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Petrology and Geochemistry of Fe-Ti Gabbros and Plagiogranites from the Western Alps Ophiolites

by *U. Pognante*¹, *B. Lombardo*² and *G. Venturelli*³

Abstract

The geochemistry and mineral chemistry of two suites of Fe-Ti gabbros and plagiogranites from the Western Alps meta-ophiolites have been investigated and compared to data from oceanic analogues and to Fe-rich differentiates from some stratiform continental intrusions. Low pressure (< 6 kb) fractionation under initial reduced conditions and late stage relative oxidation associated with filter pressing and cumulus processes were operative during the production of the Fe-Ti gabbros. In the later stages the fractionation could have been assisted by immiscibility processes in which Zr doesn't display the expected partition between the two immiscible liquids.

The stratigraphic position of the Alpine intrusive differentiates indicate that these rocks were either concentrated at various levels of gabbroic magma chambers or expelled as dykes in the host peridotites.

Introduction and Geologic Setting

Fe-Ti gabbros are well known from the Atlantic and Indian oceanic crusts (MIYASHIRO et al., 1970; BONATTI et al., 1971; THOMPSON, 1973; ENGEL and FISHER, 1975; PRINZ et al., 1976) and from some ophiolite complexes (OHNENSTETTER et al., 1975; BECCALUVA et al., 1976, 1977; CHURCH and RICCIO, 1977; LOMBARDO et al., 1978; OHNENSTETTER and OHNENSTETTER, 1980; SERRI, 1980), but are typically absent in other ophiolite suites (e. g. Troodos). Accordingly the strong Fe-Ti enrichment during differentiation of basaltic liquids was recently considered to be a typical feature of some accreting plate margins where these rocks are usually associated with subordinate amounts of plagiogranites (SERRI, 1981).

In this paper new data for two representative suites (ROCCIAVRÉ and LANZO, Fig. 1) of Fe-Ti gabbros and plagiogranites from the Western Alps meta-ophi-

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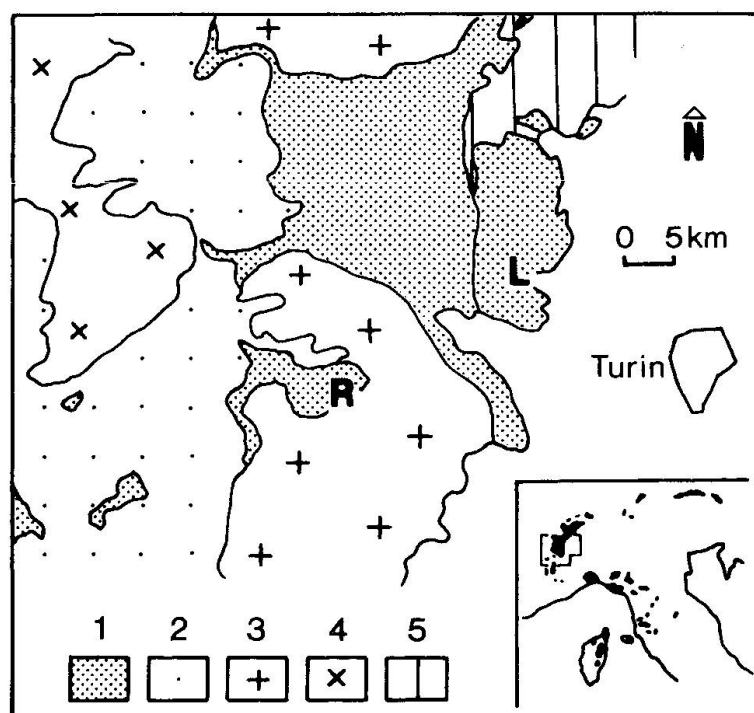


Fig. 1 Tectonic sketch map of the Western Alps with location of the Rocciavré (R) and Lanzo (L) ophiolite sections. Piedmont Ophiolite Nappe: 1) main ophiolite bodies and 2) undifferentiated metasediments with minor ophiolites; 3) Dora-Maira and Gran Paradiso continental units; 4) San Bernardo continental unit; 5) Sesia-Lanzo continental unit.

olites are presented, and the petrogenesis of these suites is discussed and compared with that of the present-day oceanic analogues and with the Fe-rich differentiates occurring in some stratiform continental intrusions.

The Alpine tectonic-metamorphic evolution and the petrographical and geochemical features indicate that both the Rocciavré and the Lanzo suites belong to the Piedmont Ophiolite Nappe. This nappe suffered an eclogitic to blueschist equilibration which is believed to reflect Late Cretaceous subduction of a Late Jurassic-Cretaceous oceanic lithosphere (DAL PIAZ, 1974).

Field Relationships

Fe-Ti gabbros occur in the Western Alps meta-ophiolites (Piedmont Ophiolite Nappe) as: 1) layered sequences within isotropic gabbros, 2) dykes cutting peridotites, 3) pods within olivine gabbros and troctolites (LOMBARDO and POGNANTE, in press). Plagiogranites are uncommon and occur associated to Fe-Ti gabbros or as dykes cutting peridotites.

This work deals with the Rocciavré and Lanzo Fe-Ti gabbro suites (Fig. 1) which still display clear relationships with the surrounding rocks and largely preserve the primary mineralogy and textures. Both suites were subjected to the

Alpine eclogitic metamorphism (400–480°C and 12–13 kb for Rocciavré; POGNANTE, 1981), but part of them largely escaped deformation and metamorphism only produced coronitic or incomplete pseudomorphic transformations.

The *Rocciavré* suite (POGNANTE, 1979, 1981) is a layered sequence included in a large body of isotropic olivine-orthopyroxene gabbros and consists of centimetric-metric layers of gabbros rich in ilmenite and Ti-magnetite (ilm-mt gabbros) interlayered with gabbro-norites. Small pods of plagiogranite rarely occur in close association with the ilm-mt gabbros. At *Lanzo*, ilm-mt gabbros, ilm-mt diorites and plagiogranites occur along with more abundant olivine gabbros as cross cutting dykes within tectonite peridotites. The latter consist of spinel lherzolites largely re-equilibrated into plagioclase lherzolites with minor dunites and harzburgites (BOUDIER, 1978).

Prior to the eclogite metamorphism the Fe-Ti gabbros and the plagiogranites suffered partial recrystallization under low pressure amphibolite facies conditions which we refer to as an «oceanic» metamorphism. At *Lanzo* this stage predates the emplacement of basalt dykes and is associated with up to kilometric ductile shear zones.

Petrographic Features

The magmatic mineralogy of the analyzed gabbro-norites, ilm-mt gabbros and plagiogranites from the Rocciavré and Lanzo suites is summarized in Table 1. The *gabbro-norites* and the *ilm-mt gabbros* are medium grained to pegmatoid rocks with panallotriomorphic to ophitic textures, and mainly differ in the amount of Fe-Ti oxides and apatite. Fine grained varieties occur in the margins of some ilm-mt gabbro dykes from Lanzo. The Lanzo ilm-mt gabbros are distinguished by the occurrence of olivine and of primary brown amphibole which appear to be absent in the Rocciavré analogues. The *plagiogranites* consist of altered Na-rich plagioclase in granophyric intergrowth with quartz and of clinopyroxene (Rocciavré), or of albite and brown amphibole (Lanzo). The accessories are zircon, apatite, allanite, Fe-Ti oxides and sphene.

Microstructural considerations suggest that both in the gabbro-norites and in the ilm-mt gabbros the first phases to crystallize are olivine and plagioclase followed by clinopyroxene, orthopyroxene and finally by ilmenite, Ti-magnetite, apatite, zircon and amphibole.

Mineral Chemistry

Compositional data for the magmatic minerals from Rocciavré and Lanzo were obtained with an ARL-SEM-Q electron microprobe and are presented in Tables 2–3.

Table 1 List of the analyzed samples (Tables 2-3-4). Abbreviations: gb = gabbro; nor = norite; plagiogr = plagiogranite; pl = plagioclase; ol = olivine; cpx = clinopyroxene; opx = orthopyroxene; amph = amphibole; ilm = ilmenite; ap = apatite; zr = zircon; all = allanite; sph = sphene; qtz = quartz. Underlined: magmatic minerals pseudomorphed by Alpine and/or «oceanic» minerals. The minerals are given in order of decreasing abundance.

	Rock type	Locality	Field occurrence	Magmatic mineralogy
Rocciavré				
R327	gabbro	Sangone valley	isotropic gabbro	<u>pl</u> , <u>cpx</u> , <u>ol</u> , <u>opx</u> , <u>ilm</u>
8881	"	Punta Vailere	"	<u>pl</u> , <u>cpx</u>
R299	ol gb-nor	Fonte Neiretto	layered sequence	<u>pl</u> , <u>cpx</u> , <u>ol</u> , <u>opx</u> , <u>ilm</u>
R305	"	"	"	<u>pl</u> , <u>cpx</u> , <u>opx</u> , <u>ol</u> , <u>ilm</u> , <u>ap</u>
R320	gb-norite	"	"	<u>pl</u> , <u>cpx</u> , <u>opx</u> , <u>ilm</u>
R322	"	"	"	<u>pl</u> , <u>cpx</u> , <u>opx</u> , <u>ilm</u> , <u>ap</u>
R323	"	"	"	<u>pl</u> , <u>cpx</u> , <u>opx</u> , <u>ilm</u>
R356	"	"	"	<u>pl</u> , <u>cpx</u> , <u>opx</u> , <u>ilm</u>
8937	"	"	"	<u>pl</u> , <u>cpx</u> , <u>opx</u> , <u>ilm</u>
8940	"	"	"	<u>pl</u> , <u>cpx</u> , <u>opx</u> , <u>ilm</u> , <u>ap</u>
R321	ilm gb-nor	"	"	<u>pl</u> , <u>cpx</u> , <u>opx</u> , <u>ilm</u>
R319	ilm-mt gb	"	"	<u>pl</u> , <u>cpx</u> , <u>ilm</u> , <u>mt</u>
R841	"	"	"	<u>pl</u> , <u>cpx</u> , <u>opx</u> , <u>ilm</u> , <u>mt</u>
R849	"	"	"	<u>pl</u> , <u>cpx</u> , <u>opx</u> , <u>ilm</u> , <u>mt</u>
8944	"	"	"	<u>pl</u> , <u>cpx</u> , <u>ilm</u> , <u>mt</u> , <u>ap</u>
8945	"	"	"	<u>pl</u> , <u>cpx</u> , <u>ilm</u> , <u>mt</u>
R296	plagiogr	"	"	<u>pl</u> , <u>qtz</u> , <u>cpx</u> , <u>ap</u> , <u>zr</u> , <u>all</u> , <u>ilm</u>
Lanzo				
VL17	ilm-mt gb	Monte Arpone	chilled dyke	<u>pl</u> , <u>cpx</u> , <u>ol</u> ?, <u>amph</u> , <u>ilm</u> , <u>mt</u>
VL18	"	"	dyke	<u>pl</u> , <u>cpx</u> , <u>ol</u> , <u>opx</u> ?, <u>amph</u> , <u>ilm</u> , <u>mt</u> , <u>ap</u>
VL23	"	"	"	<u>pl</u> , <u>cpx</u> , <u>ol</u> , <u>amph</u> , <u>ilm</u> , <u>mt</u>
VL55	plagiogr	Valdellatorre	"	<u>pl</u> , <u>amph</u> , <u>all</u>
VL58	"	"	"	<u>pl</u> , <u>amph</u> , <u>sph</u> , <u>zr</u> , <u>all</u> , <u>ap</u>
VL62	"	"	"	<u>pl</u> , <u>amph</u> , <u>ilm</u> , <u>zr</u> , <u>sph</u>
VL68	"	"	"	<u>pl</u> , <u>amph</u> , <u>ap</u> , <u>ilm</u> , <u>sph</u> , <u>zr</u> , <u>all</u>

Table 2 Representative microprobe analyses of magmatic minerals from the Rocciavré gabbro-norites and ilm-mt gabbros. Structural formulae are on the basis of 4 oxygens for olivine, 6 for pyroxenes and ilmenite, 8 for plagioclase.

	O1	Pl	Cpx				Opx		Ilm
	R305	R322	R305	R322	R841	R849	R305	R322	R841
SiO ₂	39.94	54.78	52.34	51.37	52.87	52.74	55.14	53.84	-
TiO ₂	-	0.09	0.79	1.04	0.56	0.92	0.39	0.32	48.63
Al ₂ O ₃	0.03	28.38	2.52	2.30	1.18	2.20	1.29	1.15	-
Cr ₂ O ₃	0.08	-	0.16	-	0.08	-	-	-	-
FeO _{tot}	16.53	0.17	6.23	9.52	10.81	9.66	16.11	16.58	49.78
MnO	0.17	-	0.24	0.28	0.19	0.26	0.40	0.32	0.34
MgO	42.84	-	14.97	14.73	14.50	14.31	26.39	25.48	0.66
CaO	0.02	10.47	21.74	20.56	19.01	19.48	1.18	2.30	-
Na ₂ O	-	6.02	0.69	0.41	1.03	0.67	0.07	0.11	-
K ₂ O	-	0.02	-	-	-	-	-	-	-
Tot.	99.61	99.93	99.68	100.21	100.23	100.24	100.97	100.10	99.39
Si	1.012	2.475	1.936	1.915	1.971	1.954	1.974	1.959	-
Al	0.001	1.511	0.110	0.101	0.052	0.096	0.054	0.049	-
Ti	-	0.003	0.022	0.029	0.016	0.026	0.010	0.009	1.891
Cr ₂₊	0.002	-	0.005	-	0.002	-	-	-	-
Fe _{tot}	0.350	0.006	0.193	0.297	0.337	0.299	0.482	0.505	2.151
Mn	0.004	-	0.008	0.009	0.006	0.008	0.012	0.010	0.015
Mg	1.618	-	0.826	0.814	0.806	0.791	1.408	1.382	0.050
Ca	0.001	0.507	0.862	0.821	0.759	0.773	0.045	0.090	-
Na	-	0.527	0.049	0.030	0.074	0.048	0.005	0.008	-
K	-	0.001	-	-	-	-	-	-	-
Tot.	2.988	5.030	4.011	4.016	4.023	3.955	3.990	4.012	4.107

Table 3 Representative microprobe analyses of magmatic minerals from the Lanzo ilm-mt gabbros and plagiogranites. Structural formulae are on the basis of 6 oxygens for clinopyroxene and ilmenite, 8 for plagioclase, 12 for magnetite and 23 for amphibole.

	Cpx		Amph		Pl	Ilm	Ti-Mt
	Vl 17	Vl 23	Vl 23	Vl 68	Vl 62	Vl 23	Vl 23
SiO ₂	51.66	51.92	42.35	51.13	66.71	0.19	-
TiO ₂	0.94	0.99	3.89	2.02	-	51.70	10.77
Al ₂ O ₃	2.32	2.47	10.80	5.62	20.48	0.18	1.94
Cr ₂ O ₃	-	0.31	-	0.11	-	-	Fe ₂ O ₃ 46.37
FeO _{tot}	12.87	10.42	15.10	10.64	0.28	46.78	FeO 40.19
MnO	0.36	0.28	0.19	0.31	-	0.31	-
MgO	12.68	13.89	10.96	17.57	-	0.33	0.17
CaO	18.71	18.54	10.82	7.40	0.30	-	-
Na ₂ O	0.60	0.87	3.57	2.89	12.25	-	-
K ₂ O	-	-	0.05	0.07	0.35	-	-
Tot.	100.14	99.69	97.73	97.76	100.37	99.49	99.44
Si	1.944	1.941	6.332	7.282	2.931	0.010	-
Al	0.103	0.109	1.903	0.943	1.061	0.011	0.259
Ti	0.027	0.028	0.437	0.216	-	1.971	0.918
Cr	-	0.009	-	0.012	-	-	Fe ³⁺ 3.956
Fe ²⁺ _{tot}	0.405	0.325	1.888	1.267	0.010	1.983	Fe ²⁺ 3.811
Mn	0.011	0.009	0.024	0.038	-	0.013	-
Mg	0.711	0.779	2.445	3.731	-	0.025	0.029
Ca	0.754	0.743	1.733	1.135	0.014	-	-
Na	0.044	0.063	1.035	0.798	1.044	-	-
K	-	-	0.012	0.015	0.020	-	-
Tot.	3.999	4.006	15.807	15.437	5.080	4.013	8.973

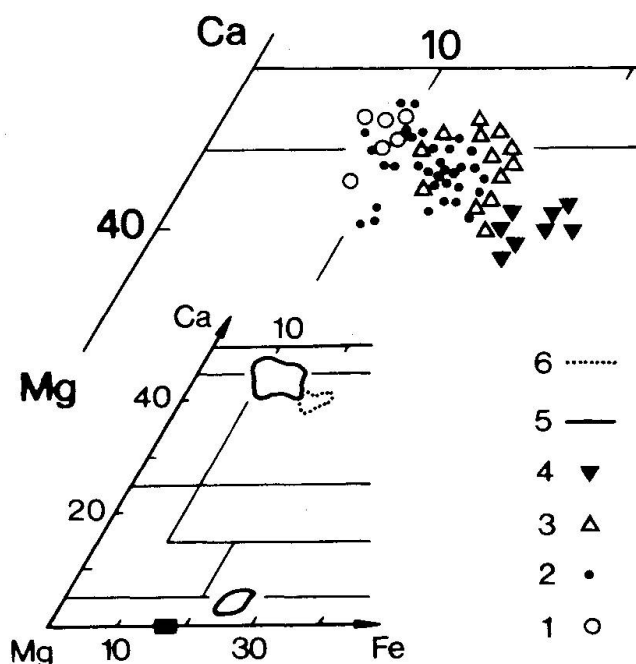


Fig. 2 Compositional variation of magmatic clinopyroxenes in the Rocciavré and Lanzo gabbros. Rocciavré: 1) isotropic gabbros; 2) gabbro-norites; 3) ilm-mt gabbros. Lanzo: 4) ilm-mt gabbros. The compositional fields of the Rocciavré pyroxenes (5) and olivines (black area), and of the Lanzo clinopyroxenes (6) are shown in the inset. Data from Tables 2-3 and 7 additional samples from Rocciavré.

Relics of *olivine* were only found in some Rocciavré gabbro-norites where it is a Mg-rich variety ranging from Fo₈₂ to Fo₈₄ (Fig. 2, Table 2).

Plagioclase occurs as rare relics in the Rocciavré gabbro-norites and in a few plagiogranites and ilm-mt diorites from Lanzo. In the gabbro-norites it displays an intermediate composition and occasionally shows slight zoning (An 45-55; Table 2). In the plagiogranites and in the ilm-mt diorites the plagioclases are albite (An 1-2; Table 3) and andesine (An 35) respectively.

At Rocciavré the *clinopyroxene* is diopside or endiopside (Ca₄₆Mg₄₅Fe₉) in the isotropic gabbros (LOMBARDO and POGNANTE, in press) and augite both in the gabbro-norites (Ca₄₄Mg₄₄Fe₁₂) and in the ilm-mt gabbros (Ca₄₄Mg₄₁Fe₁₅; Fig. 2, Table 2). A slightly Fe-richer augite (Ca₄₀Mg₄₀Fe₂₀; Fig. 2, Table 3) occurs in the Lanzo ilm-mt gabbros. A subsolidus trend toward Ca-richer compositions is obvious from Fig. 2 and is also inferred by the abundance of exsolution lamellae of Ca-poor pyroxene (Ca₂Mg₇₃Fe₂₅). The compositions of the analyzed clinopyroxenes are comparable to those from the Alps-Apennines gabbros (SERRI, 1980; LOMBARDO and POGNANTE, in press; MEVEL, pers. com.) and from the oceanic gabbros (HODGES and PAPIKE, 1976; PRINZ et al., 1976), which also exhibit only limited Fe-enrichment during differentiation. On the contrary these pyroxenes differ from those of some stratiform intrusions emplaced in the continental crust (e. g. Skaergaard and Bushveld; WAGER and BROWN, 1967) where the Fe-rich differentiates contain significantly Fe-richer pyroxenes.

The *orthopyroxenes* from the Rocciavré gabbro-norites are bronzites ($\text{Ca}_4\text{Mg}_{71}\text{Fe}_{25}$; Fig. 2, Table 2) and display a subsolidus re-equilibration toward Ca-poorer compositions with thin exsolutions of clinopyroxene. A Mg-richer variety ($\text{Ca}_1\text{Mg}_{82}\text{Fe}_{17}$) occurs in some reaction rims around olivine.

In the Rocciavré gabbro-norites and in the Lanzo plagiogranites the *Fe-Ti oxides* are mainly ilmenite ($\text{Ilm}_{99}\text{Hem}_1$; Table 2). A more complex pattern is displayed by the ilm-mt gabbros; here in fact the oxides consist of largely altered Ti-magnetite ($\text{Mt}_{69}\text{Usp}_{31}$; Table 3) rich in exsolutions of ilmenite, and of discrete grains of ilmenite ($\text{Ilm}_{97}\text{Hem}_3$, Table 2; $\text{Ilm}_{99}\text{Hem}_1$, Table 3).

The *amphiboles* from the Lanzo plagiogranites are distinguished by high values of SiO_2 and of Na_2O (Table 3), and applying the nomenclature proposed by LEAKE (1978) are classified as magnesio-katophorites. The amphiboles from the Lanzo ilm-mt gabbros are rich in TiO_2 and Na_2O (Table 3), and are classified as titanian magnesio-taramites. Excepted the low K_2O values, the latter are similar to some amphiboles dredged in the Atlantic (PRICHARD and CANN, 1982).

Bulk Rock Chemistry

14 samples from Rocciavré and 5 samples from Lanzo have been analyzed for major and some trace elements (Table 4). SiO_2 , TiO_2 , Al_2O_3 , $\text{Fe}_2\text{O}_{3\text{tot}}$, MnO , CaO , K_2O , P_2O_5 , Sc, V, Cr, Ni, Y, Zr, Sr, Rb have been determined by X-ray fluorescence (Philips 1400). MgO, Ni, Cr were determined by atomic absorption, and Na_2O by flame photometry.

The wide compositional range displayed by the investigated rocks is apparent in the diagrams of Fig. 3 where several major and trace elements are plotted against $\text{FeOt}_{\text{tot}}/\text{MgO}$. In spite of the variable element mobilization during the different metamorphic events, in the AFM diagram (Fig. 4) the analyzed rocks preserve a tholeiitic trend. However, in contrast with the present-day oceanic gabbroids, the Alpine rocks show a moderate Na-enrichment probably obtained during metamorphism.

Low values of $\text{FeOt}_{\text{tot}}/\text{MgO}$ (0.30–0.37), Ti, P, Zr, Y, V and high Cr, Ni characterize the Rocciavré isotropic gabbros, whereas higher values of $\text{FeOt}_{\text{tot}}/\text{MgO}$ (0.61–1.25), Ti, P, Zr, Y and lower Cr, Ni distinguish the gabbro-norites. A dramatic increase of $\text{FeOt}_{\text{tot}}/\text{MgO}$ (3.2–5.6), Ti and V is shown by the ilm-mt gabbros and is mainly influenced by the segregation of ilmenite and Ti-magnetite. An exception is sample 8944 which displays very high $\text{FeOt}_{\text{tot}}/\text{MgO}$, P, Y but low V reflecting the abundance of ilmenite and apatite. The relatively high Ni values distinguishing the ilm-mt gabbros from Lanzo are related to the occurrence of olivine. The plagiogranites show high amounts of Si, Na, Zr, Y and low $\text{FeOt}_{\text{tot}}/\text{MgO}$, Mg, Fe, Ca, Ti, V and Sc. The very low content of K may be the effect of metamorphism.

Table 4 Major (wt%) and trace (ppm) element abundances in the gabbroic rocks from Rocciavré and Lanzo. -, not determined; (), less accurate data.

ROCCIAVRE															LANZO				
	R327	8881	R320	R356	R299	8940	8937	R322	R323	R321	8945	R319	8944	R296	VL23	VL18	VL17	VL55	VL58
SiO ₂	51.6	52.1	51.5	51.1	54.2	50.4	49.9	52.8	50.8	50.6	45.3	44.7	45.9	64.3	43.3	44.2	44.8	61.8	69.4
TiO ₂	0.23	0.26	0.48	0.48	0.53	0.58	0.48	0.53	0.74	1.3	5.2	4.9	3.1	0.79	5.7	6.5	5.4	0.14	0.20
Al ₂ O ₃	14.8	16.2	12.5	13.8	14.4	12.9	15.5	17.3	15.2	14.1	10.9	8.6	10.0	13.3	10.2	9.8	9.8	19.4	16.0
Fe ₂ O ₃ tot	4.1	3.9	7.0	6.3	5.9	8.3	8.1	7.1	8.5	10.8	18.6	21.7	23.0	7.5	20.7	21.0	21.0	1.8	1.0
MnO	0.06	0.07	0.12	0.12	0.11	0.13	0.13	0.12	0.16	0.16	0.25	0.26	0.31	0.12	-	-	-	-	-
MgO	12.3	9.5	10.4	9.3	8.4	11.4	9.7	7.7	8.8	7.8	4.9	5.5	3.7	2.9	5.7	5.2	4.9	2.0	1.4
CaO	13.0	13.5	13.4	14.8	12.8	12.3	11.7	10.4	11.2	10.5	11.3	10.5	9.4	4.2	10.1	8.7	9.5	4.5	0.9
Na ₂ O	2.1	3.1	3.3	3.0	2.6	2.9	3.1	3.3	2.8	3.5	3.1	3.4	2.4	5.4	3.5	4.3	4.5	9.1	10.3
K ₂ O	<0.05	0.05	1.0	0.04	0.04	0.04	0.05	0.04	0.05	0.09	<0.05	<0.05	<0.05	0.06	0.05	0.10	0.06	0.04	<0.05
P ₂ O ₅	0.07	0.07	0.08	0.08	0.08	0.11	0.09	0.12	0.08	0.10	0.08	0.22	2.0	0.50	0.04	0.11	0.05	0.06	0.18
L.O.I.	1.7	1.1	1.3	0.9	1.1	0.9	1.2	0.68	1.5	1.0	0.3	0.1	0.0	0.9	0.6	0.0	0.0	1.1	0.6
Sc	36	35	46	41	40	53	40	-	41	-	49	55	34	19	59	51	51	<3	<3
V	120	130	179	-	-	-	-	-	-	-	911	1030	51	81	975	740	770	23	8
Cr	1760	345	178	90	140	96	95	50	54	75	11	<7	<7	7	18	6	<7	14	25
Ni	255	133	132	81	88	97	102	61	94	-	37	40	8	20	105	98	23	84	59
Y	8	11	16	16	17	22	18	15	21	23	25	55	(125)	(150)	25	35	30	37	70
Zr	5.5	9	17	25	23	36	29	29	26	34	50	115	79	415	44	87	55	187	550
Sr	158	182	120	147	158	144	157	167	171	186	153	69	123	88	170	184	165	1300	147
Rb	3	2	3	3	3	4	3.5	3	4	3	5	3	4	2	3	5	4	-	-

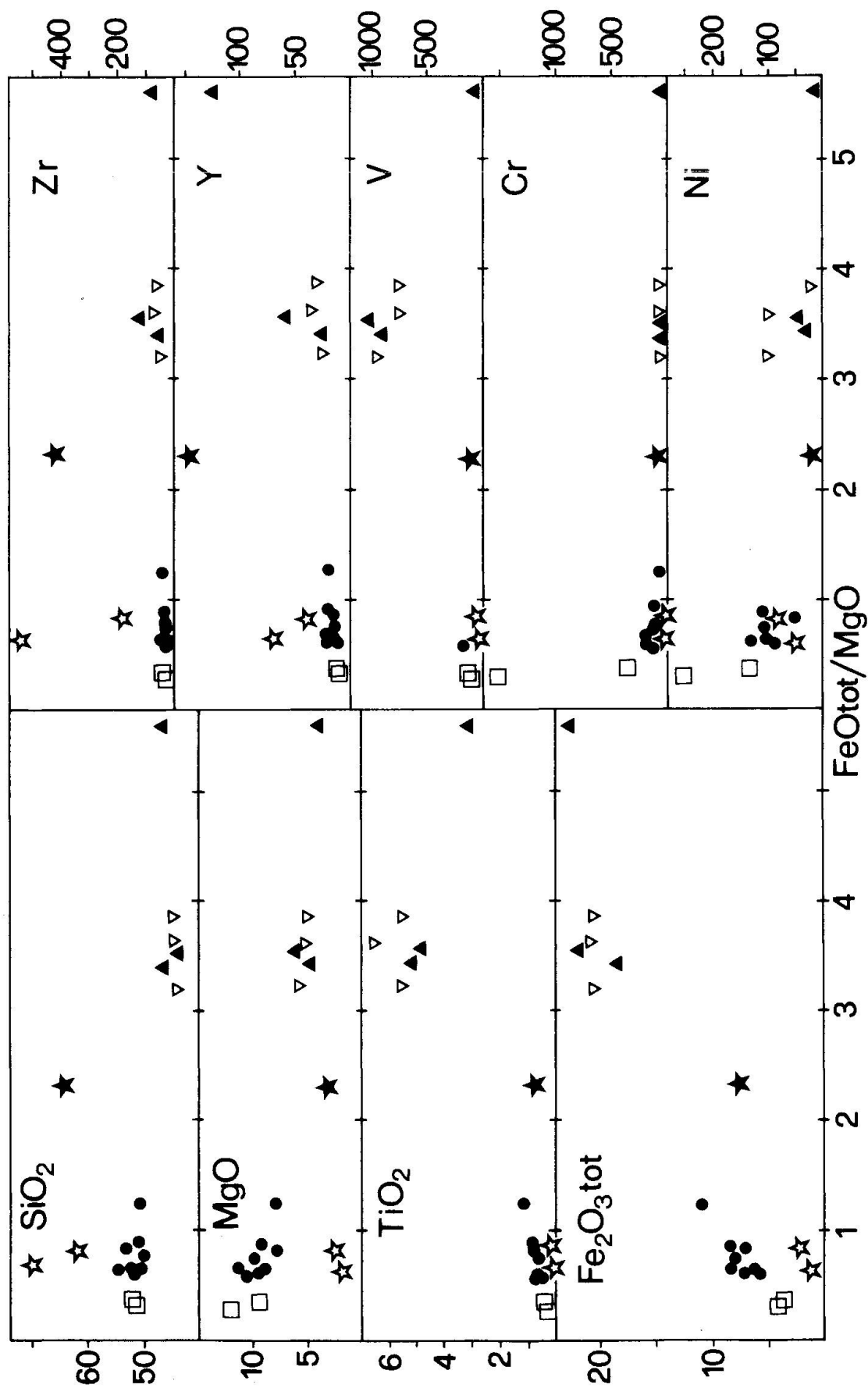


Fig. 3 Variation diagrams of some major (wt%) and minor (ppm) elements against $\text{FeO}_{\text{tot}}/\text{MgO}$ for the analyzed rocks. Rocciavré: (□) isotropic gabbros; (●) gabbro-norites; (▲) ilm-mt gabbros; (★) plagiogranite. Lanzo: (▽) ilm-mt gabbros; (☆) plagiogranites. Data from Table 4.

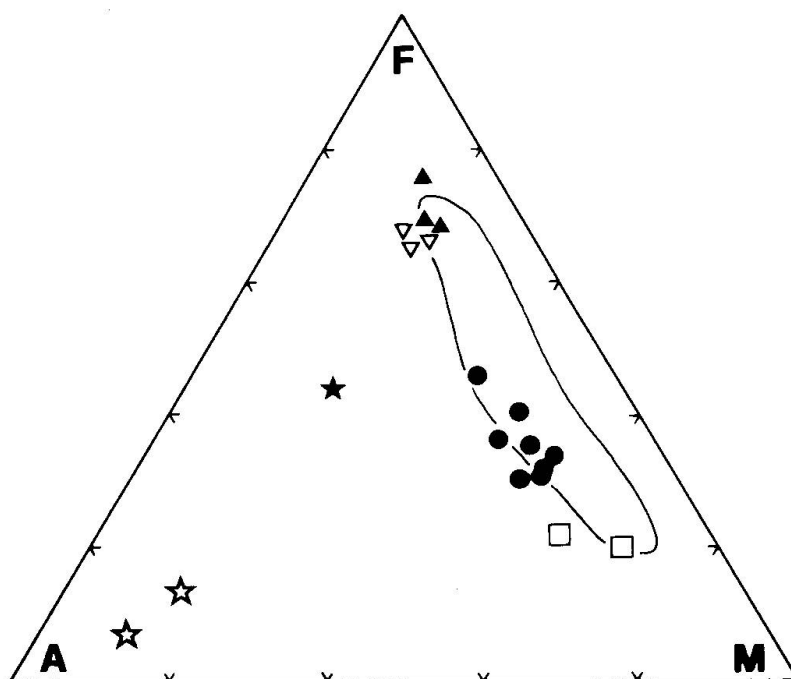


Fig. 4 AFM diagram for the gabbros and plagiogranites from Rocciavré and Lanzo. The compositional field of the oceanic gabbros is also shown (BONATTI et al., 1971; THOMPSON, 1973; PRINZ et al., 1976). Symbols as in Fig. 3.

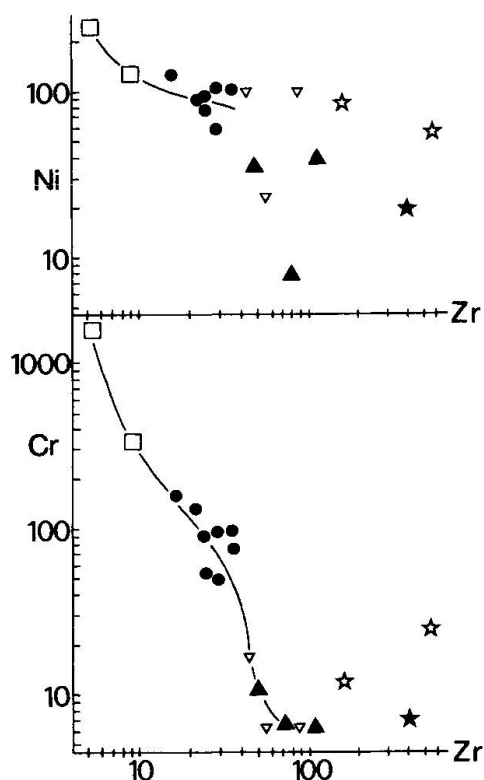
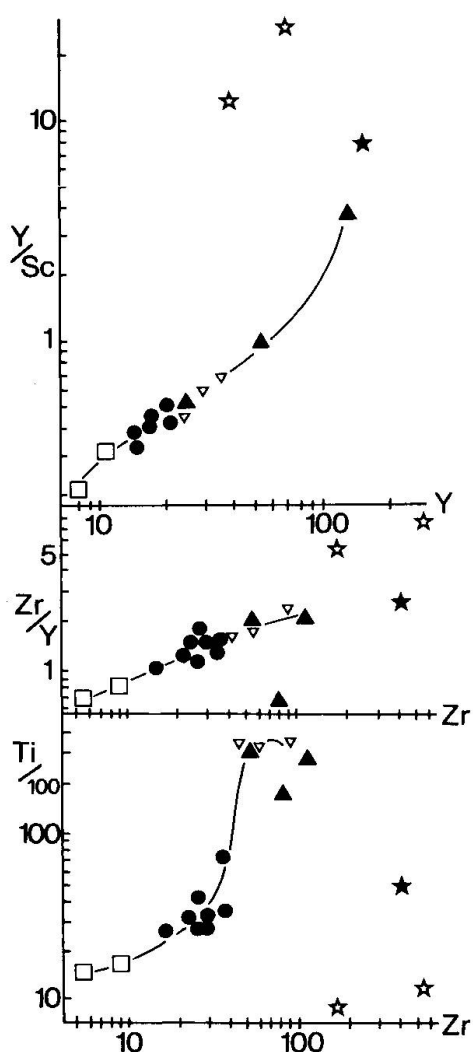
From the geochemical data here reported the fractionation range of the Rocciavré and Lanzo rocks appears to overlap with that of other gabbroids from the Alps-Apennines ophiolites (BECCALUVA et al., 1977; LOMBARDO et al., 1978; SERRI, 1980) and from modern ocean ridge areas (MIYASHIRO et al., 1970; BONATTI et al., 1971; THOMPSON, 1973; ENGEL and FISHER, 1975; HODGES and PAPIKE, 1976; PRINZ et al., 1976). Conversely both the ophiolite and ocean Fe-Ti gabbros differ from the Fe-rich differentiates of the stratiform continental intrusions (e. g. ferrodiorites from Skaergaard; WAGER and BROWN, 1967) which show higher Fe and lower Ti contents, and a strong iron enrichment of the silicates.

Petrogenesis

Magmatic evolution

Since gabbros mostly result from cumulate liquidus phases plus variable amounts of trapped liquid, their compositions should not define a liquid line-of-descent, but should only give a rough idea of the degree of fractionation of the parental magmas. However the chilled margins of Fe-Ti gabbro composition (sample VL17) in the Lanzo peridotites suggest that such liquids may exist and that gabbros cannot be always regarded as simple cumulus products.

The early stages of crystallization are characterized by the segregation of plagioclase, Cr-clinopyroxene, Mg-olivine and orthopyroxene, which produced



△
Fig. 5 Cr-Zr and Ni-Zr diagrams showing the evolutionary trend of the Rocciavré and Lanzo rocks. Symbols as in Fig. 3.

△
Fig. 6 Ti/100-Zr, Zr/Y-Zr, Y/Sc-Y diagrams showing the evolutionary trend for the Rocciavré and Lanzo rocks. Symbols as in Fig. 3.

large amounts of *isotropic gabbros*. The geochemical data, in particular the very low contents of Zr and Y, indicate that these rocks consist of little fractionated liquidus phases plus very subordinate amounts of trapped liquid.

In the *gabbro-norites* the abundance of liquidus orthopyroxene, the olivine-liquid reaction relations and the lower values of Mg, Ni, Cr point to derivation from a magma saturated in silica and more fractionated than that producing the *isotropic gabbros*.

The extreme composition displayed by the *ilm-mt gabbros* can be mainly related to fractionation, though cumulate processes where probably also operative. The evolutionary trends shown in Figs. 5-6 and the diagrams of Figs. 3-4 indicate an enrichment in Fe, Ti, V, Zr/Y, Y/Sc and a rapid fall of some compatible elements (Cr in particular) during differentiation. These trends suggest a crystallization under initial low fO_2 conditions and a crystal fractionation approaching surface equilibrium. A relative oxidation in the later stages leading to the formation of the *ilm-mt gabbros* seems however to be implied by the se-

gregation of Ti-magnetite with "Fe-poor" silicates, as shown experimentally by SPEIDEL and OSBORN (1967) and HILL and ROEDER (1974). This late stage oxidation would in turn suggest relatively reduced initial oxidation states in the parent magma (MORSE et al., 1980).

The precipitation of the Fe-Ti oxides shifts the scarce residual liquid toward SiO_2 - and alkali-rich compositions, leading to the formation of the *plagiogranites*. The abundance of primary amphibole both in the plagiogranites and in the ilm-mt gabbros, indicate that relatively high P H_2O conditions have accompanied the later stages at Lanzo.

An alternative or complementary mechanism to obtain these peculiar differentiation trends is liquid immiscibility (KHITAROV and PUGIN, 1978, with references). Recent experiments (MCBIRNEY and NAKAMURA, 1974; DIXON and RUTHERFORD, 1979) indicate that in tholeiite compositions immiscibility occurs, after about 95% of the original liquid has crystallized, producing a liquid strongly enriched in Fe, Ti, P and a SiO_2 enriched liquid. Part of the data obtained here, particularly the chemical similarities between the ilm-mt gabbros and plagiogranites and the two immiscible liquids, are in rough agreement with these experiments. However, if it is assumed that the ilm-mt gabbros represent liquids produced by immiscibility processes, Zr appears to be depleted in the Fe-Ti rich liquid, contrary to some experimental and theoretical patterns (WATSON, 1976; KHITAROV and PUGIN, 1978; RYERSON and HESS, 1978). The contradiction may be resolved if the analyzed ilm-mt gabbros are regarded as immiscible liquids in which Zr has not the expected behaviour, as observed by EBY (1979) in some Montereian Hills rocks produced by liquid immiscibility.

After their production the Fe-Ti rich and the plagiogranitic melts may have been trapped at various levels of the gabbroid magma chamber (e. g. Rocciavré) or expelled intruding as dykes the surrounding rocks (e. g. Lanzo).

Conditions of crystallization

The predominance of irregular and pegmatoid textures over rhythmic layerings, and the lack of troctolitic cumulates strongly suggest that the Rocciavré gabbro suite formed by «in situ» crystallization and by filter pressing processes in a turbulent environment rather than by undisturbed crystal settling.

Relatively low pressures of crystallization for both the Alpine suites are implied by the early appearance of plagioclase relative to pyroxenes, and by the stability of the olivine-plagioclase pair, which suggest pressures lower than 6–7 kb (KUSHIRO, 1973; EMSLIE, 1971). A pressure range of 2–5 kb is suggested for the Rocciavré rocks by some thermodynamic calculations involving the variations of the silica activity with P and T given the compositions of coexisting phases (ARCULUS and WILLS, 1980; BUCHANAN et al., 1980). In this pressure

range an upper limit of about 1050°C (HOLLOWAY, 1973; ALLEN and BOETTCHER, 1978) is set, for the crystallization of the Fe-Ti gabbros, by the stability of igneous amphibole. Temperatures calculated for clinopyroxene-orthopyroxene pairs using the geothermometer proposed by WOOD and BANNO (1973) and WELLS (1977) recalibration, range between 930 and 1050°C in the Rocciavré gabbro-norites, pointing to subsolidus re-equilibrations and then to slow cooling at depth. Temperatures for coexisting ilmenite and Ti-magnetite pairs using the geothermometer of BUDDINGTON and LINDSLEY (1964) are lower than 650°C and reflect subsolidus equilibration and/or the effects of metamorphism.

Conclusions

The petrological and geochemical study of the Fe-Ti gabbros and the plagiogranites from the Rocciavré and Lanzo suites confirms the close similarities between the intrusive rocks from the Western Alps ophiolites and those from present-day oceanic crust. Unlike the oceanic analogues, the stratigraphic position of the analyzed differentiated gabbroids can still be recognized. In particular these rocks are not segregated between the gabbro and the basalt sections, but appear to have crystallized at depth, either concentrated at various levels of gabbroid magma chambers, or expelled intruding as dykes the host peridotites.

In the formation of the Fe-Ti gabbros and plagiogranites, fractionation of a tholeiitic melt at relatively low pressure (<6 kb) associated with filter pressing and cumulus processes, have been operative. The early stages of fractionation appear to have occurred under low fO_2 conditions, while the production of Fe-Ti gabbros in the later stages was probably obtained under relatively higher oxidation conditions. Immiscibility processes producing a peculiar partition of Zr in the SiO_2 -rich liquid may have accompanied these later fractionation stages.

The ophiolite and ocean Fe-Ti rich differentiates show some significant geochemical and mineral chemistry differences with respect to those from stratiform intrusions emplaced into continental crust (e. g. Skaergaard). In fact the high fractionation of the former is controlled, in the later stages, by the precipitation of Fe-Ti oxides rather than by a significant iron enrichment of the silicates. Though these differences can be mainly explained in terms of different compositions of parent magmas, other factors could have acted during differentiation. In particular relatively reduced initial oxidation states are suggested for the parent magmas of the ophiolite and ocean Fe-Ti gabbros, possibly reflecting the lack of interaction with a continental crust.

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