a single outcrop. A peculiar texture found in a 9 cm wide dyke, cutting across normal camptonites, shows amphiboles that have crystallized perpendicularly to the walls of the dyke, some of the crystals bridging the two walls (Mokhtari, 1985).

These rocks also contain a vast range of xenocrysts of the same mineral species as those of the rock. The term xenocryst is defined by Bates and Jackson (1980) as a crystal that resembles a phenocryst but is foreign to the body of igneous rock in which it is found. The existence of xenocrysts may be suspected when crystals of a given species form more than one cluster or uniform trend in a compositional space. The criteria used to distinguish xenocrysts from phenocrysts are mostly based upon three lines of evidence: (1) Differences in chemical composition, especially minor element concentrations; (2) Shape, xenocrysts being commonly rounded. They may also have served as support for overgrowth in the liquid after an episode of partial dissolution. Regular crystal outlines may have been reconstructed. Dissolution may also produce euhedra (Donaldson, 1985; Nicolas, 1985) in the absence of overgrowth; (3) Size, in that xenocrysts may be larger than phenocrysts. Xenocrysts, as defined here, correspond closely to megacrysts as defined by

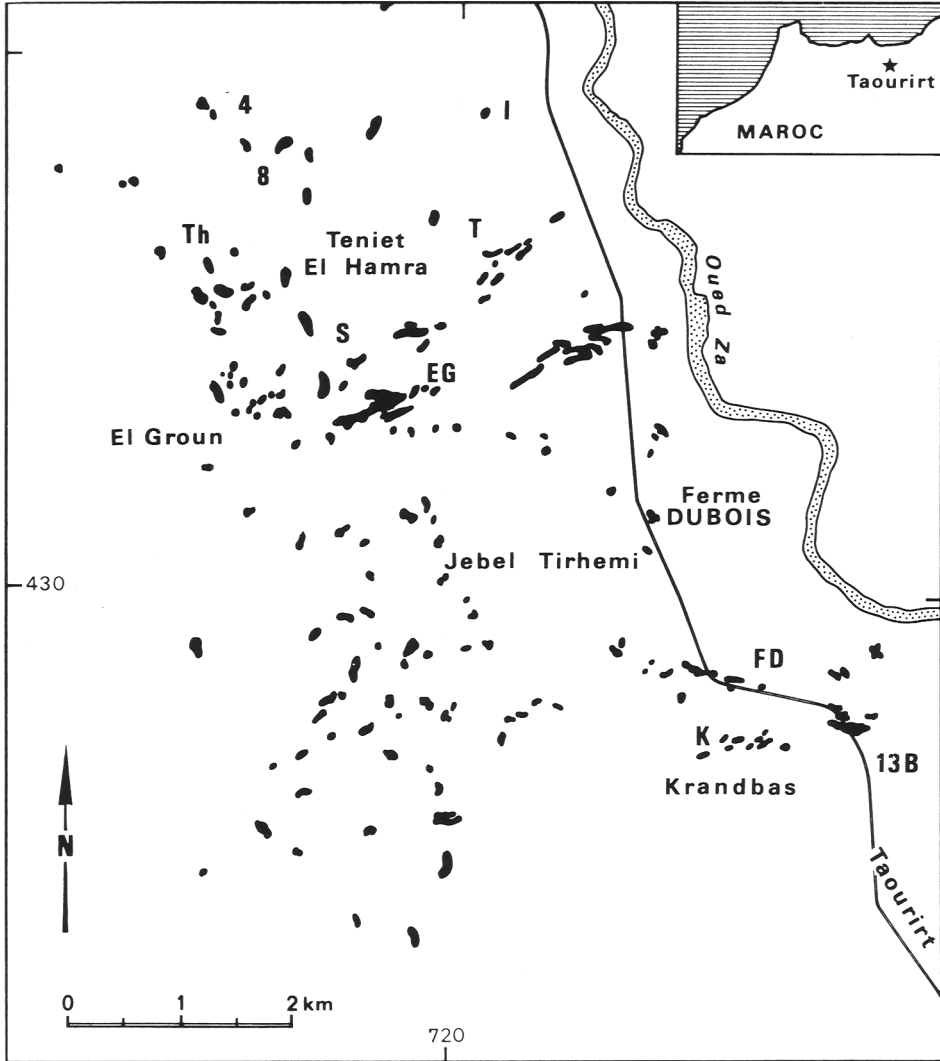


FIG. 1. Geological setting of the Ferme Dubois locality, Taourirt, Morocco.

Nixon and Boyd (1973) for kimberlite minerals. They are similar to included xenoliths which may represent either mechanically dispersed fragments (Dawson and Smith, 1986), kimberlite phenocrysts, or phenocrysts from crystal-mush magma originating in the low-velocity zone. The term megacryst is not used, since the exotic minerals are not necessarily of disproportionate size relative to genuine phenocrysts.

The object of the present paper is to examine the composition of the minerals in the Taourirt rocks in order to assess the contamination of magma by pre-existing material through a tho-

rough investigation of the xenocrysts found in selected specimens. We also place the Taourirt eruptives in the geodynamic context of Cretaceous to early Tertiary basic alkaline magmatism (Rock, 1982*b*), a type of magmatism present on both the western and eastern margins of the Atlantic ocean.

Situation of the Taourirt eruptive rocks in a geodynamical context

Igneous rocks with compositions close to those of the Taourirt camptonites are known along the eastern margin of the Atlantic ocean. Their N-S

TABLE 1 - CHEMICAL COMPOSITIONS AND MODES OF THE TAOURIRT CAMPTONITES

	1 EG1 A	2 Th6 M	3 4 A	4 8 A	5 EG# A(M)	6 T4 M	7 13B7 M	8 FD8 M	9 76C M	10 13B9 -
SiO ₂	44.54	40.71	43.97	42.74	39.62	38.16	38.36	36.67	39.42	37.58
Al ₂ O ₃	14.91	12.62	15.58	14.04	10.83	12.57	13.53	12.59	14.00	13.56
Fe ₂ O ₃	4.92	6.35	6.57	6.35	6.36	6.71	6.24	5.71	7.97	5.35
FeO	4.95	4.55	3.70	4.94	5.81	3.67	4.84	5.72	3.82	6.58
HgO	7.31	10.47	5.15	7.74	12.30	8.18	11.17	8.51	6.51	8.67
CaO	9.32	12.25	7.77	10.34	13.52	14.91	12.84	11.94	12.44	10.70
Na ₂ O	3.62	2.02	4.04	2.89	1.71	2.32	2.17	2.77	4.28	1.57
K ₂ O	2.93	2.55	3.39	2.96	1.71	1.59	1.55	1.77	1.26	2.51
H ₂ O	0.16	0.12	0.18	0.16	0.15	0.16	0.15	0.20	0.19	0.39
TiO ₂	3.25	3.73	3.16	3.29	3.73	3.36	3.76	3.37	3.34	4.30
P ₂ O ₅	0.76	0.53	0.87	0.58	0.77	0.69	0.67	0.83	1.15	0.94
H ₂ O ⁺	3.56	4.39	5.30	4.45	2.57	7.83	3.81	9.85	4.85	5.34
H ₂ O ⁻			0.37	-	-	0.69	0.62	0.92	0.55	1.61
Total	100.23	100.29	100.05	100.48	99.08	100.84	99.71	100.85	99.78	99.10
Fe (t)	0.57	0.51	0.66	0.59	0.50	0.56	0.50	0.57	0.64	0.58
Fe+Hg										
Na	0.55	0.44	0.54	0.49	0.50	0.59	0.58	0.61	0.77	0.38
Na+K										
S							1262			2970
V	239	268	267			321	322	289	406	429
Cr	163	228	62		447	214	39	30	30	34
Ni	85	183	35		218	122	49	20	31	44
Zr					273					
Ba					506					
Str					1264					
Olivine	8	5	-	3	-	2	3	1	-	6
Clinopyroxene	16	31	13	10	20	38	32	19	36	10
Micas		20			7		14	7	9	
"X"							3	2		
Amphiboles	27		24	33	35					
"X"				5			6	1		
Oxides	3	15	9	12	5	5	11	7	6	5
Groundmass	46	29	54	37	33	48	31	63	49	70

A = amphibole-bearing; M = mica-bearing; "X" = xenocrysts

alignment and their mostly Mesozoic to early Cenozoic ages suggest a link with the opening of the Atlantic ocean. We should now consider the available age determinations and the possible relationship between the Moroccan basic rocks and the Atlantic igneous province.

Rock (1982b, notably Fig. 5) has given an outline of the known occurrences of eruptive rocks along the eastern margin of the Atlantic ocean. Numerous outcrops are distributed from northern Scotland in the north, to the Gorrige bank in the south. Ages from the Gorrige bank (Féraud *et al.*, 1986) vary from 140 to 66 Ma. The age of the Pyrenean province is given as 82 Ma (Rock, 1982b). Since then, new determinations indicate that the ages are 95–110 Ma in the western part and 90 Ma in the eastern part of the chain (Thuizat *et al.*, 1985; Montigny *et al.*, 1986). The Taourirt rocks, with one available determination at 57 Ma, are almost contemporaneous with a number of similar Portuguese and British rocks.

Igneous provinces with similar rock types are known on the western margin of the Atlantic ocean. Alkali gabbros and lamprophyres from the New England-Quebec provinces are dated from late Jurassic to early Cretaceous (McHone and Butler, 1984), an age probably similar to that of the south-east New England seamounts (Pe-Piper

and Jansa, 1987). Recent age determinations on the related Montereian intrusives (Foland *et al.*, 1986) indicate an age of 124 Ma. Further inland the Arkansas alkalic province is Cretaceous (Morris, 1987). Consequently the symmetry known between the Triassic and Jurassic tholeiitic dykes and sills found in Morocco, Spain and southern France in the east and the Carolinas in the west can be extended to later periods of igneous activity with a slight offset in time, being late-Jurassic to Cretaceous in the west and mostly Cretaceous to early Tertiary in the east.

Petrography

Two major rock types are present: one with kaersutite, the second with essential phlogopite. These minerals coexist in only one of the specimens examined (76c, Table 1). Other major phases are clinopyroxene, oxides and feldspars. Xenocrysts are present in both types.

Two specimens will be described as examples of the amphibole- and biotite-bearing varieties, respectively. Their texture is close to aphanitic. Specimen EG11 is composed of altered olivine (4 mm × 2 mm), Ti-magnetite (0.3 mm) and clinopyroxene (3 mm × 2 mm) in a groundmass with small amphibole prisms (0.7 mm × 0.05 mm), rare

TABLE 2 - TRACE ELEMENTS (INAA RESULTS) IN SPECIMEN EGa AND CONSTITUENT MINERALS

	Rock	Amph	Cpx	Apatite	Mica	Sphene 1	Sphene 2
U	1.34	0.32	0.79	13.1	0.12	56.4	69.2
Th	4.6	1.06	2.07	89.2	0.32	157	162
Zr	273	213	320	820	44	3771	4048
Hf	5.6	5.6	8.3	0.14	1.06	49.6	50.3
Ta	7.0	9.54	1.97	0.21	7.12	257	227
Ba	506	829	16.9	50.8	4190		
Sr	1264	1714	465	6083	776	837	771
Ce	0.83	2.1	0.18	0.05	4.0		
Rb	43.0	77.9	5.5		251		
Sb	0.07	0.02	0.04	0.01	0.04	0.18	0.23
Cr	447	153	373	61	116	419	288
Co	56.1	70.5	30.6	1.11	0.07	8.0	7.0
Ni	218	259	93	7	406		
Sc	28.8	26.2	40.4	0.21	14.0	59.7	65.9
La	51.8	29.8	24.8	1304	3.0	1080	1080
Ce	105	68.7	62.7	2243	8.1	1928	1869
Eu	3.54	2.84	2.9	40.4	0.33	47.5	43.8
Tb	0.98	0.92	0.92	10.8	0.07	10.6	10.4
Sm	8.5	7.5	6.9	112	0.64	95.4	102
Yb	1.31	0.91	1.41	8.6		21.2	20.5
Nd	62		34.7	893			456

clinopyroxene (0.15 mm × 0.1 mm), oxides and feldspars. Irregular ocelli are present, exclusively composed of small clinopyroxenes, amphiboles and feldspars. Specimen Th6 is composed of partly altered olivine (2 mm × 1.8 mm) and clinopyroxene (2 mm × 1.5 mm); deeply coloured phlogopite (1 mm × 0.1 mm) coexists in the groundmass with clinopyroxene (1 mm × 0.2 mm), Ti-magnetite (0.05 mm) and feldspar. In both rock types the phenocrysts are zoned and show a normal evolution toward Fe-rich species with falling temperature. Some rare clinopyroxene, amphibole and mica xenocrysts are recognizable in specimen Th6 and spinels have been found in specimen EG11.

Modes of all analysed samples are listed in Table 1.

Rock chemistry

Ten new analyses were performed using X-ray fluorescence methods, with ignition loss and iron oxidation state determined by classical wet methods (Table 1). One specimen was also analysed for a range of elements by INAA, as were its constituent minerals (Table 2).

All bulk chemical analyses show common characters: hydration and secondary alteration are important and ignition loss (representing H₂O as

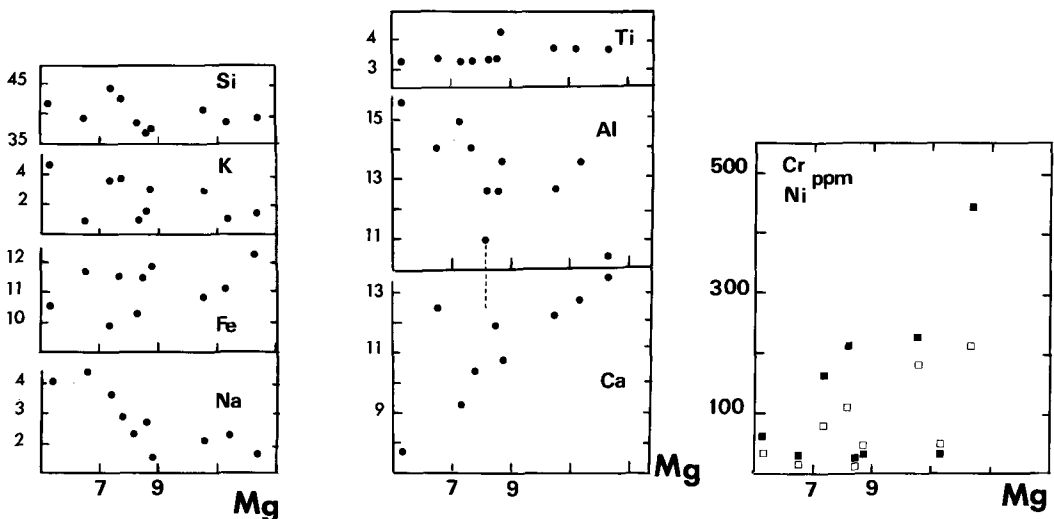


FIG. 2. Bivariate distribution of major oxides (weight %), Cr (solid squares) and Ni (open squares) vs. MgO in the Taourirt rocks.

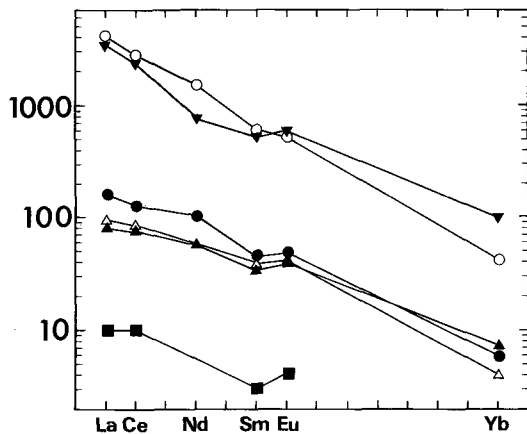


FIG. 3. Rare earth (normalized to chondrites) profiles for specimen EGa (solid circles), and its constituent minerals: titanite (down pointing solid triangles), apatite (open circles), amphibole (open triangles), pyroxene (solid triangles, point up), and mica (solid squares). Two fractions of titanite were isolated, one slightly more magnetic than the other; chemical results are very similar (see Table 2).

well as CO_2) varies from 2.5% to almost 10 wt. %. Similarly Fe appears mostly in the trivalent state. Taking into account the variations that could be due to secondary alteration the following remarks can be made: the rocks are strongly undersaturated with respect to silica as demonstrated by the presence of nepheline, leucite and even larnite in the CIPW norm. MgO and CaO vary strongly but the most aphyric rock analysed (specimen 13B9) shows moderate MgO (8.67%) and CaO (10.70%). Higher values in other analyses could correspond to the presence of xenocrystic amphibole and/or clinopyroxene. The $(\text{FeO} + \text{Fe}_2\text{O}_3)/(\text{FeO} + \text{Fe}_2\text{O}_3 + \text{MgO})$ ratio is, for all specimens, higher than 0.50, a value considered by Tilley *et al.* (1964) as being the discriminant between 'cumulative' rocks (< 0.50) and lavas corresponding to crystallized liquids (> 0.50).

The variations in most elements are moderate

or negligible. Linear trends are observed only for CaO and Al_2O_3 and to a lesser extent for Na_2O on a classical MgO diagram showing the variations of major oxides (Fig. 2).

The compositions of the Taourirt rocks can be matched almost identically with the published compositions of the Gorringer lavas (Cornen, 1981) or the Monchique basic rocks (Rock, 1979). They are theralites or basanites (e.g. Chayes, 1975, p. 548). They do not differ much from the average compositions of camptonites and monchiquites published by Métais and Chayes (1963, p. 157).

The rare earth profile of EGa (Fig. 3) is similar to those of alkali basalts except for a visible positive Eu anomaly. Such an anomaly has been described in some basalts (e.g. Lemarchand, 1984) but not completely explained. There is a similarity between the bulk rock composition and that of an amphibole for major element concentrations (Varne, 1968) which holds when considering the trace element concentrations. Fig. 3 shows that the rare earth concentrations are almost identical for the amphibole fraction separated from specimen EGa and its host rock.

The transition element contents, in particular Ni and Cr, show considerable variations. The Cr content varies from 30 ppm (Table 1) to 447 ppm and the Ni content between 20 and 218 ppm. There is a concomitant variation between the Cr and Ni contents but no direct relationship between MgO and either the Cr and Ni contents (Fig. 2). These trends are compatible with the hypothesis that variations in Cr content are mostly due to inherited Cr-rich spinels. The rough correlation between Cr and Ni would indicate that the incorporation of Cr-bearing spinel is associated with incorporation of Ni-bearing olivine, suggesting a peridotitic xenolith origin for significant proportions of both of these constituents.

Mineralogy

Clinopyroxenes. Groundmass clinopyroxenes which crystallized with amphibole or biotite (Table

TABLE 3 - ELECTRON MICROPROBE ANALYSES AND STRUCTURAL FORMULAE (4 CATIONS AND 6 OXYGENS) OF CLINOPYROXENES

	1				2				
	Th6	Th6	EG11	4 EG11	Th6	Th6	EG11	4 EG11	
SiO_2	47.53	41.92	48.56	43.03	Si	1.777	1.588	1.799	1.624
Al_2O_3	5.49	9.62	4.83	9.02	Al	0.242	0.429	0.211	0.401
FeO^{2+}	5.88	6.85	5.86	7.33	Fe^{3+}	0.099	0.139	0.082	0.151
MgO	13.10	11.41	14.16	11.44	Fe^{2+}	0.085	0.077	0.099	0.081
CaO	23.62	23.05	23.39	22.85	Mg	0.730	0.644	0.782	0.644
Na_2O	0.59	0.51	0.38	0.66	Ca	0.946	0.935	0.928	0.924
MnO	0.15	0.07	0.10	0.06	Na	0.043	0.037	0.027	0.048
TiO_2	2.64	5.14	2.46	4.32	Mn	0.005	0.002	0.003	0.002
Cr_2O_3		0.02		0.07	Ti	0.074	0.146	0.069	0.123
Total	99.00	98.59	99.74	98.78	Cr		0.001		0.002

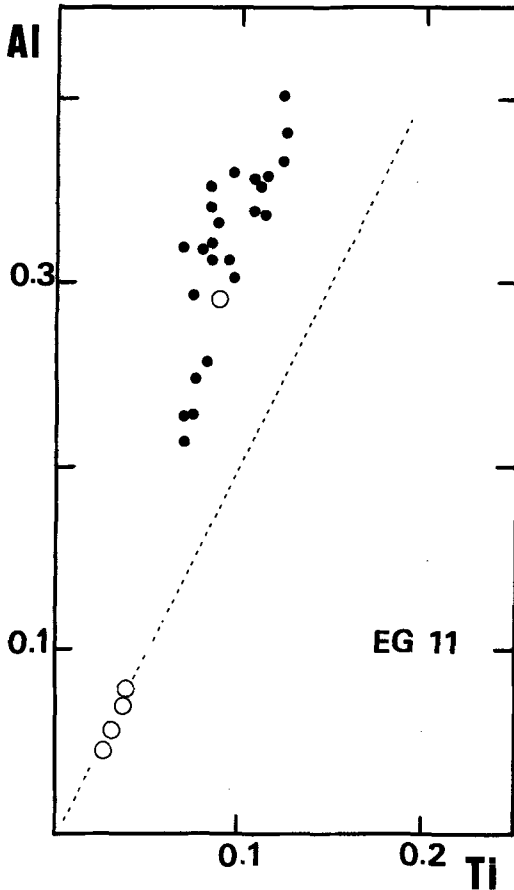


FIG. 4. Bivariate distribution of Ti and Al in clinopyroxenes from specimen EG 11. Formulae calculated on the basis of 6 oxygens and 4 cations. Solid circles, composition of clinopyroxenes in the normal rock. Open circles, composition of clinopyroxenes in light-coloured veins. The dotted line represents $Al = 2Ti$.

3) are low in Si, rich in Al and also contain significant amounts of Ti. The Al content is higher than needed to satisfy the equation $Ti = 2Al$ (Fig. 4). The $Fe/(Fe+Mg)$ ratio does not vary significantly in crystals from the same rock specimen and the representative points form a cluster in a Ca-Fe-Mg diagram (Fig. 5). There is no difference in composition between clinopyroxenes that coexist with biotite and those that coexist with amphibole. The Cr content is usually below the detection limit of the electron microprobe in routine conditions. Feldspar-rich veins contain green clinopyroxenes. The Al content of these small crystals is low (below 0.1 ion per formula unit). Their Fe content is greater than that of groundmass clinopyroxenes, their Na content is

always below 0.17 ions per formula unit and they plot in the ferrosalite field.

Late-crystallizing clinopyroxene compositions trend toward acmite (Table 4), without reaching the acmite end-member. Pure colourless acmite was observed, however, in specimens G4 and EG15 as a reaction product around foreign quartz inclusions.

TABLE 4 - ELECTRON MICROPROBE ANALYSES OF ACMITIC CLINOPYROXENES

	1 EG15	2 EG15	3 EG6	4 76b	5 FD8	6 G4
SiO ₂	51.91	52.50	51.43	50.61	52.81	52.25
Al ₂ O ₃	0.23	0.07	1.06	0.70	0.80	0.33
FeO ²⁺	23.95	24.36	23.63	20.41	27.48	29.12
MgO	2.79	2.20	0.14	5.27	0.09	0.38
CaO	6.02	1.06	3.55	14.78	1.42	0.24
Na ₂ O	10.05	12.59	12.40	6.91	13.29	13.23
MnO	0.08	0.24	0.56	0.66	0.22	0.09
TiO ₂	1.35	2.34	3.96	0.77	1.55	0.53
Total	96.38	95.36	98.73	100.11	97.66	96.17
Si	2.000	2.024	1.948	1.896	2.002	2.009
Al ₃₊	0.010	0.003	0.047	0.031	0.036	0.015
Fe ²⁺	0.648	0.754	0.742	0.634	0.849	0.922
Fe ²⁺	0.127	0.032	0.069	0.005	0.023	0.014
Mg	0.161	0.126	0.008	0.294	0.005	0.022
Ca	0.250	0.044	0.144	0.593	0.058	0.010
Na	0.754	0.941	0.911	0.502	0.977	0.987
Mn	0.003	0.008	0.018	0.021	0.007	0.003
Ti	0.039	0.068	0.113	0.022	0.044	0.015

These clinopyroxenes have high TiO₂ contents (up to 3.96% in specimen EG6). Their trend, on a Na-Mg-Fe²⁺ diagram (Fig. 6), is similar to that reported by Gomes *et al.* (1970) for clinopyroxenes from alkali rocks from Brazil.

Amphiboles. All analysed amphiboles are calcic amphiboles according to the Leake (1978) terminology. The reddish brown amphiboles from specimen EG11 (Table 5) which coexist with augite and salite plot in the kaersutite field. They are similar to those described by Rock (1982a) in basic rocks from the Monchique province of Portugal. The compositional variations observed are limited to Ti and $Fe/(Fe+Mg)$ contents. In specimen EG11 they define a line that parallels the clinopyroxene evolution trend (Fig. 5). Groundmass crystals in specimen EG11, for example, are richer in Ti than larger crystals, containing more than 7% TiO₂. Unusual sector-zoning has been found in some specimens (Mokhtari and Velde, 1987).

Late-crystallizing green amphiboles are either hastingsite or magnesio-hastingsite (Table 6).

Micas. Groundmass micas in specimen Th6 have a pronounced red colour. Their Al content is above that required by the theoretical formula (Table 7) and usually very close to 2.8 per structural formula calculated on 22 oxygens (total iron expressed as FeO). Their Si content is lower than 6.0, a common character of micas found in silica-

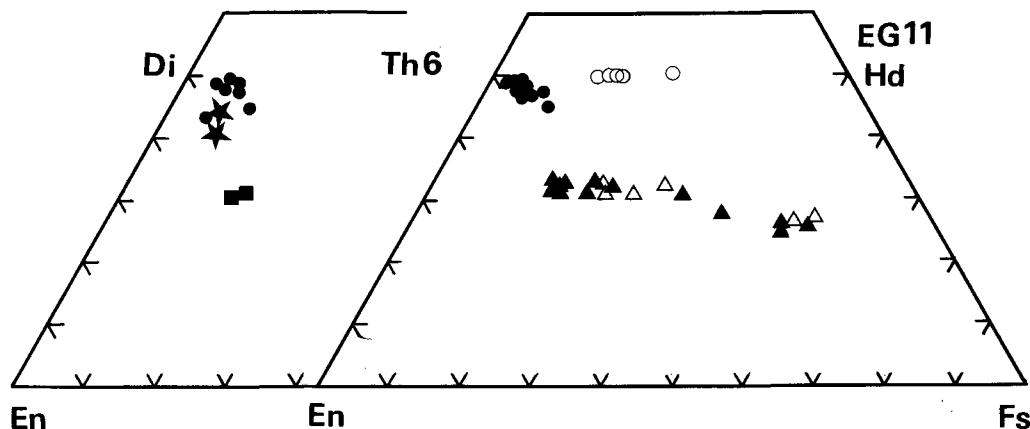


FIG. 5. Composition of clinopyroxenes and amphiboles from specimens Th6 and EG11 in the Di-Hd-En-Fs quadrilateral. Solid and open circles, as in Fig. 1. Solid stars, clinopyroxenes interpreted as xenocrysts. Solid squares, amphiboles interpreted as xenocrysts. Solid triangles, amphiboles from the normal rock, open triangles, amphiboles from the light veins.

TABLE 5 - ELECTRON MICROPROBE ANALYSES OF KAERSUTITES

	1	2	3		1	2	3
	EG11	I	Th6		EG11	I	Th6
	m	m	X				
SiO ₂	37.27	39.83	39.66	Si	5.590	5.881	5.827
Al ₂ O ₃	13.60	12.90	14.42	Al ₂ ⁺	2.404	2.245	2.497
FeO ²⁺	10.62	10.10	8.16	Fe ²⁺	1.332	1.247	1.003
MgO	12.67	12.21	14.38	Mg	2.832	2.687	3.149
CaO	11.99	11.99	11.85	Mn	0.013	0.019	0.011
Na ₂ O	2.41	3.17	2.05	Ti	0.793	0.745	0.529
K ₂ O	1.66	0.68	2.35	Ca	1.927	1.897	1.866
MnO	0.10	0.15	0.09	Na	0.701	0.909	0.584
TiO ₂	7.03	6.71	4.79	K	0.318	0.128	0.440
SrO ²	0.15	0.12	0.02	Sr	0.013	0.010	0.002
Total	97.50	97.86	97.77				

m = microcryst X = xenocryst

undersaturated rocks. Fe/(Fe + Mg) is 0.19 to 0.21, with one analysis at 0.24. The annite-ferriannite solid solutions have been found in some specimens as late-crystallizing phases (Mokhtari *et al.*, 1985).

Fe-Ti oxides. Titanomagnetite is the common species in the camptonites. It is found in the groundmass or as inclusions in the silicate phases. Fig. 7 shows the compositions of the titanomagnetites in specimen G5 which shows ilmenite exsolution lamellae. An exsolution temperature calculated for this specimen (Ghiorso and Carmichael, 1979) gives 850 °C for log $fO_2 = -14$. Zn and Cr are the common trace elements in these oxide minerals. The alteration of magnetite, however, is so pervasive that no exhaustive study could be made. Altered olivines contain Cr-bearing spinels. Representative analyses are listed in Table 8.

Feldspars. Most specimens are altered and the presence of feldspar can only be suspected from

the low-temperature assemblage of zeolites that probably replaces them (and nepheline?). Feldspars were recognized and analysed in nine specimens. Specimen G5 shows the coexistence of an anorthite-rich plagioclase with K-rich alkali feldspar, whereas specimen Th1 shows the coexistence of andesine with an Na-K alkali feldspar (Fig. 8). Sodium-rich plagioclase is common in late feldspathic veins.

Olivines. Olivines have been found in five

TABLE 6 - ELECTRON MICROPROBE ANALYSIS OF Mg-HASTINGSITE

SiO ₂	38.13	Si	6.190
Al ₂ O ₃	12.56	Al ₂ ⁺	2.403
FeO	28.78	Fe ²⁺	3.907
MgO	2.03	Mg	0.491
MnO	1.52	Mn	0.209
TiO ₂	0.12	Ti	0.015
CaO	10.16	Ca	1.767
Na ₂ O	2.16	Na	0.680
K ₂ O	2.62	K	0.543
Total	98.08		

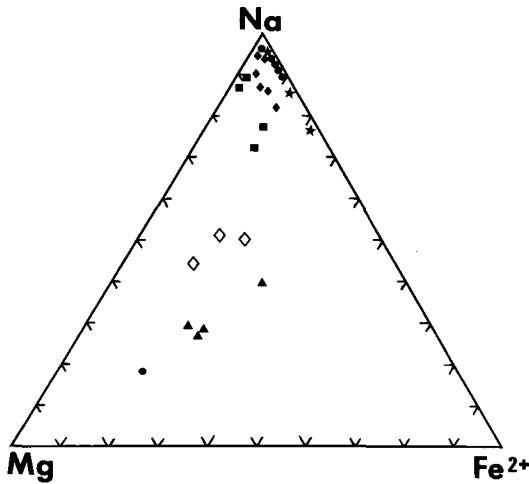


FIG. 6. Composition of late-crystallizing sodic clinopyroxenes from camptonites. Solid circles, EG6; solid diamonds, G4; solid stars, FD8; open diamonds, 76b; solid triangles, EG7; solid squares, EG15.

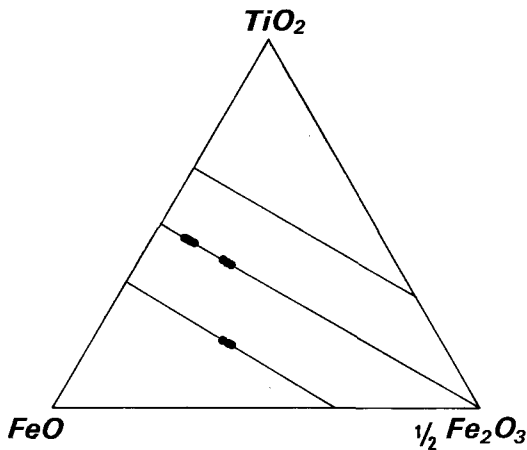


FIG. 7. Composition of coexisting magnetites and ilmenites from specimen EG5 in an FeO-Fe₂O₃-TiO₂ diagram. Mole %.

TABLE 7 - ELECTRON MICROPROBE ANALYSES OF TRIOCTAHEDRAL MICAS

	1 Th6 m	2 Th6 X	3 Th6 X	4 sl X	5 sl X
SiO ₂	35.57	37.53	35.72	34.77	37.89
Al ₂ O ₃	16.49	16.97	15.57	14.91	14.34
FeO ³	7.94	8.01	15.57	19.35	13.00
MgO	17.11	18.06	13.95	11.30	13.21
CaO	0.07				
Na ₂ O	0.74	0.66	0.70	0.56	0.47
K ₂ O	8.68	9.26	8.81	8.98	9.13
MnO	0.04	0.05	0.31	0.53	1.08
TiO ₂	8.23	6.44	5.19	4.80	1.30
BaO ²	1.52	0.52	0.78	0.71	0.36
Total	96.39	97.52	97.11	95.74	94.67
Si	5.156	5.321	5.315	5.348	5.676
Al	2.817	2.836	2.731	2.703	2.532
Fe	0.963	0.950	1.959	2.489	1.629
Mg	3.696	3.816	3.094	2.590	3.842
Ca	0.011				
Na	0.208	0.181	0.202	0.167	0.137
K	1.605	1.675	1.733	1.729	1.716
Mn	0.005	0.006	0.039	0.069	0.137
Ti	0.897	0.687	0.581	0.555	0.146
Ba	0.086	0.029	0.045	0.043	0.021

m = microcryst; X = xenocryst

specimens (K4, 8, Th3, Th6 and EG15). In specimen K4 the crystals are euhedral whereas in others they are anhedral, usually rounded and could, therefore, be xenocrysts. Analyses (Table 9) indicate that the olivines in specimen K4 have variable forsterite contents (Fo 81-85%) relative to crystals analysed in other samples. Their Ni content is also lower (NiO between 0.05 and 0.20) than recorded in other specimens (0.15 to 0.30).

In most specimens the crystals are partly or completely altered and the mineral site is now occupied by carbonates, serpentine or clays. In one specimen, however, olivine is replaced by an association of chlorite + garnet (Table 10). The composition of the two phases are very close to those determined by Coombs *et al.* (1977) for coexisting chlorite and andradite in an olivine pseudomorph from an epimetamorphic augite cumulate rock from New Zealand.

Accessory phases. Häuyné was observed in five specimens (76b, Th3, 13B7 and FD2) and is particularly abundant in specimen FD8. It had

TABLE 8 - ELECTRON MICROPROBE ANALYSES AND STRUCTURAL FORMULAE OF Fe-Ti OXIDES, AND SPINEL INCLUDED IN ALTERED OLIVINE.

	1 G5 Ilm	2 G5 Ma	3 EG11 Sp		1 Ilm	2 Ma	3 Sp
Al ₂ O ₃	0.12	5.89	14.61	Al ₃ ⁺	0.003	0.258	0.563
FeO ^{2,3}	38.15	66.76	51.15	Fe ₂ ³⁺	0.124	0.898	0.684
MgO	7.18	2.30	9.84	Fe ₂ ²⁺	0.640	1.177	0.715
MnO	1.96	3.22	0.39	Mg	0.256	0.127	0.480
TiO ₂	51.97	15.08	8.48	Mn	0.040	0.101	0.011
Cr ₂ O ₃	0.	0.03	12.96	Ti	0.936	0.422	0.209
ZnO ³	0.	0.56	0.11	Cr		0.001	0.335
Total	99.38	93.84	97.54	Zn		0.015	0.003

TABLE 9 - ELECTRON MICROPROBE ANALYSES OF OLIVINES

	1 Th6	2 K4	3 K4	4 EG15	5 Th3
SiO ₂	40.22	39.46	40.02	40.40	40.14
FeO	15.58	17.35	14.22	12.83	13.70
MgO	44.14	42.70	45.27	46.22	45.64
CaO	0.21	0.27	0.28	0.21	0.23
MnO	0.21	0.18	0.17	0.17	0.14
NiO	0.15	0.08	0.16	0.25	0.20
Total	100.51	100.04	100.12	100.08	100.05
Si	1.007	1.002	1.001	1.004	1.002
Fe	0.326	0.368	0.297	0.267	0.286
Mg	1.647	1.615	1.687	1.712	1.697
Ca	0.006	0.007	0.008	0.006	0.006
Mn	0.004	0.004	0.004	0.004	0.003
Ni	0.003	0.002	0.003	0.005	0.004

TABLE 10 - ELECTRON MICROPROBE ANALYSES OF CHLORITE AND GARNET IN AN OLIVINE PSEUDOMORPH (EG11)

	Ch1	Gt
SiO ₂	33.06	33.77
Al ₂ O ₃	14.84	0.67
FeO	14.47	
Fe ₂ O ₃		31.77
MnO	0.12	0.03
TiO ₂	0.07	1.47
NiO	0.10	nd
Total	86.66	96.52

TABLE 11 - ELECTRON MICROPROBE ANALYSES AND STRUCTURAL FORMULAE OF XENOCRYSTIC SPINELS

	1 FD4	2 K10	3 K10	4 FD4	5 FD4
Al ₂ O ₃	61.33	61.47	58.10	55.32	30.04
FeO	16.76	16.03	11.53	11.65	16.78
MgO	20.59	20.47	20.47	20.01	14.99
MnO	0.09	0.14	0.16	0.09	0.16
TiO ₂	0.54	0.53	0.06	0.06	0.04
Cr ₂ O ₃	0.32	0.44	8.77	12.43	37.60
Total	99.63	99.08	99.09	99.56	99.61
Al ₃₊	1.842	1.854	1.775	1.705	1.045
Fe ²⁺	0.131	0.117	0.043	0.035	0.076
Fe ³⁺	0.226	0.226	0.207	0.219	0.338
Mg	0.782	0.781	0.791	0.780	0.659
Mn	0.002	0.003	0.004	0.002	0.004
Ti	0.010	0.010	0.001	0.001	0.001
Cr	0.006	0.009	0.180	0.257	0.877

not been reported in the Taourirt rocks before. Perovskite is present in four specimens. When present it is abundant as small euhedral crystals showing no textural relationship with the titanomagnetite.

Xenocrysts in camptonites

Xenocrysts may resemble phenocrysts but are foreign to the body of rock in which they are found. The igneous rocks from Taourirt provide excellent material for examining various xenocrysts, indicating possible discriminants and evaluating the resulting contamination.

Spinels. Spinels are rare (one grain, uncommonly two, per thin section) and have been found in half

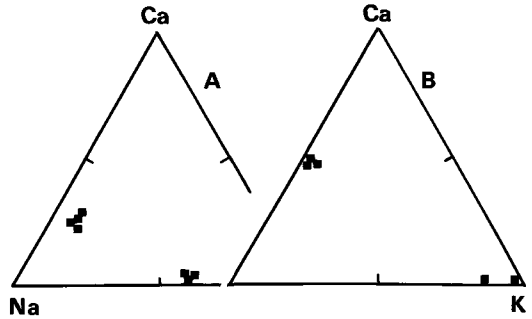


FIG. 8. Feldspar compositions from specimens Th1 (A) and G5 (B) in a Ca-Na-K diagram.

of the outcrops visited. Four different types of spinels are present in specimens FD4 and K10. The most common are grey crystals, usually reaching a 4 mm size (Fig. 9A and C). They sometimes contain sulphide inclusions and may be associated with phlogopite. Similar grains are also seen isolated in the groundmass. Analyses (Table 11, columns 1 and 2) show high Al and Mg contents. Another type, present as an isolated yellow crystal with fractures and concave faces in the groundmass (Fig. 9D and Table 11, analysis 3), is also Al- and Mg-rich but it contains 8.77% Cr. An orange crystal, enclosing altered olivine and Cr-bearing diopside, also shows an Al-rich, Mg-rich composition, with a slightly higher Cr content (Fig. 9B and Table 11, analysis 4). A completely altered peridotite fragment contains a red-brown Cr-rich spinel. Finally an orange spinel with inclusions of altered olivine and Cr-bearing diopside has been found (Table 11, analysis 5).

Specimen K4 contains three types of spinel: an aluminous spinel included in phlogopite; a Cr-bearing spinel found in clinopyroxene and numerous groundmass Cr-rich spinels (Cr₂O₃ around 35%) with oxidized, Ti-magnetite-rich rims.

The presence of various chemical types of large spinel crystals in the eruptive rocks is not compatible with the hypothesis that these spinels crystallized from the camptonite liquid, since the various compositions cannot all represent crystals in equilibrium with the same liquid, even at different moments of the crystallization sequence. It is our belief that all spinels found are indeed xenocrysts and originated in spinel-bearing rocks. In a recent study of ultrabasic rocks found as inclusions in recent basalts of the Middle Atlas of Morocco (Moukadiri, 1983) analyses are given for spinels found in various types of ultrabasites. The range of spinel compositions found is not very different from that found for isolated crystals within the

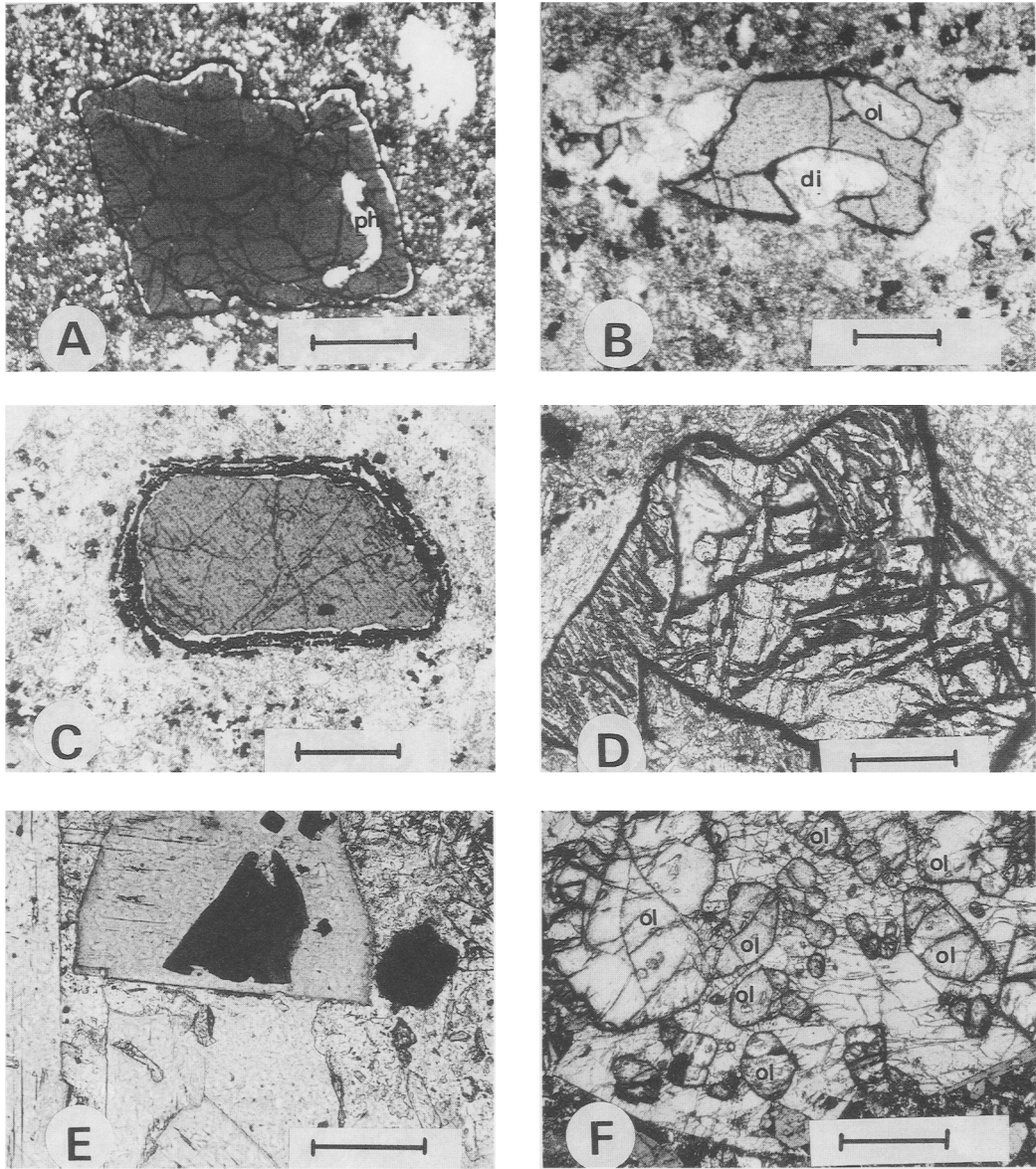


FIG. 9. Photographs of xenocrysts from various specimens of the Taourirt area. Plane polarized light. A. Aluminous spinel with phlogopite inclusion (ph) from specimen FD4. Length of bar, 1 mm. B. Aluminous spinel from specimen FD4 with inclusions of altered olivine (ol) and Cr-diopside (di). Length of bar, 0.2 mm. C. Aluminous spinel from specimen K10. Length of bar, 0.4 mm. D. Aluminous spinel from specimen K10. Length of bar, 0.05 mm. E. Rhönite inclusion in phlogopite, specimen FD2. Length of bar, 0.2 mm. F. Clinopyroxene with abundant inclusions of rounded and altered olivines (ol). Specimen I. Length of bar, 1.5 mm.

eruptive rocks of the Taourirt area (Fig. 10). The main difference is the existence in the ultrabasics of some very Cr-rich spinels, whose equivalents have not been found in the Taourirt rocks.

It is interesting to note that the spinels have not dissolved in the magma: their margins are usually sharp, but for a small oxide (Ti-magnetite) rim which isolates them from the groundmass (Fig.

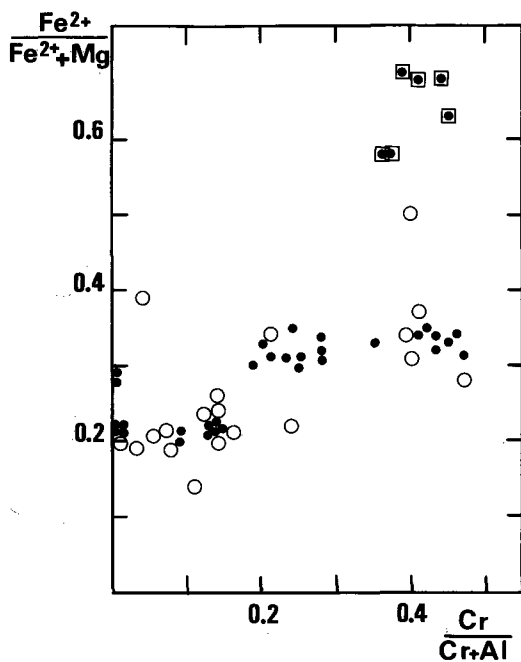


FIG. 10. Composition of spinels in terms of $\text{Cr}/(\text{Cr} + \text{Al})$ and $\text{Fe}^{2+}/(\text{Fe}^{2+} + \text{Mg})$. Formulae calculated on the basis of 32 oxygens and 24 cations. Solid circles, xenocrystic spinels found in various eruptive rocks from the Taourirt area. Open circles, spinel compositions determined in ultrabasics found in basalts from Middle Atlas area (Moukadiri, 1983).

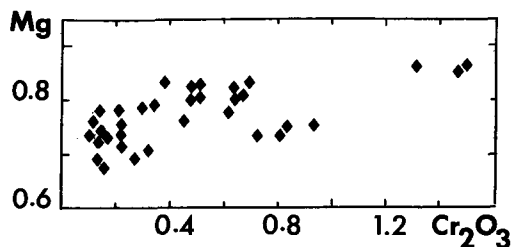


FIG. 11. Cr_2O_3 content of clinopyroxene xenocrysts as a function of their Mg content (formulae computed on the bases of 6 oxygens and 4 cations). Only clinopyroxenes with Cr_2O_3 contents above 0.1% are represented.

ical assemblage remains unaffected by the accidental inclusion of refractory aluminous phases.

Clinopyroxenes. Most xenocrystic clinopyroxenes show various and complex types of zoning. Representative analyses are listed in Table 12.

Cr-bearing diopsides, a variety of clinopyroxene, whose occurrence is restricted to peridotites, have been found in three specimens (I, K4 and FD4). The Cr_2O_3 contents vary between 0.6 and 1.45%. These diopsides have low Fe contents and plot in the diopside field in the pyroxene quadrilateral. They are often found with spinels. Either spinels are included in the clinopyroxene, or clinopyroxene is included in a large amoeboid spinel. One particular Cr-bearing diopside (Specimen I, $0.4\% < \text{Cr}_2\text{O}_3 < 0.7\%$) contains numerous rounded inclusions of an altered mineral considered to have been olivine and now replaced by an association of low-temperature phases (Fig. 9F). Similar associations have been described as xenocrysts in basalts (e.g. Berger, 1981, p. 386 and photographs 7 and 8 on plate II). Other Cr-rich clinopyroxene compositions may be found in the Taourirt camptonites. These occur as intermediate zones in complex pyroxenes and are best interpreted as having crystallized from the liquid after the accidental incorporation and partial dissolution of Cr-bearing spinels. This hypothesis was first mentioned by Berger (1984). Fig. 11 represents all clinopyroxenes with $\text{Cr}_2\text{O}_3 > 0.10$. Except for diopsides richest in Cr there is a large Mg variation for a given Cr_2O_3 content.

Green salites and ferrosalites occur. One specimen (13B8) contains a rounded inclusion of a coarse-grained association of green clinopyroxene, amphibole, rarer biotite and abundant apatite. In most parts of the inclusion, there has been partial fusion (with abundant crystallization of magnetite) of the hydrous minerals, biotite and amphibole. Apatite has not been affected and clinopyroxene remains for the most part unchanged. Clino-

TABLE 12 - ELECTRON MICROPROBE ANALYSES OF CLINOPYROXENE XENOCRYSTS

	1 Th2	2 FD4	3 13B8	4 I	5 EG15
SiO_2	51.17	54.49	50.41	49.85	47.01
Al_2O_3	0.80	2.91	3.53	6.16	9.27
FeO^{2+}	17.11	1.82	4.46	4.74	5.43
MgO	7.14	16.12	15.21	15.27	13.47
CaO	19.29	21.76	24.34	21.06	21.82
Na_2O	2.47	1.54	0.65	0.66	0.85
MnO	0.97	0.07	0.12	0.09	0.05
TiO_2	0.67	0.04	1.47	1.25	2.20
Cr_2O_3	0.02	1.49	0.15	0.69	0.00
Total	99.64	100.24	100.34	99.77	100.10
Si	1.971	1.963	1.839	1.825	1.721
Al	0.036	0.124	0.152	0.266	0.400
Fe^{3+}	0.167	0.013	0.131	0.041	0.098
Fe^{2+}	0.384	0.041	0.005	0.104	0.068
Mg	0.410	0.865	0.827	0.833	0.735
Ca	0.796	0.840	0.952	0.826	0.856
Na	0.184	0.108	0.046	0.047	0.060
Mn	0.032	0.002	0.004	0.003	0.002
Ti	0.019	0.001	0.040	0.034	0.061
Cr	0.001	0.042	0.004	0.020	

9C). Furthermore specimen FD4 is one of those in which the aluminum-poor ferriannite-rich micas have been found. Thus the bulk composition of the rock may be contaminated by a spinel component but the residual magmatic mineralogi-

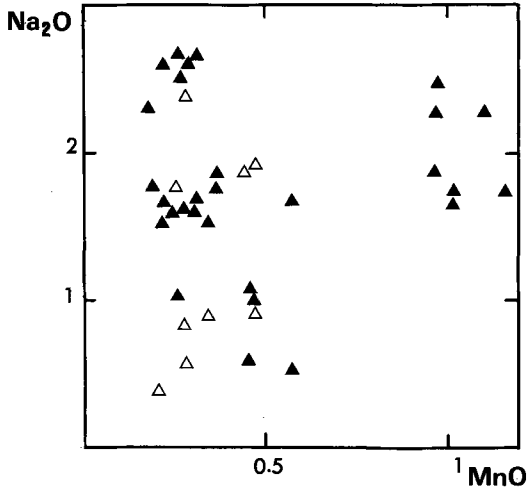


FIG. 12. Composition of clinopyroxene with FeO contents between 9 and 17% represented in terms of Na_2O and MnO contents. These clinopyroxenes are interpreted as xenocrysts. Solid triangles, clinopyroxenes from various rocks of the Taourirt area. Open triangles, clinopyroxenes from Uganda (Lloyd, 1981). Clinopyroxenes represented have $\text{MnO} > 0.17$ wt. %, and $\text{Na}_2\text{O} < 3.0$ wt. %.

pyroxene analyses from this inclusion have high Na_2O contents. Another inclusion in specimen Th2 contains green ferrosalite whose peculiarities are high Na_2O and unusually high MnO (Fig. 12).

The composition of the clinopyroxene xenocrysts differs considerably from the authigenic clinopyroxenes and the foreign origin may be easily established.

Trioctahedral micas. Three types of xenocrystic micas have been identified:

(1) Mn- and Fe-rich micas (specimen S1, Table 7, analysis 5) form green crystals, showing the crystallization of secondary magnetites in spaces with geometrical contours within the primordial crystal, as described by Brearley (1987) for thermally altered crystals. These micas are unusually Mn- and Fe-rich which precludes their origin as high-pressure phases crystallized from the magnesium-rich camptonite melt.

(2) Fe-rich biotites (Th6, S1, Table 7, analyses 3 and 4) may form the centres of crystals whose narrow outer rims have precipitated from the camptonite melt. This rim composition is identical with that of groundmass micas. The cores of these biotites are dark brown in colour and usually rounded with a conspicuous circular morphology. Often, though not systematically, they are decomposed with the appearance of magnetite

crystals, resembling the decomposition pattern reproduced experimentally by Brearley (1987).

(3) Phlogopites (Table 7, analysis 2) are conspicuous in thin section. Their general outline is made evident when a more intensely coloured outer zone occurs which is interpreted as having precipitated from the camptonite melt. The central part of the crystal commonly has a rounded appearance, interpreted as resulting from partial dissolution. The core differs from that of the surrounding zone in its Fe, Ba and to a lesser extent Ti content, the variations in composition being abrupt (Fig. 13). Their foreign origin is hence favoured though not proven.

Amphiboles. Xenocrystic kaersutites are present in both the phlogopite and the amphibole-bearing facies. They may be recognized by the large crystal size (commonly 1–2 mm in diameter) and the rounded morphology of the crystals. In the amphibole-bearing camptonites, the xenocrysts are surrounded by a zone whose composition is similar to that of the groundmass amphiboles. Exceptionally the amphibole may be surrounded by a polycrystalline rim of mica or a monocrystalline zone of clinopyroxene (specimens FD5 and K4 respectively).

The alkali content of the xenocrystic amphibole differs from that of the groundmass amphibole (Table 5): the K_2O content of the xenocrysts is always at least equal to and generally greater than the Na_2O content (Fig. 14).

Some phlogopite agglomerates with rhönite totally included in the mica are probably related to amphibole xenocrysts. Rhönite has only been found as large crystals within phlogopites (Fig. 9E). Its composition (SiO_2 23.15; Al_2O_3 17.52; FeO 18.44; MgO 14.25; CaO 12.97; Na_2O 0.74; MnO 0.19; TiO_2 = 10.75; Cr_2O_3 = 0.02; Total 98.03%) is similar to that of rhönite occurring in lavas, either as a rock forming mineral (e.g. Magonthier and Velde, 1976, although they appear to be more Mg-rich and Fe-poor than in basanites) or as reaction product appearing when amphibole is destabilized at low pressure. In one specimen, the association phlogopite (+ rhönite) + clinopyroxene has a regular outline, resembling a precursor amphibole crystal (see also Fig. 3, in Jeremine, 1948). This assemblage of phlogopite and rhönite consequently belongs among the xenocrystic phases, though its possible derivation from pre-existing amphibole can only be suspected.

Discussion

The Taourirt eruptive rocks contain evident xenocrystic material. The possible origin of these

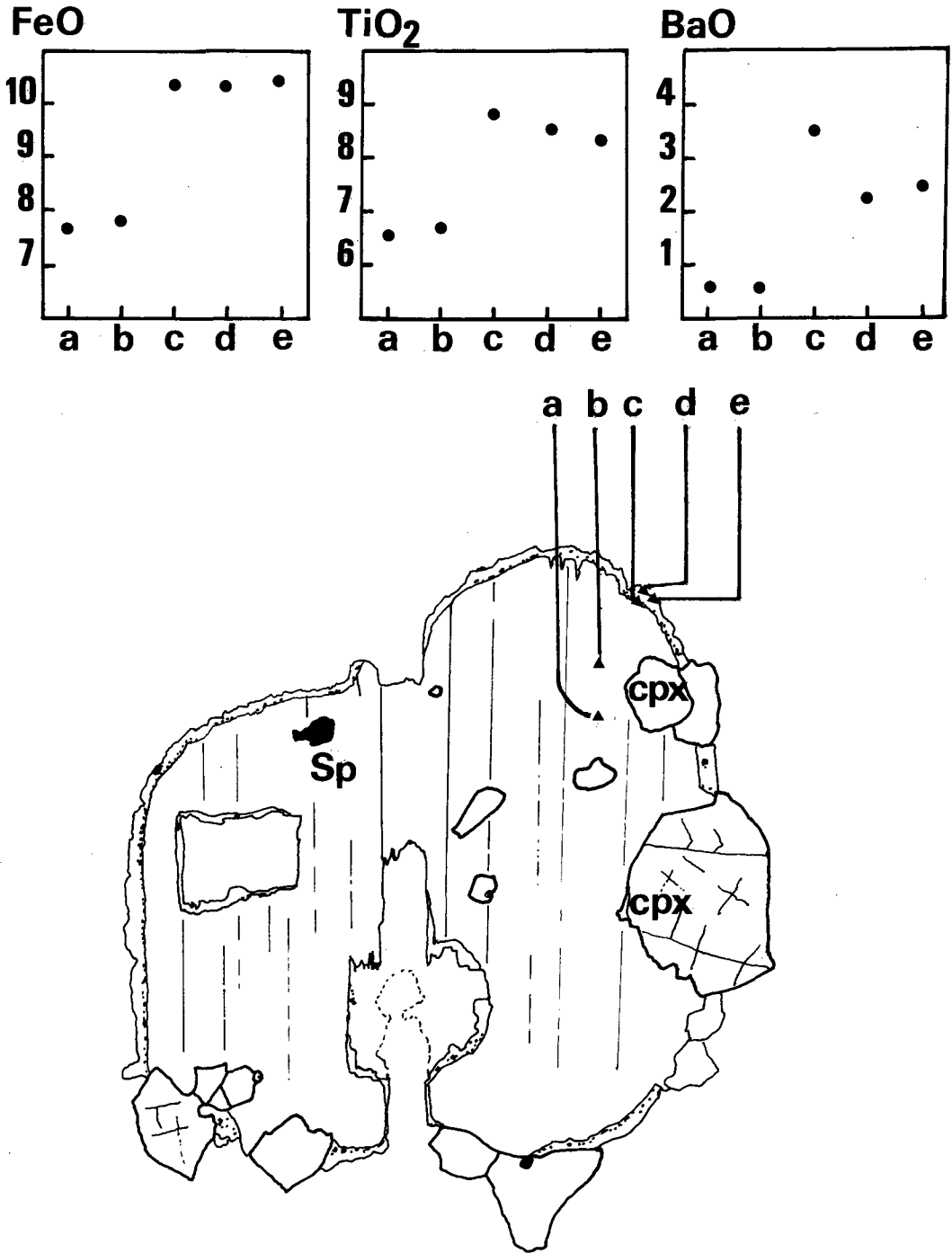


FIG. 13. Line drawing of a xenocrystic mica from specimen K4. The variations in composition between the central and overgrowth zones are represented for FeO, TiO₂ and BaO (wt. %).

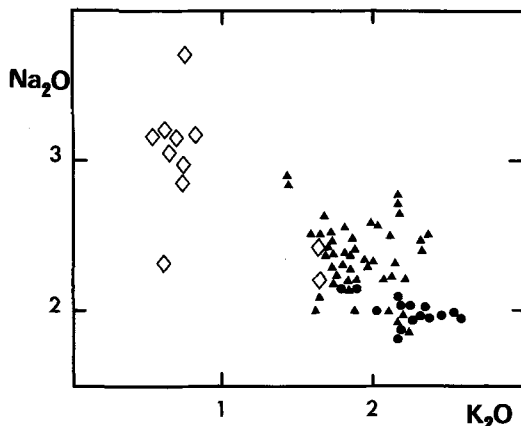


FIG. 14. Na₂O and K₂O contents of amphiboles from the Taourirt rocks. Excluded are amphiboles with FeO > 20%. Open diamonds, small amphibole crystals; solid triangles, large amphibole crystals; solid circles, crystals interpreted as xenocrysts.

xenocrysts should now be considered. Multiple mineral compositions (for example, spinels, clinopyroxenes or micas) within the same specimen indicate that the camptonite magma might have been contaminated at more than one level on its ascent to the surface. The mineralogical associations encountered are broadly similar to the mineralogical assemblages found in deep crustal or mantle magmatic bodies.

The similarity between the compositions of the spinels found by Moukadiri (1983) in ultrabasic inclusions from Tertiary basalts and those in the camptonites is striking (Fig. 10) and most of the Taourirt spinels may be interpreted as having originated in mantle peridotites similar to those sampled in Tertiary basalts whose outcrops are situated less than 200 km south and west of Taourirt.

The compositions of the clinopyroxenes are for the most part similar to those reported by Lloyd (1981, Fig. 9). Their origin has been sought in disaggregated mantle clinopyroxenites. The compositions of xenocrystic amphiboles in the camptonites resemble those of some of the kaersutite megacrysts reported by Dawson and Smith (1982). They are also similar to kaersutites described in amphibole-bearing clinopyroxenite inclusions from recent alkali basalts (Boivin, 1982). These amphibole-bearing ultrabasic rocks have been interpreted by these authors as resulting from the fragmentation of pre-existing amphibole-rich vein material within peridotites.

Mantle phlogopites from kimberlite xenoliths (e.g. Delaney *et al.*, 1980) are extremely Mg-rich

and different from those described above. The only trioctahedral micas to which our analyses may be compared have been reported in phlogopite-amphibole-bearing clinopyroxenite xenoliths found as inclusions in alkali basalts (e.g. Boivin, 1982).

The origin of the isolated crystals found may thus be sought in various types of ultramafic and ultrabasic rocks. Peridotites would be the source of the olivines and most spinels. Hornblendites and clinopyroxenites known to occur as veins and dykes in peridotites could be the source of clinopyroxenes, phlogopites and kaersutites. Such rock types are common inclusions found in basaltic lavas the world over, as well as in the recent volcanic province of Morocco. The unusual features of the Taourirt camptonites are the presence of these minerals as unaltered isolated crystals rather than nodules and the persistence of the less refractory of the phases, micas and amphiboles, which seldom survive their incorporation in basaltic lavas.

The influence of the xenocrysts on the chemical composition is difficult to estimate, but the transition elements may be used to make an evaluation. The highest Cr contents (Table 1) would correspond to 0.1 to 0.5% spinel inclusions, depending on the Cr content of the spinel (Table 11). The Ni contents recorded would be compatible with the incorporation of 10% olivine with 2000 ppm Ni, a common average value in peridotitic olivines. The modal composition of lherzolites varies between 67–84% olivine, 1–6% spinel, 8–18% orthopyroxene and 1–16% clinopyroxene (Berger, 1981, p. 176). The Cr and Ni concentrations mentioned above could then correspond to the incorporation of 10% peridotite in a basic melt with Ni and Cr initial concentrations close to the lowest ones recorded in Table 1. The assimilation of both diopside and orthopyroxene cannot be quantified.

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