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The Trace Element Geochemistry of Corsican Ophiolites*

L. Beccaluva[1], D. Ohnenstetter[2], M. Ohnenstetter[2], and G. Venturelli[3]
[1] Institute of Petrography, University of Parma, Italy
[2] Laboratoire de Pétrologie, CO 140, F-54037 Nancy Cédex, France
[3] Institute of Mineralogy, University of Parma, Italy

Abstract. Ultramafic rocks, gabbros, plagiogranites, dolerites and basaltic dikes and pillows lavas of the ophiolite slices of eastern Corsica have been metamorphosed in both oceanic and orogenic environments. The trace element content of the metabasaltic rocks which exhibit a tholeiitic differentiation trend towards a ferrobasaltic composition, is similar to that of oceanic basalts. The cumulate sequence is interpreted to have been formed by fractional crystallization from an olivine-tholeiite magma. The troctolites representing cumulates derived from melts representing liquid fractions in the range $F=1$–0.85, gabbros from melts with $F=0.85$–0.45, and ferrogabbros and plagiogranites from melts with $F<0.45$. An oceanic environment with moderate spreading rates and magmatic processes similar to present-day normal oceanic ridge segments is considered the more probable original setting of the Corsican ophiolites.

Geological Setting and Previous Work

In the Mediterranean area the ophiolites of Corsica form the most western fragment of the Tethyan ophiolitic belts. In north eastern Corsica, numerous ophiolite units are found as imbricated slices within the "Schistes lustrés" nappe (Durand Delga, 1974, 1975) to the east of the western shield (Maluski et al., 1973) (Fig. 1). As in the Apennines radiolarian cherts and limestones of Malm age cover the pillow lava sequence (Amaudric du Chaffaut et al., 1972).

Three main types of metamorphism have been recognized in the ophiolite sequence. The first metamorphism, compared to sub-sea floor metamorphism, produced hydrous minerals of the greenschist facies and involved migration of elements such as Ca, Mg and Na as well as high temperature metamorphism

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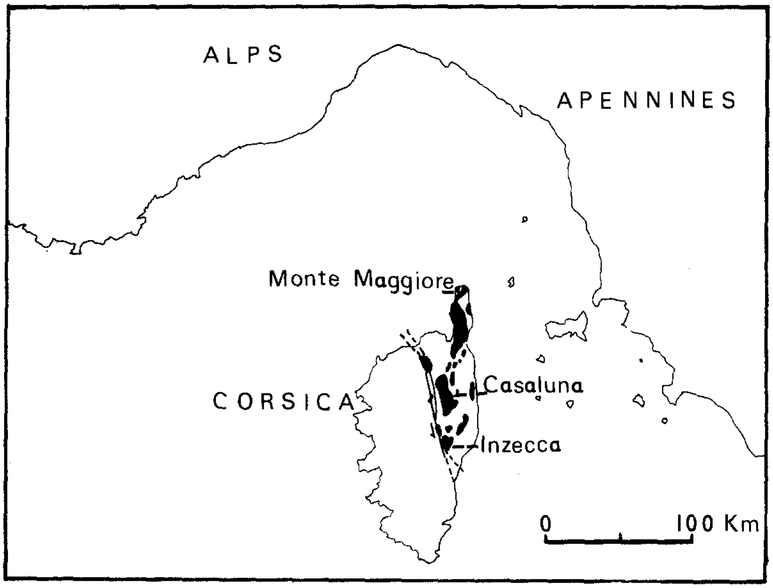

Fig. 1. Schematic map showing Corsican ophiolite outcrops (in black) in the Alpine-Apennine system

and deformation (amphibolite to granulite grade) of some gabbros and ultramafic rocks. The second metamorphic event of high pressure- low temperature type may be related to subduction processes possibly during an "eoalpine" (Upper Cretaceous) tectonism (Mattauer and Proust, 1976). Not every ophiolite fragment has been affected by all these metamorphic events which together have been only recognized in some outcrops (Ohnenstetter et al., 1976).

The ophiolite sequence reconstructed by Ohnenstetter and Ohnenstetter (1975) has been considered on the basis of petrographic and major element geochemical studies to be a remnant of Jurassic oceanic crust. From base to top these ophiolites are built up of 1) an ultramafic unit, 2) a mafic unit composed of troctolite, euphotide, ferrogabbro and acid residue, 3) hypabyssal rocks mainly massive dolerites and 4) pillow lavas with some dikes. The ultramafic rocks consist of poorly layered lherzolites, clinopyroxene-poor lherzolites and minor harzburgites and dunites with accessory aluminous phases (plagioclase and/or spinel). Alternating layers of dunites, often with squeletal olivine, anorthosites, and troctolites with accessory clinopyroxene and chromite form the base of the gabbroic sequence. The troctolites are overlain by poorly layered euphotide rocks, the most abundant type of gabbro, in which altered plagioclase and calcic augite are locally associated with transformed olivine. In some areas, euphotide rocks alternate with iron-rich gabbros (intermediate gabbros) in which branching clinopyroxene occurs. In the ferrogabbros cumulus magnetite, apatite and sulfides are well developed along with cumulus plagioclase, clinopyroxene and transformed accessory orthopyroxene and olivine. Albite-granites with albite as the main phase and lesser amounts of pyroxene and amphibole now converted to sodic pyroxene and sodic amphibole, quartz, zircon, magnetite, apatite and allanite, are locally abundant within the ferrogabbros and gabbros and the pillow lava units. Adcumulates, heteradcumulates and crescumulates (Wager et al., 1960; Wager and Brown, 1968) are important components of the cumulate sequences. Mesocumulates and orthocumulates are also locally well developped in the ferrogabbros and acid rocks. However no evidence for the existence of continuous magmatic currents is found. Massive dolerites have been previously considered as the chilled margins of a magmatic chamber (Bebien et al., 1975). They are overlain by pillow lavas which although mainly variolitic and aphyric are locally porphyritic. The effusive and hypabyssal rocks are olivine tholeiites. However the more differentiated dolerites fall in the quartz tholeiite field. The massive dolerites and dike rocks show a clear tholeiitic evolution with strong Fe and Ti enrichment and Si and Al decrease. The major element variation can be directly related to fractional crystallization reflected not only in the crystallization order in the cumulates and dolerites and the nature of phenocrysts in basaltic rocks, but also in the physical nature of the cumulates formed by diffusion in a supersaturated medium. The early stage of fractionation is characterized by olivine and plagioclase precipitation whereas the more advanced stage is marked by the formation of clinopyroxene and magnetite.

In this paper new data on the trace element content of the basaltic rocks and cumulates of the Corsican ophiolites is provided in support of the hypothesis that they formed by crystal fractionation within a magma chamber below a mid-ocean rift.

Analytical Methods

The trace element contents of 32 samples out of 87 rocks already analysed for major elements were determined by L. Beccaluva and G. Venturelli using atomic absorption (Perkin-Elmer 303) and X-ray fluorescence (Siemens Kristalloflex IV) with the following precision:

Atomic absorption: Sr 3%, Li 2%, Ni 3%, Co 4%, Cr 4%, Cu 4%, Zn 4%, V 4%.

X-ray fluorescence: Rb 5–15%, Nb 18%, Y 3–8%, Zr 3%.

Al_2O_3, Fe_2O_3 as total iron, MgO, CaO, K_2O and TiO_2 were obtained by X-ray fluorescence (Siemens SRS) by R. Montanari. SiO_2 and Na_2O were determined by atomic absorption (Perkin-Elmer 306) by Y. Perrin. P_2O_5 determinations by colourimetric methods were carried out by L. Beccaluva and G. Venturelli. Trace element values obtained on international standard rocks during the analyses of Corsican ophiolites are reported on appendix II. The data are reported on Tables 1 and 2. Localities and mineralogical composition of 4 massive dolerites, 5 pillows, 4 dikes, 6 peridotites, 10 gabbros and 3 plagiogranites are reported in Appendix 1.

Chemistry and Original Setting of Basaltic Rocks

Although fresh basalts from different tectonic settings show distinctive chemical features for some major and trace elements (Pearce and Cann, 1973) such an approach is difficult to apply when the rocks are chemically altered. It is well known that weathering, spilitization and metamorphism induce strong chemical mobilization, particularly of the alkali and alkaline-earth elements. Ophiolites, presumed to have formed in an oceanic environment, are often strongly altered and have undergone secondary element mobilization (Montigny et al., 1973; Allegre et al., 1973; Mevel, 1975; Ohnenstetter and Ohnenstetter, 1975; Pearce, 1975). In Corsica, basaltic rocks and cumulates, especially those

Table 1. Chemical data of volcanic and plutonic ophiolite rocks from Corsica, western Mediterranean area (oxidas as wt %, elements as ppm)

Basaltic rocks

Samples	Dykes				Dolerites				Pillow lavas				
	2093	596a	594	16911	2761	2763	7991	256112	2563	2295	2293	3084A	3087
SiO_2	49.03	52.82	49.86	54.54	48.35	48.00	50.00	48.31	52.51	50.95	49.16	49.41	51.47
TiO_2	1.13	1.93	2.41	2.55	1.13	1.32	2.33	3.03	1.61	1.70	1.37	1.69	1.61
Al_2O_3	16.06	13.83	14.11	12.87	16.32	16.26	14.73	13.56	18.14	15.55	17.28	13.41	15.08
Fe_2O_3tot	8.14	8.65	11.92	11.20	6.95	9.23	12.64	14.74	7.22	9.80	9.55	9.69	8.43
MnO	0.15	0.15	0.20	0.15	0.13	0.17	0.17	0.28	–	–	0.15	–	–
MgO	8.76	6.84	5.72	5.25	9.67	8.42	7.30	7.42	6.35	5.32	3.20	9.93	2.68
CaO	8.20	8.41	8.03	5.05	8.18	7.02	5.12	5.46	1.92	6.44	9.03	9.26	16.57
Na_2O	3.08	4.82	4.60	6.37	2.69	4.74	5.56	5.24	3.77	4.80	5.25	2.33	–
K_2O	1.25	0.03	0.02	0.15	1.22	0.05	0.01	0.20	4.27	1.26	0.42	0.05	<0.01
P_2O_5	0.10	0.20	0.20	0.36	0.11	0.13	0.24	0.30	0.13	0.14	0.17	0.19	0.19
L.I.^{a}	3.83	2.30	2.76	1.77	4.46	3.93	2.83	2.47	3.89	3.23	4.21	4.14	4.34
Total	99.76	99.98	99.83	100.26	99.21	99.27	100.92	101.01	99.81	99.19	99.79	100.10	100.18
Fe O*/MgO	0.84	1.14	1.88	1.92	0.65	0.98	1.56	1.79	1.02	1.69	2.69	0.89	2.83
Ni	160	93	79	50	170	137	39	41	120	153	95	134	85
Co	39	41	51	37	31	56	38	53	36	48	44	44	50
Cr	380	152	88	n.d.	231	30	n.d.	34	379	350	350	301	186
Cu	22	7	41	52	53	76	13	36	60	84	48	59	35
Zn	49	27	83	27	51	68	60	103	58	69	92	81	90
V	183	268	313	292	182	193	277	395	184	235	202	213	252
Sr	152	123	48	44	215	64	41	34	12	121	63	23	20
Li	7	9	11	6	18	15	13	19	16	32	24	19	4
Rb	24	8	6	<6	18	<6	<6	<6	–	36	16	8	<6
Nb^b	–	–	8	6	7	–	–	8	7	–	–	–	–
Zr	88	161	180	260	96	104	203	188	132	129	120	166	121
Y	36	62	68	85	40	36	67	50	40	54	49	48	37
88/Zr	1.00	0.55	0.49	0.34	0.92	0.85	0.43	0.47	0.67	0.68	0.73	0.53	0.73
Zr/Nb	–	–	22	43	14	–	–	–	24	19	–	–	–

of the upper units, have been affected by weathering and several metamorphisms and therefore tend to be spilitic. Some meta-basaltic pillows also show a K_2O enrichment, probably due to sea-water interaction. Such alteration is not found in the massive dolerites.

In this paper, Ti, P, Cr, Y, Nb, Zr are selected to characterize the magmas (Pearce and Cann, 1971, 1973; Pearce, 1975; Floyd and Winchester, 1975; Winchester and Floyd, 1976). A clear tholeiitic affinity appears in the P_2O_5-Zr and TiO_2-Zr/P_2O_5 diagrams of Figure 2 as well as by the high Y/Nb ratios. On the Ti-Zr-Y discrimination diagram (Fig. 3) all the samples fall in field B. The Ti-Zr diagram shows that most of the samples group in or near the ocean-floor basalt field (OFB) but that some iron-rich dolerites and dikes extend beyond the limits of this field at high Ti and Zr values (Fig. 4). The Ti-Cr

Table 1 (continued)

Samples	Troctolites				Gabbros			Ferrogabbros			Plagiogranites		
	11914	11912	11911	119151	12924	2096	1711	2383	2095	297131	2879	30731	23861A
SiO_2	45.62	39.58	47.65	49.50	48.81	48.61	49.60	40.31	46.34	54.00	79.45	68.91	60.48
TiO_2	0.07	0.05	0.09	0.20	0.30	0.92	0.27	4.78	5.01	1.44	0.15	0.19	0.79
Al_2O_3	19.40	9.65	23.35	18.88	17.00	15.47	14.50	12.90	11.27	14.15	12.08	16.52	16.99
Fe_2O_3tot	4.78	7.64	2.76	3.70	4.02	8.31	4.00	16.25	18.06	15.78	1.35	3.01	6.25
MnO	0.08	0.10	0.08	0.09	0.10	0.10	0.08	0.25	0.15	n.d.	n.d.	n.d.	0.06
MgO	13.40	26.14	5.53	10.35	9.29	8.02	12.25	10.27	5.51	2.76	0.10	2.17	1.49
CaO	9.86	5.12	12.00	12.68	13.55	10.87	13.42	3.96	8.86	2.22	0.01	0.03	1.84
Na_2O	2.18	0.40	3.04	2.60	2.57	3.83	3.24	5.34	3.53	8.02	6.59	7.84	11.28
K_2O	<0.01	<0.01	0.01	<0.01	<0.01	0.01	<0.01	<0.01	0.10	0.09	<0.01	<0.01	0.05
P_2O_5	<0.02	0.02	<0.02	0.03	<0.02	<0.02	0.02	0.04	0.13	0.40	0.05	0.02	0.15
L.I.[a]	4.40	11.17	3.19	1.29	4.39	3.42	3.20	4.64	1.57	1.36	0.54	1.28	0.65
Total	99.79	99.91	99.78	99.32	100.13	99.66	100.58	98.70	100.55	99.82	100.26	99.97	100.03
Fe O*/MgO	0.32	0.26	0.33	0.32	0.39	0.93	0.29	1.42	2.95	5.14	12.10	1.25	3.78
Ni	474	1130	254	283	153	167	217	76	64	110	–	63	22
Co	50	80	30	43	52	83	34	59	59	25	8	12	10
Cr	110	1100	490	1080	484	378	1260	45	–	–	–	–	–
Cu	48	119	35	63	211	73	17	54	57	18	22	71	10
Zn	29	36	20	30	26	51	20	130	97	208	17	25	65
V	26	28	33	77	100	174	135	507	558	49	–	37	–
Sr	147	70	176	109	71	236	108	19	99	37	–	10	27
Li	2	1	2	2	2	3	19	47	4	15	9	13	11
Rb	<6	<6	<6	–	<6	<6	<6	<6	<6	<6	<6	–	<6
Nb	–	–	<2	2	3	4	6	7	10	11	25	26	16
Zr	14	–	20	20	25	32	46	85	113	620	305	345	2200[c]
Y	<3	–	<3	3	10	12	24	49	41	170[c]	180[c]	370[c]	124
88/Zr	6.28		4.4	4.4	3.52	2.75	1.91	1.03	0.78	0.14	0.29	0.26	0.04

[a] loss on ignition

[b] only some relatively high values are reported

[c] approximate values

n.d. = not detected, – = not determined

diagram, which is useful in discriminating between OFB and island arc tholeiites (LKT), confirms the ocean-floor origin of the Corsican ophiolites. It is interesting to note, however, that some dolerite samples have an LKT affinity. This may be due to fractionation of small amounts of chromite bringing about a drop of Cr content for little change in the titanium content of the magma during the early differentiation stages (see also later). Use of the Ti-Cr diagram to discriminate OFB and LKT may lead therefore to an erroneous interpretation of the tectonic environment in which the basalts formed. Figure 4 also shows the field of ophiolite basalts from the Northern Apennines (Beccaluva et al., 1975, 1976; Ferrara et al., 1976). On all these diagrams, except for Ti-Zr-Y,

Table 2. Ultramafic rocks (oxides as wt%, elements as ppm)

	2591	2594	1398c	1398b	227152	29619
SiO_2	40.38	46.36	37.81	42.32	39.59	38.84
TiO_2	0.06	0.15	0.04	0.09	0.02	0.11
Al_2O_3	2.46	3.70	1.74	1.27	0.62	3.13
Fe_2O_3tot	7.55	6.16	9.92	8.55	9.94	8.54
MnO	0.12	0.10	0.10	0.10	0.09	0.10
MgO	34.53	26.00	43.10	42.85	35.80	32.20
CaO	2.70	9.40	0.47	0.98	0.01	4.86
Na_2O	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
K_2O	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
P_2O_5	<0.02	0.02	0.02	<0.02	0.02	0.02
L.I.[a]	11.49	7.85	5.83	2.01	13.20	11.78
total	99.29	99.72	99.01	98.17	99.26	99.56
FeO*/MgO	0.20	0.21	0.21	0.18	0.25	0.24
Ni	2040	1080	2400	2260	2450	2150
Co	100	62	129	123	118	90
Cr	2870	4100	5980	2090	3270	2960
Cu	15	17	19	29	11	29
Zn	–	39	67	60	50	58
V	72	95	44	61	n.d.	93
Sr	n.d.	7	n.d.	n.d.	n.d.	n.d.
Li	n.d.	4	2	n.d.	n.d.	3

[a] loss on ignition. n.d. = not detected, – = not determined

fractionation trends in dolerites and dikes are clearly demonstrated. Such processes should be considered (cf. Shibata and Fox, 1975) when attempting to correlate TiO_2 of basic volcanics to the spreading rate of the oceanic diverging plates. However, disregarding this effect, on the basis of Nisbet and Pearce's (1973) correlation Ti and the spreading rate, a moderate half-spreading rate about 2 cm/year is suggested for the accretion of the Corsican ophiolites (Ohnenstetter and Ohnenstetter, 1975). Similar values have been proposed for the Austrian Alps (Bickle and Pearce, 1975) and for the Northern Apennines (Beccaluva et al., 1975; Ferrara et al., 1976).

Zr/Nb ratios between 14 and 105 for the basalts are comparable to those of normal Mid Oceanic Ridge basalts (Table 3). The difference in Nb values, independant of shallow depth fractionation (Erlank and Kable, 1976) between the Apennine and Corsican basalts (Beccaluva et al., 1976) may reflect different degrees of depletion of the mantle source. However in terms of the chemical characterization of oceanic ridge basalts of Hart et al. (1973), Schilling (1973, 1975), and Bryan et al. (1976) both the Corsican and Apennine basalts seem to belong to "a normal ridge segment". The very flat REE pattern (Allegre et al., 1976; Noiret and Allegre, 1976) of some Inzecca samples, Corsica, agrees with this assumption.

Pronounced chemical differences also occur between western and eastern Mediterranean ophiolites e.g. Corsica and Apennines, versus Troodos, respec-

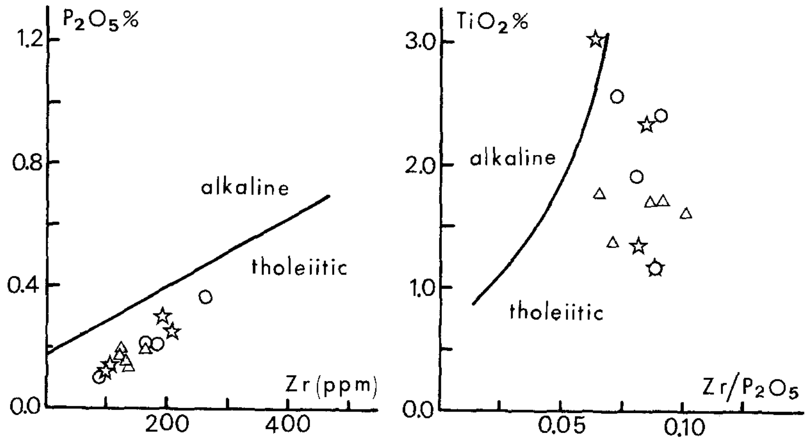

Fig. 2. P_2O_5%-Zr and TiO_2%-Zr/P_2O_5 diagrams (Floyd and Winchester, 1975; Winchester and Floyd, 1976) illustrating the difference between tholeitic and alkaline basic rocks. Corsican ophiolite basaltic rocks: *1* Dolerites; *2* Dikes; *3* Pillow lavas

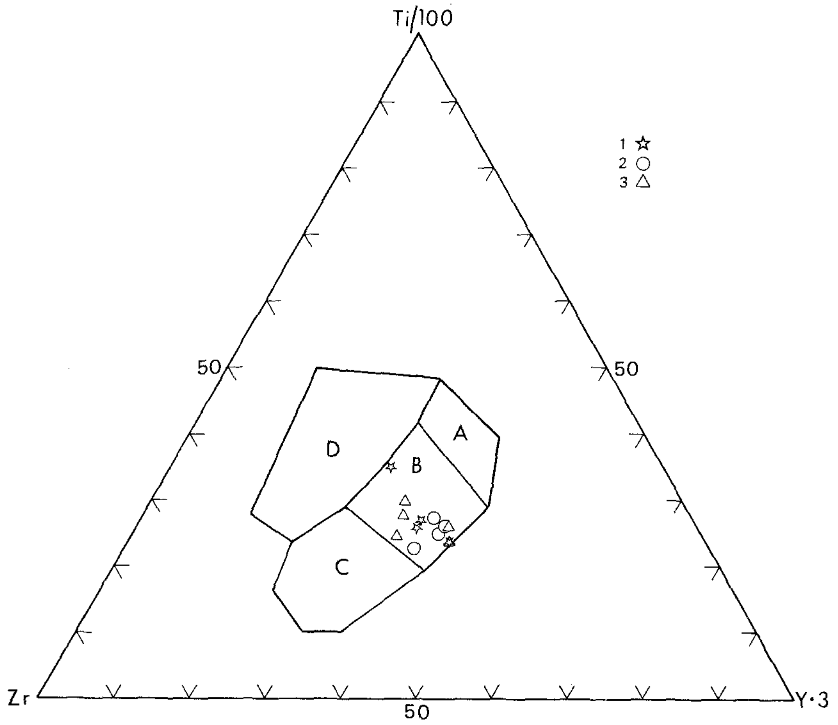

Fig. 3. Ti-Zr-Y discrimination diagram for basic volcanic rocks (Pearce and Cann, 1973). "Within plate" basalts plot in field *D*, ocean floor basalts in field *B*, low potassium tholeiites in fields *A*, and *B*, calc-alkali basalts in fields *C* and *B* Corsican ophiolite basaltic rocks: *1* Dolerites; *2* Dikes; *3* Pillow lavas

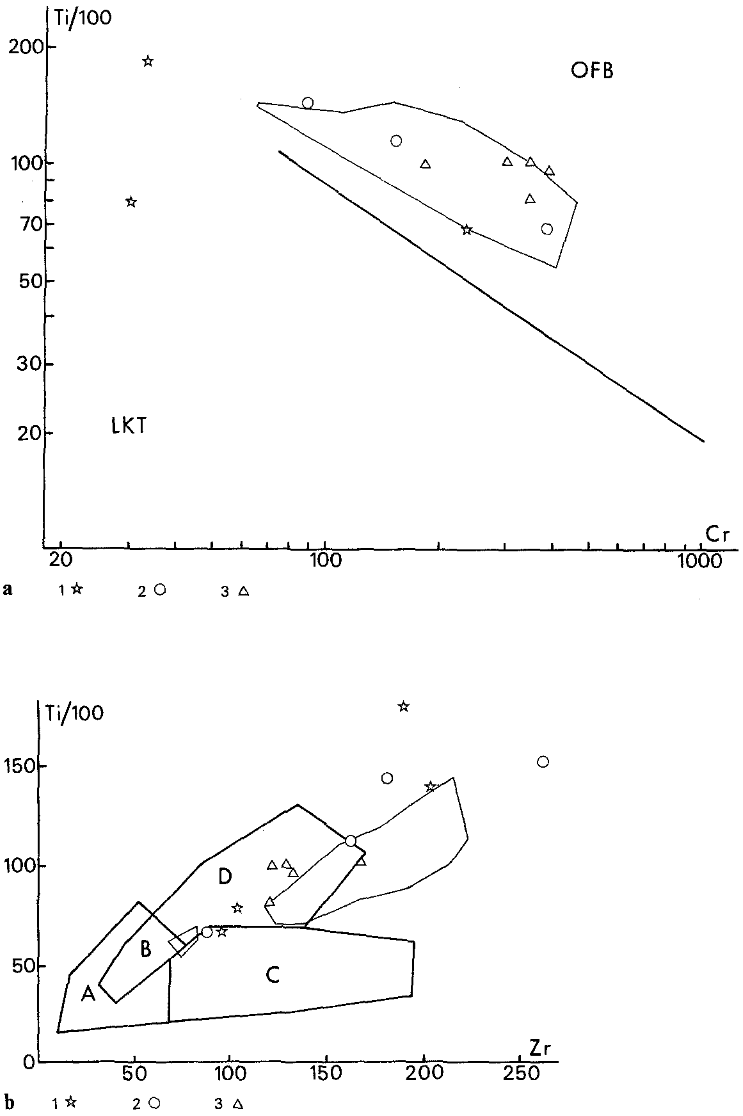

Fig. 4a and b. Ti-Zr discrimination diagram (Pearce and Cann, 1973). Ocean-floor basalts plot in fields *D* and *B*, low-potassium tholeiites in fields *A* and calc-alkali basalts in fields *C* and *B*. Ti-Cr discrimination diagram (Pearce, 1975). *OFB* ocean-floor basalts; *LKT* island-arc tholeiites. Corsican ophiolite basaltic rocks: *1* Dolerites; *2* Dikes; *3* Pillow lavas. Distribution fields (light line) of basalts from Apennine ophiolites are also reported (data after Beccaluva et al., 1975, 1976; Ferrara et al., 1976).

Table 3. Average chemical composition of some Mediterranean ophiolitic lavas, Mid-Atlantic ridge basalts, and island arc volcanics

	1	2	3	4	5	6
SiO_2	50.06	48.74	54.18	53.22	49.21	51.42
TiO_2	1.44	1.60	0.58	0.69	1.39	0.81
Al_2O_3	15.14	15.97	14.84	14.47	15.81	17.97
FeO Tot	8.25	8.69	8.48	7.94	9.11	9.88
MnO	0.16	0.17	0.14	0.12	0.16	–
MgO	7.12	7.21	5.59	5.88	8.53	4.89
CaO	8.16	8.17	5.34	7.69	11.14	8.90
Na_2O	4.02	4.48	4.11	2.62	2.71	2.94
K_2O	0.50	0.39	0.61	0.76	0.26	0.26
P_2O_5	0.19	0.24	–	–	–	0.09
Ni	104	110	38	47	123	23
Co	44	43	50	54	–	28
Cr	216	256	43	106	296	43
Cu	45	68	76	72	87	94
Zn	66	92	–	–	–	–
V	245	231	288	286	289	297
Sr	74	218	84	118	123	131
Li	15	16	–	–	8	–
Rb	9	8	–	8	–	2.3
Nb	7	5	–	1	–	–
Zr	150	155	–	66	100	37
Y	52	47	–	26	43	23

1 = Corsican basaltic rocks (Ohnenstetter and Ohnenstetter, 1975; and this work.)
2 = Northern Apennine basalts (Beccaluva et al., 1975, 1976; and Ferrara et al., 1976.)
3 = Pillow lavas, flows and dykes from Troodos Basal Group (Desmet, 1977.)
4 = Lower pillow lavas and sheeted dikes and sills of the Troodos (Desmet, 1977; Y, Nb, Zr and Rb data after Pearce, 1975 and Beccaluva and Venturelli, unpublished data.)
5 = Average Mid-Atlantic ridge basalt (Thompson, 1973.)
6 = Basalts and andesites from Eua, Tonga Islands (Ewart and Bryan, 1972.)

tively (Table 3). Metabasalts (Q tholeiites) from the lower pillow lava unit and sheeted complex of Troodos – the so-called axis sequence (Smewing et al., 1975) – show lower Ti, Zr, Nb, Y, Cr and Ni contents (Pearce, 1975; Kay and Senechal, 1976; Desmet, 1977) than Corsican and Apennine basaltic rocks. Stronger differences, except for Cr, exist between the Troodos upper pillow lavas and the basaltic rocks of Corsica and the Apennines. Thus, important geochemical differences clearly exist between western and eastern Mediterranean ophiolites, the eastern ophiolites appearing to be more calk-alkaline (Miyashiro, 1973; Thayer, 1973; Bebien et al., 1975; Rocci et al., 1975; Paupy, 1976). The differences in geochemical characters are too marked to assign the same origin to the two groups of ophiolites. On the basis of geochemical and petrographic data, it appears that the Troodos ophiolite has a closer affinity with the low-K tholeiites of immature island arcs e.g. Eua (Ewart and Bryan, 1972) than with typical ocean floor basalts (Table 3). The nature of these "calk-alkaline" ophiolites raises the problem of their genesis (Ohnenstetter and Ohnenstetter, 1975;

Rocci et al., 1975; Cann, 1976). Similarly in the Appalachian province such a diversity exists between the ophiolites of the Internal and External domains (Church, 1977; Church and Riccio, 1977).

Evolutionary Paths of Magmatic Liquids and Cumulate Products

1. Choice of Parameters and Variation Diagrams

The chemical variations of basaltic rocks in Corsica ophiolites are considered to be the result of fractional crystallization, on the basis of petrographic considerations and chemical differentiation indexes. Parameters, such FeO total/MgO, although slightly sensible to alteration are nevertheless often inadequate in evaluation of the amount of residual liquid. Thus in the following estimation immobile elements such P, Zr, Ti, and Y which strongly increase during the differentiation are used (Fig. 5). The P_2O_5-Zr pair shows the highest increase and the most significant correlation coefficient (0.93) with a regression line passing near the origin. This trend indicate that Zr and P have a residual character (solid/liquid mean partition coefficient $\bar{D}^{Zr}$ and $\bar{D}^{P} \ll 1$) during fractional crystallization (Treuil, 1973; Treuil and Joron, 1975).

An evaluation of the liquid fraction F at a defined differentiation stage is given by the ratio C^A/C_1^A: initial concentration in the original magma versus concentration in the liquid of the residual element A (Rayleigh model). In determining a value for different basalt samples (dolerites and dikes), the concentration of Zr is used because of its better analytical precision besides a residual character. The value obtained is only approximate, not only because of the limits of the theoritical assumptions, the possible occurence of trapped liquid in the comagmatic cumulates, the difficulty of estimating the initial content of Zr in the primary liquid, and analytical error, but also because of other factors such as metamorphic mobilization of the element, the presence of Zr-bearing cumulus phases, liquid inhomogeneity, etc...

The initial Zr content of the primary basaltic magma was estimated on the basis of the distribution of Ni and Cr which are strongly incorporated in the early crystallizing minerals. In Ni+Cr versus Zr diagram (Fig. 6), dolerites and dikes which define two different trends, show a strong variation of Cr+Ni at low Zr values. At this early differentiation stages, the lowest Zr values (88 ppm) approach the least differentiated composition and is chosen to calculate F. This value which in any case must be considered an excess estimation, is similar to those of relatively undifferentiated oceanic basalts from different areas (Cann, 1970). The least differentiated dolerites (sample 2761) and dikes (sample 2093) show the following compositional ranges: MgO 8.8–9.7, Fe_2O_3 tot. 8.1–7.0, Al_2O_3 16.1–16.3, TiO_2 1.1, P_2O_5 0.10–0.11%, Y 36–40, Zr 88–96, V 180, Ni 160–170, Cr 380–231, Co 39–31 ppm, FeO/MgO 0.84–0.65.

2. Mineralogical Control on Differentiation

In Figure 7, variations of some major and minor elements which give good indications of differentiation processes are plotted varsus 88/Zr ratio. Alkali

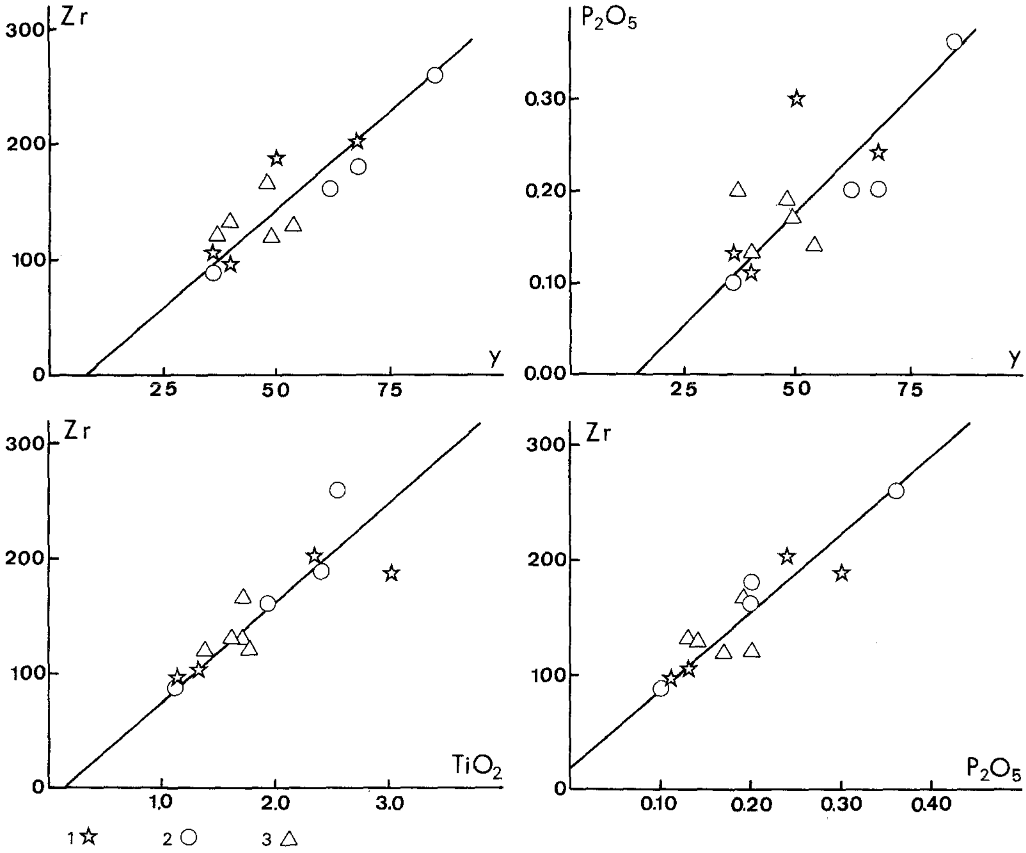

Fig. 5. Binary diagrams of 'immobile' element pairs, illustrating the strong increase exhibited by Corsican basaltic rocks during differentiation: *1* Dolerites; *2* Dikes; *3* Pillow lavas

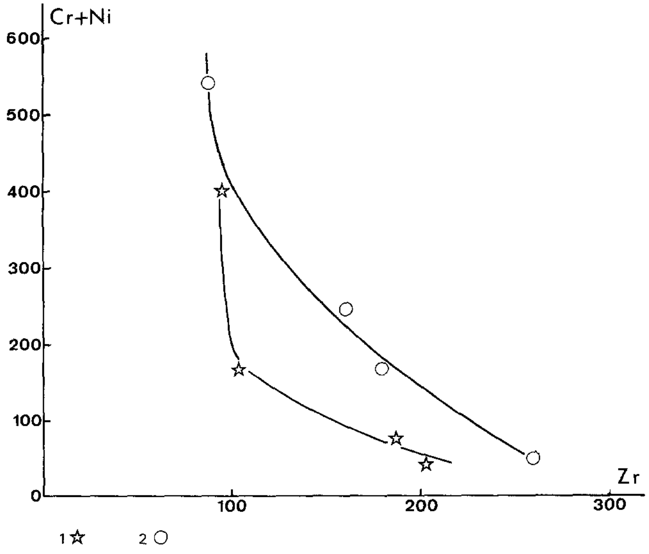

Fig. 6. Zr – Cr + Ni diagram. Evolutionary trends of dolerite. (*1*) and dike (*2*) basaltic rocks from Corsican ophiolites

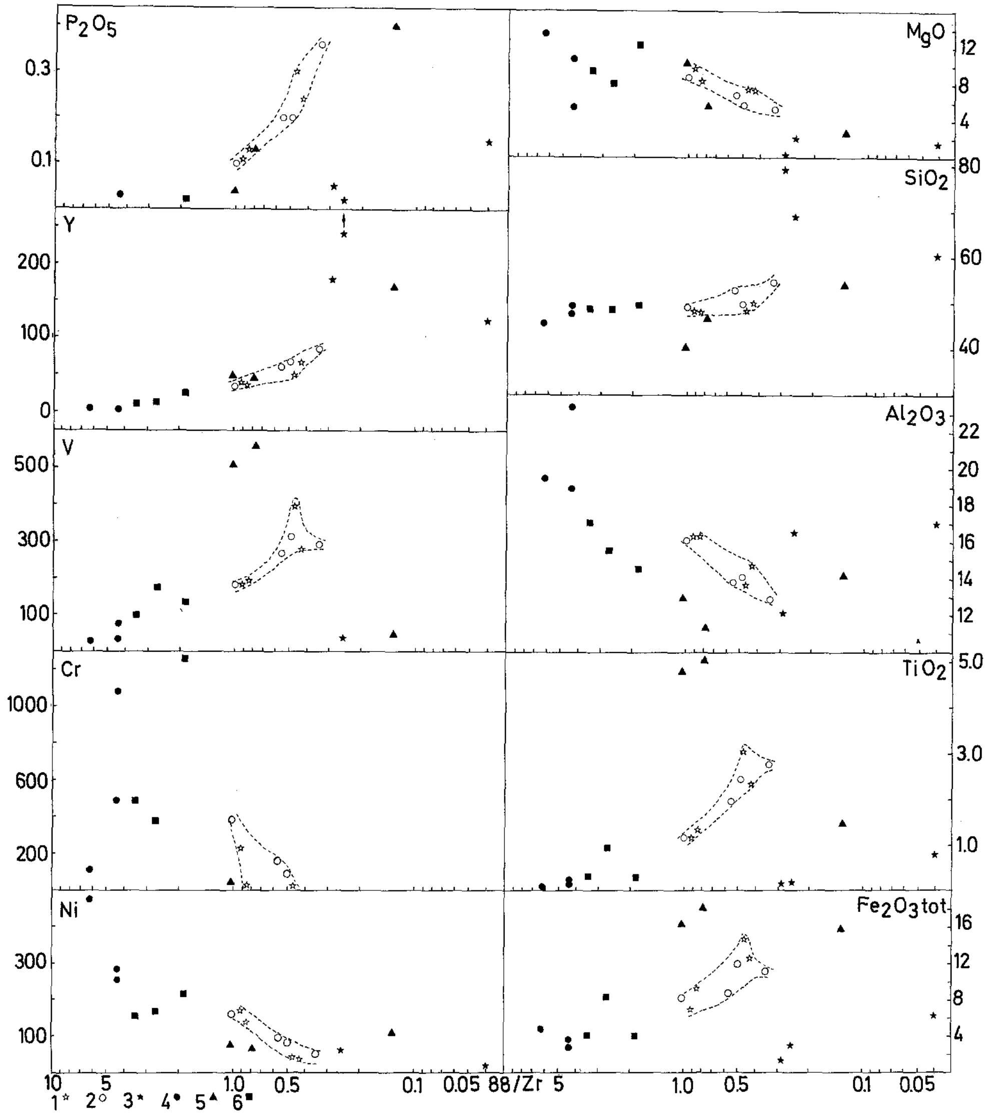

Fig. 7. Variations of some major and trace elements vs. 88/Zr ratio for Corsican ophiolites: *1* Dolerites; *2* Dikes; *3* Plagiogranites; *4* Troctolites; *5* Ferrogabbros; *6* Gabbros. Evolutionary trends of basaltic liquids (dolerites and dikes) are limited by dashed lines

and alkaline-earths which show wide dispersion are not reported. Sr, despite alteration, however seems to decrease in a regular way during the differentiation. Besides the dolerites and dikes, the basic cumulates, composed of troctolites, euphotides, ferrogabbros and plagiogranites are plotted because these rocks are thought to be partly responsible for the variation in composition of the basaltic rocks as may also be the case of Morb basalts (Melson and Thompson, 1970; Miyashiro et al., 1970; Bonatti et al., 1971; Shido et al., 1971; Thompson, 1973). The lavas are excluded because of their high degree of alteration.

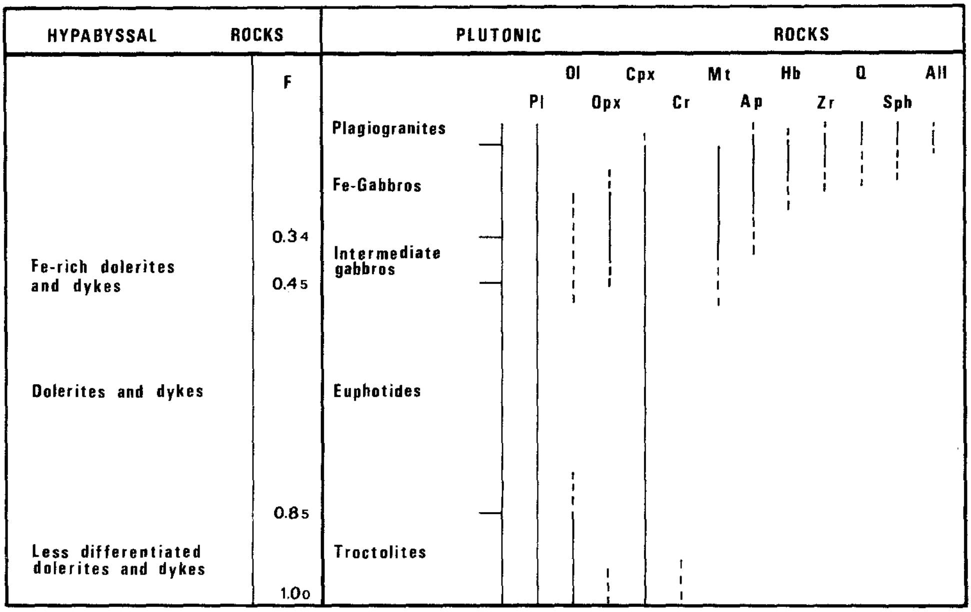

Fig. 8. Generalized section of Corsican plutonic mafic units showing the appearance and the disappearance of the main magmatic minerals: *Pl* plagioclase; *Ol* olivine; *Opx* orthopyroxene; *Cpx* clinopyroxene; *Cr* chromite; *Mt* magnetite; *Ap* apatite; *Hb* hornblende; *Zr* zircon; *Q* quartz; *Sph* titanite; *All* allanite. The corresponding fractionation stages of the basaltic liquid fractions (*F*) are shown on the left side of the diagram along with the relative rock types

The cumulates whose succession and mineralogy are reported in Figure 8 do not correspond to magmas represented by the basaltic effusive since they result from an average of cumulus phases with variable amount of pore material (trapped liquid). The 88/Zr may only serve to evaluate the proportion of this trapped liquid. Its value approaches infinity for rocks made entirely of cumulus minerals. If the magmatic relations between differentiation trends of the basaltic rocks and the cumulates are considered, it is apparent that the distribution of major and minor elements in basaltic rocks define two main discontinuities separating three stages of differentiation.

The early stages of basaltic liquid differentiation: $F = 1$–0.85, if referred to dolerites, are characterized by a rapid fall of Ni and Cr which enter the early crystallizing mafic minerals, in particular the Cr content falls abruptly in dolerites. At this stage Al_2O_3 and MgO also decrease whereas SiO_2 is almost constant and all the other elements increase. The variation can be interpreted to result from the removal of plagioclase, olivine and Cr-spinel (troctolites) all of which occur as phenocrysts in the least differentiated rocks. Assuming that the troctolites formed from a magma with Zr content near 88 ppm, the high 88/Zr ratio together with the low content of other residual elements such Y, P and Ti of these cumulates suggest low amounts of trapped liquids (not more than 15–25%) in agreement with the adcumulate, mesocumulate and crescumulate growth structures shown by these rocks.

During the middle stage of differentiation: $F=0.85$–0.45 a typical tholeiite trend towards a ferrobasaltic composition is shown by the regular increase in Ti, Fe, V, Zn, Y, P, FeO total/MgO and Zr in the liquids and the decrease in Al, Mg, Ni and Cr. Removal of plagioclase, clinopyroxene and minor olivine, leaving gabbroic cumulates: olivine gabbros and euphotides, may yield such iron rich liquids. Similarly in normal ridge basalts, removal of plagioclase and olivine (Kay et al., 1970; Cann, 1971; Thompson et al., 1972; Bence et al., 1975) as well as clinopyroxene (in spite of the fact that phenocrysts of this mineral are scarce or completely lacking in oceanic tholeiites except in ferrobasalts (Mazzulo and Bence, 1976) has been used to explain such a trend (Miyashiro et al., 1970; Shido et al., 1971; Ayuso et al., 1976; Bryan et al., 1976; Byerly et al., 1976; Clague and Bunch, 1976; Schilling et al., 1976; Shibata, 1976). In Corsica, petrographic evidence show that clinopyroxene is always present as an accessory heteradcumulus phase in troctolite, olivine gabbro, and even more importantly in euphotide. It occurs only as liquidus phase in the late stages of differentiation when it is present as a phenocryst phase in ferrobasaltic rocks. Thus element diffusion between intercumulus liquid and the overlying magma (Hodges and Papike, 1976) may have operated. In this manner the presence of clinopyroxene in gabbros and its absence in the corresponding basaltic rocks during the early and middle stages may be explained. However, the decrease of the 88/Zr ratio in the euphotide gabbros does not necessarily mean a contemporaneous increase of pore materiel since the cumulate textures testify that elimination, to a greater or lesser extent, of the original intercumulus liquid has taken place, but may be only, or also, due to the increase of the zirconium content in the trapped liquid during the differentiation.

At advanced stages of differentiation: $F<0.45$ a decrease of Ti, Fe, V and Zn in the basaltic liquids is apparent in both dolerite and dike rocks. The decrease in concentration of these elements may be related to the removal of titaniferous magnetite and possibly minor sulfides as cumulus phases, leading to ferrogabbroic cumulates which are obviously enriched in the same elements. Orthopyroxene precipitation in such cumulates may indicate silica saturation (O'Hara, 1968). Finally, it must be noted that dolerite and dike samples showing a decrease in P and Zr have not been found. It may therefore be concluded that apatite and zircon, which appear in some ferrogabbros, are removed in appreciable amounts only from the most differentiated magmas: at least $F<0.35$ and that, apatite- and zircon-bearing ferrogabbros and the more evolved cumulates are formed from liquids not represented amongst the dolerite, dike and pillow lava units of the sequence. Sample 297131 low in V and Ti and high in Si, Na, Y and P may correspond to an intermediate fractionation stage between ferrogabbroic composition and more acid residues.

The fractionation products of the latest magmatic stages are represented by albitegranites composed of Na-rich plagioclase, clinopyroxene and/or amphibole, Fe-Ti oxides, zircon, apatite, titanite, allanite and Quartz (Table 1). Petrographic observations suggest that the albitegranites represent cumulus solid fractions with variable amounts of trapped liquid (ortho- to mesocumulates). The very low content of the residual elements K and Rb may be related to the lacking of K-feldspar and biotite as well as to secondary mobilization.

The Sr content in these albitegranites are lower than those reported by Coleman and Peterman (1975). In Corsica potassic-rich rocks representing an ultimate residual liquid have yet to be found. In oceanic environment such rocks are very scarce having been reported only from the Indian ocean in the form of a quartz-monzonitic dikelet with K-feldspar and biotite (Engel and Fisher, 1975).

Conclusion

The repartition of trace elements in basaltic rocks of Corsican ophiolites confirms their ocean-floor character. Their tholeiitic trend of differentiation is marked by a strong increase in Fe, Ti, V, Zr, Y, P, Zn and decrease in Mg, Al, Ni, Cr. The mineral phases which control the fractional crystallization are the same as those found in the underlying gabbroic sequence. The troctolitic rocks crystallized from magma with an F value in the range 1–0.85, euphotide from magma with an F value of 0.85–0.45, and intermediate gabbros, ferrogabbros and albitegranites from magma with an F value of less than 0.45. The petrographic and geochemical features of the ophiolites indicate that accretion occured during Jurassic time (Ohnenstetter et al., 1977) in the western Mediterranean area according to magmatic processes similar to those thought to be active in present-day normal mid-oceanic ridge segments. The abundance of gabbroic adcumulates in Corsica (Ohnenstetter et al., 1975) and in the Atlantic Ocean (Hodges and Papike, 1976) coupled with their low content of residual elements is compatible with a slow cooling of successive magma batches under a high geothermal gradient. Beneath mid-oceanic ridges, olivine-tholeiite produced or reequilibrated at pressures of 5–10 kb (Green and Ringwood, 1967; O'Hara, 1968) evolve towards liquids of ferrobasaltic composition.

In Corsica, the presence of ultramafics with cumulus textures raises the problem of the existence and significance of 'peridotite' fractionation. Such lherzolites, equilibrated at pressures of 7–9 kb (spinel-plagioclase transition) may have separated from a more primitive olivine-rich picritic liquid (O'Hara, 1968) derived from a deeper zone e.g. the low velocity zone. According to this assumption, the abyssal tholeiites reach the surface after polybaric fractionation, leaving peridotite with a lherzolitic character located between gabbros constituing layer 3 and the upper part of the underlying mantle of the oceanic lithosphere.

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Appendix 1: List of Samples

Pillow Lavas

They are issue from the Inzecca massif. Primary minerals are transformed into a greenschist assemblage. But high pressure minerals may be locally present.

30.8.4A. Col de Grata. Variolitic pillow with large varioles (1 cm), vacuoles (0.1 mm). ab, q, chl, epi, pum, act.

25.6.3. Défilé de l'Inzecca. Brecciated variolitic pillow with transformed olivine microphenocrysts (lantern like form) in a recrystallized fine groundmass. ab, q, chl, ser, pum, hem.

22.9.5. Fatachio. aphanitic pillow. aug, chl, ab, q, epi, lw, pum, tit, ser.

22.9.3. Fatachio. Porphyritic pillow with plagioclase phenocrysts. ab, q, epi, lw, pum, chl, tit.

30.8.7. Col du Cardo. Hematitic pillow with plagioclase phenocrysts and squelettic transformed olivine microphenocrysts and hollow plagioclase microlites in a recrystallized glass.

Dykes

They cut the upper gabbros (euphotide, intermediate gabbro). No magmatic mineral has been preserved. Assemblages are characteristic of a greenschist facies with occurrence of pumpellyite; sodic amphiboles are locally present.

20.9.3. Monte Piano Maggiore. Intersertal texture. act, chl, ab, q, tit.

5.9.6.A Monte Piano Maggiore. Sub-ophitic texture with plagioclase phenocrysts. act, chl, tit, ab, q, pum.

5.9.4. Inzecca massif. Sub-ophitic to intersertal texture with plagioclase phenocrysts. act, ab, epi, pum, q, hem, tit, chl, ser.

16.9.11. Monte Piano Maggiore. Sub-ophitic to intersertal texture with plagioclase and magnetite phenocrysts, numerous squelettic Fe-Ti oxides in the groundmass. act, ab, tit, epi, pum, q, ser.

Dolerites

Inzecca massif. They intrude the pillow lava carapace. The following magmatic mineral proportion is only a broad estimation due to alteration products.

27.6.1. Ophitic texture. Mode is: plagioclase (2/0.7 mm) 67%, clinopyroxene (10/.6 mm) 20%, olivine (2 mm) 11%, ilmenite 2%. Clinopyroxene is the only relictual magmatic phase. Ab, cpx, chl, pum, tr, il, tit, ser, q, cros.

27.6.3. Ophitic to nesophitic textures. Mode is: pl. (2.5/0.5 mm) 76%, Cpx. (6/4 mm) 20%, il. 3%. Cpx., ab., Chl., pum., il., tit., q.

7.9.9.1. Intersertal to sub-ophitic textures; locally graphic intergrowth of pl. and cpx. Mode is: pl. (4/1 mm) 74%, cpx. (3/0.7 mm) 21%, mt. 5. %, ap. 0.1%. Aug., ab., q., mt., leuc., act.

25.6.11.2. Intersertal texture. Close association of cpx. and mt. Clinopyroxene crystallized before pl., is sometimes bent. Mode is: pl. (5/1 mm) 62%, cpx. (3/0.5 mm) 27%, mt. 11%, ap. 0.1%. Fe and Ti rich aug., ab., mt., leuc., Fe-chl., aeg., cros., ser., q.

Ultramafics

25.9.1. Cap Corse. Ol., opx., and cpx mesocumulat (lherzolite). Diopside is fresh. opx and ol. are serpentinized.

25.9.4. Cap Corse. Ol. websterite adcumulate serpentinized.

13.9.8.c. Casaluna. Deformed dunite. Protogranular texture. Ol. (Fo_{88}) brown aluminous Cr-spinel, transformed pl. into hydrogrossular.

13.9.8.b.	Casaluna. Deformed harzburgite. Transformed pl. and Cr-spinel are accessory; ol. (Fo_{90}); enstatite ($2V_Z = 76° \pm 1$). Protogranular texture; olivine shows elongate tablets bigger than orthopyroxene ones, and parallel to the plagioclase foliation.
22.7.15.2.	Inzecca serpentinite. Liz, mt.
29.6.19.	Inzecca. serpentinite. Liz., mt., hydrogrossular.

Troctolites

Samples come from the Casaluna massif. They are composed of plagioclase (An_{80-70}), olivine (Fo_{90-85}), and diopsidic augite ($2V_Z = 53° \pm 2$; $ZZcc = 40° \pm 2$).

11.9.15.1.	Pl.-ol.-Cpx. mesocumulate (olivine gabbro). Pl. size varies from 0.2 to 1.2 cm., cpx. is poikilitic.
11.9.11.	Pl.-ol.-cpx. heteradcumulate (troctolite). Pl. (1.5 cm), very abundant are locally separated from olivine by a narrow zone of chl. (0.1 mm). Secondary minerals: liz., mt., pre.
11.9.12.	Ol.-pl. heteradcumulate (plagioclase dunite). Sub-automorph ol. and few chromites are inclosed in heteradcumulus pl. Other phases: liz., mt., pre.
11.9.14.	Pl.-ol mesocumulate (troctolite). Locally accessory heteradcumulus cpx. Secondary minerals: liz., mt., pre., tr.

Gabbros

20.9.6.	Casaluna. Pl.-cpx.-Mt. adcumulate. Aug. is fresh. act., chl., ab., q.
12.9.24.	Casaluna. Pl.-cpx.-ol. heteradcumulate (olivine gabbro). Cpx. is fresh (diallage). Chl. pseudomorph ol. which are separated from pl. by corona texture. Tr., Mg-chl., ab., pre.
1.7.11.	Inzecca. Pl.-cpx. heteradcumulate. Diallage is deformed (kink-bands), Tr., chl., pre.

Ferrogabbros

20.9.5.	Casaluna. Pl.-cpx.-mt.-opx.-ap. mesocumulate. Cpx. and ap. are the two preserved magmatic minerals. Other phases: brown hb., act., Fe-act., chl., cros.
29.7.13.1.	Inzecca metagabbro. All the magmatic minerals are transformed except ap. and zircon. (0.2–1 mm). Aeg., aegyrinic pyroxenes, cros. stil., ser., ab.
23.8.3.	Inzecca massif. Metagabbro. Aegyrinic pyroxenes, aeg., cros., stil., Fe-chl., ab., leuc., tit.

Plagiogranites

23.8.6.1.A.	Inzecca massif. Pl.-cpx.-Zr.-ap. mesocumlate. Cumulus structure is well preserved despite metamorphic recrystallization. Igneous lamination is marked by pl. Ab., jadeitic and aegyrinic pyroxenes, Fe-chl., zr., ap.
30.7.3.1.	Inzecca. Plagiogranite. No magmatic texture is preserved; mortar texture ab., q., Fe-chl., zr., mt.
28.7.9.	Inzecca. Plagiogranite. Mortar texture. Ab., q., he., stil., ZR.

Abbreviation of the minerals: ab = albite; *act* = actinolite; *aeg* = aegyrine; *aug* = augite; *chl* = chlorite; *cpx* = clinopyroxene; *cros* = crossite; *epi* = epidote; *hb* = hornblende; *hem* = hematite; *il* = ilmenite; *leuc* = leucoxene; *liz* = lizardite; *lw* = lawsonite; *mt* = magnetite; *ol* = olivine; *opx* = orthopyroxene; *pl* = plagioclase; *pre* = prehnite; *pum* = pumpellyite; *q* = quartz; *ser* = sericite; *stil* = stilpnomelane; *tit* = titanite; *tr* = tremolite; *zr* = zircon.

Appendix II. Trace element concentrations obtained and used for interlaboratory standards

	GSP-1	AGV-1	BCR-1	PCC-1	DTS-1	BR	BM	T-1	SY-1	MRG-1	SY-2	SY-3
Ni	8	20	12	2375	2350	–	64	–	34	203	–	–
	(12.5)	(18.5)	(15.8)	(2339)	(2269)	–	(57)	–	(43)	(190)	–	–
Co	–	16	42	113	133	–	–	–	18	96	–	–
		(14.1)	(38)	(112)	(133)				(19)	(87)		
Cr	–	–	22	2800	3950	–	150	–	55	439	–	–
			(17.6)	(2730)	(4000)		(123)		(56)	(450)		
Cu	36	64	16	13	–	–	45	53	24	126	–	–
	(33.3)	(59.7)	(18.4)	(11.3)			(45)	(47)	(23)	(135)		
Zn	94	108	131	42	–	–	112	166	240	–	258	–
	(98)	(84)	(120)	(36)			(107)	(190)	(219)		(250)	
V	54	123	398	30	–	–	182	79	88	540	–	–
	(52.9)	(125)	(399)	(30)			(180)	(96)	(89)	(520)		
Li	29	12	13	2	–	–	79	12	–	4	95	91
	(32.1)	(12)	(12.8)	(2)			(70)[1]	(8)		(4)	(86)	(85)
Rb	250	67	47	–	–	–	12	32	–	12	204	187
	(254)	(67)	(46.6)				(12)	(32)		(10)	(214)	(198)
Sr	–	662	333	–	–	–	–	396	–	267	263	302
		(657)	(330)					(380)		(270)	(270)	(310)
Y	34	26	44	–	–	–	29	–	–	–	151	874
	(30.4)	(21.3)	(37.5)				(26)				(136)	(750)
Nb	29	16	14	–	–	91	–	–	–	–	33	–
	(29)	(15)	(13.5)			(92)					(27)	–
Zr	490	221	190	–	–	–	101	–	–	103	274	323
	(500)	(225)	(190)				(105)			(110)	(270)	(320)

In brackets bibliographic averages or recommended values: GSP-1, AGV-1, BCR-1, PCC-1, DTS-1, BM, data from Flanagan (1973); BR, data from Roubault et al. (1970); T-1, data from Thomas (1963); SY-1, data from Abbey (1975); MGR-1, SY-2, SY-3, data from Abbey et al. (1975)

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