CRYSTAL CHEMISTRY OF AMPHIBOLES FROM GABBROIC TO GRANODIORITIC ROCK-TYPES OF THE ADAMELLO MASSIF (NORTHERN ITALY)

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ABSTRACT. — Further study was carried out on the minerals of the igneous rocks of the Tertiary South-Alpine pluton of Adamello (Northern Italy). The amphiboles from 37 of the most important lithotypes coming from the three main masses composing this composite to multiple epibatholith were selected.

Bulk chemistry on 37 concentrates and some microprobe analyses on zoned areas were carried out. All the amphiboles turn out to be calcic, belonging to the Mg-hornblende. In the more basic rocks, an important role is played by the edenitic-pargasitic and tschermakitic components. On the basis of the $Mg/Mg+Fe^{2+} = mg$ ratio, the amphiboles from the three masses are easily discriminated, and good correlation with the distribution of some elements is also possible.

Among inter-element correlations, of particular interest is that between $(OH+F)$ and occupancy of monovalent ions of A site and of tri-quadrivalent ions of C site, and the correlation between the contents of Fe^{3+} and Ti, responsible for color variations and absorption intensity.

Compositional variations depend on bulk chemistry, mineral assemblages, and physical conditions of formation. Some peculiar characteristics are attributed to intense fluid activity. i.e., the low ratios of Fe^{3+}/Fe_{tot}, and the relatively high contents of Al^{vi} found in amphiboles of foliated rocks characterized by the absence of opaques.

RIASSUNTO. — Vengono esposti i risultati dello studio cristallochimico eseguito sugli anfiboli di 37 rocce rappresentanti i litotipi fondamentali delle tre masse principali dell'epibatolite multiplo-composito dell'Adamello.

Le analisi sono state eseguite mediante le tecniche tradizionali e con la microsonda. Gli anfiboli risultano delle Mg-orneblende, arricchite dei termini puri estremi edenitico-tschermakitico o tschermakitico nelle rocce più basiche. Il rapporto $Mg/Mg+Fe^{2+}$ (mg) appare un fattore chiaramente discriminante per gli anfiboli delle tre masse ed è spesso correlabile con i contenuti di alcuni elementi.

Correlazioni esistono inoltre tra vari elementi; tra queste particolarmente interessanti sono quella tra $(OH+F)$ e le quantità di ioni monovalenti e tri-quadrivalenti rispettivamente nelle posizioni reti-colari A e C, e quella tra i contenuti di Fe^{3+} e Ti, responsabile delle variazioni di colore e di intensità di assorbimento.

Le differenze compositive sono in relazione col chimismo globale della roccia ospite, con l'associazione mineralogica e con le condizioni fisiche di formazione. Una intensa attività dei fluidi sembra responsabile di alcune peculiari caratteristiche, come ad esempio i bassi rapporti Fe^{3+}/Fe_{tot} ed i relativamente elevati contenuti di Al^{vi} degli anfiboli delle rocce foliate sostanzialmente prive di opachi.

Introduction

This paper gives the results of a study on amphiboles from the igneous rocks of the largest Alpine batholith in the Alps, i.e. the Adamello Massif. It is part of a comprehensive study on the mineralogy of the Adamello rocks (see JOBSTRAIBIZER et al., 1983; DE PIERI & JOBSTRAIBIZER, 1983). The last paper contains a brief account of the geology and petrography of the Adamello Massif. For a more account on both the arguments see BIANCHI et al., 1970 and CALLEGARI & DAL PIAZ, 1973.

Textural features of the amphibole change markedly in the different igneous masses of this composite to multiple batholith (fig. 1). In the M. Re di Castello mass it forms small elongated or needle-like prisms; in the W-Adamello and in the Presanella masses it appears as coarse grained crystals, short prismatic in the former and elongated in the latter. Optical properties also change in the mineral of the three masses (BIANCHI et al., 1970).

Very little in known about the chemistry of the Adamello amphiboles. Beside the data

on two amphiboles from gabbros (GOTTFRIED, 1929; CALLEGARI, 1963, 1966) the only published analyses refer to nine optically homogeneous amphiboles, mainly from tonalitic rocks (COCCO & DE PIERI, 1981); the latter will be included in this paper after a minor revision of SiO_2 content owing to the reconnaissance of a systematic error.

The purpose of this study is: *a*) to ascertain the compositional range covered by the amphiboles in the different lithologies of a single igneous mass; *b*) to identify the main chemical parameters responsible for the observed variations and attempt possible correlations with the chemical and/or physical parameters controlling the crystallization of these phases from the magma.

In order to compare bulk rock chemistry with amphibole bulk chemistry we have carried out the analyses on concentrates of hornblende from the rocks; this has also the advantage of giving a better picture of inter-elemental correlation owing to discrete determination of H_2O, F and oxidations state.

To recognize the compositional range inside the single rock (zoning pattern) we analysed by microprobe some selected crystals from seven rocks used for the extraction of the amphibole concentrates.

Sampling and petrographical observations

For this study we utilized the same powdered rocks from which we extracted either the K-feldspars or the biotites which we had previously studied.

However, we added one ultramafic and some mafic rocks to our sample collection in order to cover the entire spectrum of the hornblende-bearing rock-types. Sample localities are shown in fig. 1; better specifications are found in CALLEGARI et al. (1974) and DE PIERI & JOBSTRAIBIZER (1983). The new samples are as follows:

– clinopyroxene-bearing hornblende gabbros (RC 23, RC 24, RC 26, RC 27, RC 29) and hornblende gabbro (RC 28) collected on the western slopes of Cornone di Blumone east of Lago Vacca (Bazena, southernmost part of Adamello Massif). Together with RC 30 (see below), they represent the

mafic members of the M. Re Castello mass;
– olivine-bearing hornblendite RC 30 from M. Mattoni (Bazena);
– one tonalite (A 5) and one pegmatitic gabbro (CAB) from Lago Baitone, belonging to the Adamello mass.

With the above integration of samples, therefore, we had the following rock-types from which amphiboles were separated (RC, A, P refer to M. Re Castello, Adamello and Presanella masses respectively):

– hornblendite = RC 30;
– gabbros = RC 23, RC 24, RC 26, RC 27, RC 28, RC 29, CAB;
– diorites = RC 21, RC 22, RC 25;
– tonalites = RC 1, RC 2, RC 3, RC 4, RC 5, RC 11, RC 12; A 1, A 2, A 3, A 5, P 1, P 2, P 3, P 19, P 20, P 21;
– hornblende-bearing biotite tonalites = QD 3; QD 10; P 4, P 5, P 6, P 7;
– hornblende biotite granodiorites = RC 6, RC 7, RC 9.

Monte Re di Castello mass. In order to represent basic rocks, we chose those outcropping in the southern sector of Re di Castello. These were fine-grained diorites and gabbros with short prismatic amphibole, often pecilitic, with inclusions of plagioclase and rare clinopyroxene (RC 21, RC 22, RC 29); the clinopyroxene sometimes became an essential component in the gabbroic rocks (RC 23, RC 24).

In order to represent the slightly mafic rocks outcropping in variable-grain metre-thick bands, we chose pyroxene-amphibolic gabbros (RC 26, RC 27) with calcic plagioclase. We also included the amphiboles of a gabbroic pegmatite (RC 28) and a fluidally arranged diorite with needle-shaped amphibole (RC 25). All these rocks came from a small area between Passo della Vacca and the western part of the Cornone di Blumone. Lastly, we also analysed the amphibole of a hornblendic ultramafite outcropping on M. Mattoni (RC 30, Bazena area). It coexisted with olivine, ortho- and clinopyroxene, and opaques, mainly Fe-sulphides; of all the analysed amphiboles, it was distinguished for its marked zoning with brown core, often with fine opaque segre-
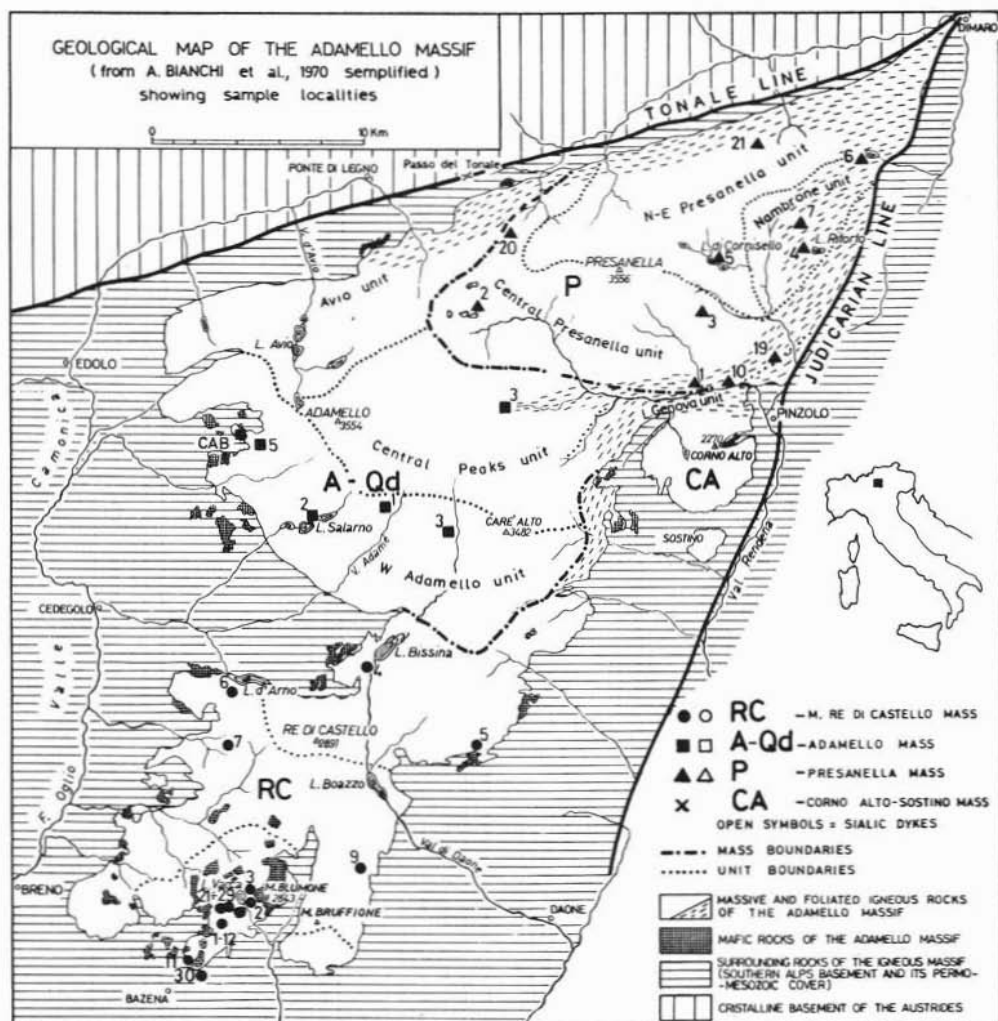
Fig. 1. — Geological sketch map of Adamello Massif, with sample locations (from BIANCHI et al., 1970, simplified).

gations, greenish-brown mantle, and a pale green or colorless oscillatory-structured rim.

In the amphiboles from the above gabbroic rocks, zoning was less marked; they are brown (RC 27, RC 28) or reddish-brown (RC 23, RC 24, RC 29). In the diorite amphiboles zoning was more marked, showing a change in color towards greenish-brown (RC 22) or brownish-green (RC 21, RC 25). All the selected rocks should have hornblende as a primary phase; some of them also contained a pale green or colorless amphibole deriving from subsolidus of pre-existing clinopyroxene uralitization. This amphibole was eliminated during separation,

and data on its composition were only collected by microprobe (RC 30, RC 26). In the gabbroic rocks, the amphibole was sometimes found with opaques, mainly magnetite; opaques were plentiful in all the rocks with the exception of RC 27, RC 28, RC 30. The plagioclase of these rocks was homogeneous and essentially anorthitic in RC 26, RC 27, RC 28 but more or less strongly zoned in the other samples.

In order to represent the amphibole of tonalites, we selected both rocks from the more southerly area (Bazena) and from the more northerly part (Re Castello unit *s.s.*). Considering the variability of the tonalitic

rocks in the Bazena area, it should be pointed out that RC 3 represents the homogeneous tonalitic mass of Lago della Vacca; RC 1 and 2 represent intermediate rocks between quartzdiorites and tonalites with fluidal texture and stumpy prismatic amphibole, outcropping near Passo della Vacca; and RC 11 and 12 represent amphibolic variants of the biotitic leuco-tonalite from Val Fredda, RC 12 being a dyke rock, RC 11 an apophysis at the contact with the marbles. The amphibole of RC 11 is green and probably reflects contamination by nearby carbonatic sediments. In the tonalites the amphibole is normally more or less markedly zoned, brownish-green at the core and green in the rim.

In the granodiorites selected to represent the large unit of Lago Boazzo - Lago Arno, the amphibole is distinguished by greater idiomorphism, more homogeneous composition and pleochroism with more or less intense green tones. As in the tonalites, the amphibole is associated with opaques in the granodiorites.

Adamello mass. The Western Adamello tonalitic unit is clearly distinguished from the preceding tonalites due to the morphology of the amphiboles which form large euhedral crystals with stumpy prismatic habitus. Under the microscope they are homogeneous, with marked green pleochroism. This mineral is commonly associated with opaques. Similar features are found in the amphibole of the hornblende-poor biotitic tonalites of the Central Peaks unit (QD 3). The only basic rock selected was a pegmatitic gabbro with decimetric amphibole collected north of Lago Baitone (CAB).

Presanella mass. The rocks of this mass have long prismatic amphibole, coarse grain in the normal tonalites, smaller in the hornblende-bearing biotite tonalites.

We chose samples P 1, P 2, P 3, P 19 and P 20 to represent the tonalites of the Central Presanella unit, and P 5 and P 21 for the NE Presanella unit. In these rocks the amphibole shows green pleochroism, oscillatory zoning and, occasionally, partial replacement or recrystallization phenomena of pale green amphibole after brownish-green amphibole. Common inclusions are plagioclase, biotite and opaques.

In the hornblende-poor tonalites of the Nambrone unit, differently from that of the other two units, the amphibole is characterized by the absence of oscillatory internal zoning, the presence of large pinkish-brown patches on a sludge-green mineral, and the rarity or absence of opaque inclusions (which are also lacking in the host rock). Of the five samples selected, QD 10, collected in the southern part of Val Nambrone at the boundary with the low Val Genova unit, shows a green amphibole; sample P 5 is a tonalite outcropping in a belt between the Nambrone unit and the NE Presanella unit: by analogy with the optical and chemical features of the amphibole (and biotite), it was grouped with the hornblende-poor tonalites of the Nambrone unit (P 4, P 6, P 7).

Analytical techniques

The amphibole concentrates were obtained from fractions of 100-200 microns by isodynamic and heavy liquid separation techniques.

Purity degree was estimated under the microscope to be more than 99 %. Observed impurities were only some needle-like apatite and sometimes very scarce biotite flakes. Estimated apatite impurities correspond roughly to P_2O_5 content. In these analyses, therefore, this oxide was not included, and the corresponding CaO content was subtracted. In any case, 24 out of 37 analysed amphiboles gave P_2O_5 values usually much less than 0.1 %; others showed P_2O_5 of less than 0.18 %. No correction was made for biotite contamination, since this mineral when present did not exceed 0.1 %.

The chemical data were collected with the same techniques used previously for the coexisting biotites (DE PIERI & JOBSTRAIBIZER, 1983). Analyses performed on the concentrates were: Fe_{tot}, Ti, Mn, Mg, Ca, Na, K and P by atomic absorption and X-ray fluorescence spectrometry (except Na); Si and Al by X-ray fluorescence. Particular attention was devoted to the determination of H_2O and ferrous iron; the latter was determined by titration with $KMnO_4$. Water content was obtained by a double-stage technique: after 3-4 hours' pre-heating at 650° C, the am-

phiboles were heated at $1000°$ C for 6 hours; ignition loss was then corrected for iron oxidation during heat treatment. Fluorine content was determined potentiometrically using an ion-selective electrode. The accuracy of H_2O and F measurements is estimated to be better than 5 %.

Table 1 gives the analytical data of the 37 selected amphiboles, together with number of atoms for 24 (O, OH, F).

Microprobe analyses were performed on strongly zoned amphiboles using an ETEC Autoscan-Autospec microprobe. A computer-adapted program according to MASON et al. (1969) was used for calculations. Total iron determined as FeO was subdivided into ferrous-ferric iron assuming FeO/Fe_2O_3 ratio as obtained from wet analysis of the corresponding amphibole concentrate.

Table 2 shows the microprobe data on the amphiboles, together with number of atoms for 23 (O). Each analysis is the average of the data obtained on 4 adjoining points; letters B, G, VG and C refer to brown, green, very green and colorless areas of the crystals.

Crystal chemistry

Following the criteria already adopted in discussing biotite chemistry from the same rocks (DE PIERI & JOBSTRAIBIZER, 1983), we will use here the term « tonalite » for rocks containing essential amounts of hornblende besides biotite; tonalitic rocks containing very subordinate amounts of amphiboles will be referred to as «bi*-tonalites».

Following the I.M.A. classification scheme (LEAKE, 1978), all the analysed amphiboles are members of the calcic amphibole group. In rocks from dioritic to granodioritic composition, they invariably show bulk compositions corresponding to « magnesio-hornblende ». In rocks of gabbroic composition, however, their bulk chemistry corresponds either to « magnesio-hornblende » or to tschermakitic hornblende (RC 28), tschermakite (CAB) and pargasitic hornblende (RC 27). The amphiboles of Adamello Massif can be easily distinguished on the basis of atomic ratio $Mg/Mg+Fe^{2+}$ = mg: M. Re di Castello, mg > 0.63; Adamello, mg ≃ 0.60; Presanella, mg = 0.57÷0.50.

Fig. 2 shows the behaviour of the atomic fractions of the elements against mg. It is apparent that, apart from differences in Fe^{2+} and Mg, no significant compositional variations exist between the hornblendes from tonalites of different igneous masses. On the contrary, notable variations are observed in the amphiboles from either gabbroic or bi*-tonalitic igneous units; in the former the hornblendes show higher Al^{vi} and Al^{iv}, Ca, Na, Ti and lower Si, K, and Mn contents; in the latter they have the highest Si values, together with lower values of Fe^{3+} and Na. The hornblendes from bi*-tonalites are distinctive for their very low content of Fe^{3+} and their high Al^{vi}.

The comparative analysis of Mg, Fe^{2+} and mg trend reveals that there is a charge balance compensation in the octahedral site between Mg and $(Fe^{2+}+Mn)$: these bivalent ions give a constant contribution of charge by means of averaged 4.04 atoms in all the amphiboles excepting those from bi*-tonalites where the averaged sum is 4.30. Therefore, charge unbalancing related to the $Si \leftrightharpoons Al^{iv}$ substitution must be compensated by reciprocal substitution of monovalent and trivalent ions (plus Ti), as is also apparent in fig. 3.

This plot shows most of the analysed amphiboles are « common hornblendes ». However, those from the gabbros tend to be more pargasitic-edenitic (RC 27, RC 28, CAB), while amphiboles from bi*-tonalites and RC 11, RC 30 have the lowest values of tschermakitic end-member.

Following the procedure of CZAMANSKE et al. (1973, 1977), it is possible to balance the substitution of Ti for bivalent metals in the octahedral site by substitution of Na for Ca in the B sites and of 2 Al for Si in T sites. This allows calculation of the percentage of the two theoretical end-members Na_2Ti $(Mn,Fe^{2+})_4Si_8O_{22}(OH)_2$ and $Ca_2Ti(Fe^{2+},Mn)_4$ $Al_2Si_6O_{22}(OH)_2$. The positive correlation of Ti contents against Al^{iv} and Na, and the negative correlation of Ti against Mn and Fe^{2+} suggest the possibility of using the $Na_2Ti(Fe^{2+},Mn)_4Si_8O_{22}(OH)_2$ end-member in these calculations. This is also suggested by the relationships between Na_B, $(Na+K)_A$, Al^{iv}, $(Al^{vi}+Fe^{3+})$ which seem to exclude the possibility of obtaining the richterite end-member using Na_B.

TABLE 1
Chemical analyses of the amphiboles from Adamello Massif

Sample	RC30	RC23	RC24	RC26	RC27	RC28	RC29	RC25	RC21
SiO_2	48.83	45.49	45.40	45.42	43.86	44.21	45.64	46.56	46.24
TiO_2	0.44	2.26	2.15	1.65	2.07	1.84	1.90	1.15	1.23
Al_2O_3	8.78	9.74	9.68	9.39	12.01	10.88	9.23	8.85	8.89
Fe_2O_3	2.38	3.20	3.66	3.10	3.20	3.45	4.11	4.76	5.24
FeO	6.00	10.55	10.44	10.57	8.71	10.63	10.71	10.69	10.75
MnO	0.15	0.53	0.53	0.37	0.17	0.27	0.48	0.55	0.50
MgO	18.03	12.96	12.49	13.19	13.41	12.50	12.41	12.00	11.82
CaO	11.93	11.71	11.72	12.25	12.42	12.10	11.88	11.82	11.67
Na_2O	1.34	1.53	1.50	1.38	1.87	1.50	1.27	0.97	1.04
K_2O	0.01	0.15	0.20	0.26	0.49	0.44	0.33	0.39	0.62
F	0.04	0.06	0.08	0.06	0.06	0.06	0.06	0.06	0.05
H_2O^+	1.73	1.60	2.02	2.39	1.85	2.30	2.19	2.27	1.97
	99.68	99.83	99.94	100.04	100.13	100.20	100.23	100.18	100.08
$O \equiv F$	0.02	0.02	0.03	0.02	0.02	0.02	0.02	0.02	0.02
Total	99.66	99.81	99.91	100.02	100.11	100.18	100.21	100.16	100.06

Numbers of atoms on the basis of 24(O,OH,F)

Si	6.959	6.687	6.646	6.612	6.389	6.452	6.660	6.793	6.790
Al^{IV}	1.041	1.313	1.354	1.388	1.611	1.548	1.340	1.207	1.210
Al^{VI}	0.433	0.375	0.316	0.222	0.450	0.322	0.246	0.314	0.328
Ti	0.047	0.250	0.237	0.181	0.227	0.202	0.209	0.126	0.136
Fe^{3+}	0.255	0.353	0.403	0.339	0.350	0.379	0.450	0.522	0.579
Fe^{2+}	0.715	1.297	1.277	1.286	1.060	1.297	1.307	1.304	1.319
Mn	0.018	0.066	0.066	0.045	0.021	0.033	0.060	0.068	0.063
Mg	3.828	2.838	2.724	2.860	2.910	2.717	2.698	2.608	2.586
Ca	1.816	1.833	1.823	1.909	1.936	1.886	1.852	1.825	1.823
Na	0.370	0.436	0.425	0.390	0.528	0.424	0.359	0.275	0.296
K	0.002	0.028	0.037	0.050	0.091	0.082	0.061	0.072	0.116
F	0.018	0.028	0.037	0.028	0.028	0.028	0.028	0.028	0.023
OH	1.643	1.568	1.971	2.320	1.797	2.238	2.132	2.208	1.930
T	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000
C	5.000	5.000	5.000	4.933	5.000	4.950	4.970	4.942	5.000
B	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000
A	0.484	0.476	0.308	0.349	0.573	0.392	0.272	0.172	0.246
(OH)	1.661	1.596	2.008	2.348	1.825	2.266	2.160	2.236	1.953
mg^*	0.843	0.686	0.681	0.690	0.733	0.677	0.674	0.666	0.662

$mg^* = Mg/Mg+Fe^{2+}$

TABLE 1 (*segue*)

Sample	RC22	RC1	RC2	RC3	RC4	RC5	RC11	RC12	RC6
SiO_2	45.96	45.77	45.92	45.81	44.60	45.03	48.87	46.93	45.88
TiO_2	1.69	1.37	1.43	1.13	1.50	1.35	0.88	0.95	0.95
Al_2O_3	8.98	8.87	8.43	8.70	9.31	8.79	6.35	7.97	8.53
Fe_2O_3	4.62	5.64	5.04	4.67	5.10	5.35	3.06	4.79	6.04
FeO	10.86	11.30	10.85	11.33	11.79	13.01	10.99	11.27	10.65
MnO	0.59	0.51	0.58	0.61	0.51	0.55	0.64	0.77	0.84
MgO	12.41	11.00	11.91	12.05	11.58	10.77	13.64	11.82	11.50
CaO	11.68	12.05	11.81	11.52	11.40	11.30	11.68	11.57	11.77
Na_2O	1.19	0.89	1.08	0.86	0.96	0.96	1.08	1.23	1.19
K_2O	0.50	0.62	0.49	0.66	0.87	0.71	0.48	0.62	0.56
F	0.05	0.06	0.07	0.08	0.08	0.07	0.06	0.08	0.09
H_2O^+	1.85	2.00	2.06	2.09	2.25	1.93	2.37	2.08	1.91
	100.40	100.13	99.70	99.68	100.13	99.98	100.13	100.12	100.04
$O \equiv F$	0.02	0.02	0.03	0.03	0.03	0.03	0.02	0.03	0.04
Total	100.38	100.11	99.67	99.65	100.10	99.95	100.11	100.09	100.00

Numbers of atoms on the basis of 24(O,OH,F)

Si	6.734	6.749	6.768	6.772	6.597	6.719	7.082	6.891	6.785
Al^{IV}	1.266	1.251	1.232	1.228	1.403	1.281	0.918	1.109	1.215
Al^{VI}	0.284	0.290	0.232	0.287	0.219	0.264	0.166	0.270	0.272
Ti	0.187	0.152	0.158	0.125	0.167	0.151	0.096	0.105	0.106
Fe^{3+}	0.509	0.625	0.559	0.520	0.567	0.600	0.334	0.529	0.672
Fe^{2+}	1.330	1.393	1.337	1.400	1.459	1.623	1.332	1.384	1.317
Mn	0.073	0.064	0.073	0.076	0.064	0.070	0.078	0.096	0.105
Mg	2.709	2.416	2.615	2.654	2.551	2.393	2.944	2.585	2.533
Ca	1.828	1.892	1.858	1.789	1.768	1.772	1.807	1.811	1.838
Na	0.338	0.255	0.308	0.247	0.275	0.278	0.303	0.349	0.341
K	0.093	0.117	0.092	0.124	0.163	0.134	0.089	0.116	0.107
F	0.023	0.028	0.033	0.037	0.037	0.033	0.028	0.037	0.042
OH	1.807	1.966	2.025	2.060	2.219	1.919	2.291	2.037	1.883
T	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000
C	5.000	4.940	4.974	5.000	5.000	5.000	4.950	4.969	5.000
B	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000
A	0.351	0.264	0.258	0.222	0.232	0.285	0.199	0.276	0.291
(OH)	1.830	1.994	2.058	2.097	2.256	1.952	2.319	2.074	1.925
mg*	0.671	0.634	0.662	0.655	0.636	0.596	0.688	0.651	0.658

TABLE 1 *(segue)*

Sample	RC7	RC9	A1	A2	A3	A5	QD3	CAB	P1
SiO_2	45.96	46.15	44.94	45.25	45.80	44.70	45.19	41.94	45.80
TiO_2	1.24	0.92	1.00	1.06	0.93	1.02	0.72	2.15	0.93
Al_2O_3	8.30	8.31	9.12	8.81	8.59	9.36	8.68	14.15	9.14
Fe_2O_3	4.85	4.95	5.13	4.92	4.89	6.08	5.54	3.54	5.34
FeO	11.80	11.45	12.84	12.63	11.75	12.74	12.77	8.12	13.53
MnO	0.59	0.78	0.71	0.64	0.67	0.55	0.96	0.14	0.62
MgO	11.76	12.07	10.59	11.06	11.69	10.11	10.64	13.89	9.82
CaO	11.24	11.76	11.24	11.38	11.46	11.75	11.61	11.55	11.56
Na_2O	1.13	1.08	0.93	1.03	0.94	0.96	1.03	1.98	1.00
K_2O	0.65	0.60	0.74	0.74	0.66	0.77	0.70	0.30	0.60
F	0.08	0.08	0.08	0.08	0.08	0.06	0.08	0.07	0.07
H_2O^+	2.29	1.92	2.11	2.20	2.13	1.99	1.96	2.32	1.55
	100.08	100.09	99.55	99.95	99.72	100.11	99.98	100.26	99.97
O=F	0.03	0.03	0.03	0.03	0.03	0.02	0.03	0.03	0.03
Total	100.05	100.06	99.52	99.92	99.69	100.09	99.95	100.23	99.94

Numbers of atoms on the basis of 24(O,OH,F)

Si	6.773	6.808	6.707	6.716	6.779	6.654	6.745	6.067	6.843
Al^{IV}	1.227	1.192	1.293	1.284	1.221	1.346	1.255	1.933	1.157
Al^{VI}	0.214	0.252	0.311	0.256	0.278	0.295	0.272	0.479	0.453
Ti	0.137	0.102	0.112	0.119	0.103	0.114	0.081	0.234	0.104
Fe^{3+}	0.538	0.549	0.575	0.549	0.544	0.681	0.622	0.386	0.599
Fe^{2+}	1.454	1.412	1.602	1.567	1.454	1.585	1.594	0.982	1.690
Mn	0.073	0.097	0.090	0.080	0.084	0.070	0.121	0.017	0.078
Mg	2.582	2.653	2.355	2.445	2.577	2.241	2.366	2.993	2.186
Ca	1.735	1.854	1.771	1.778	1.789	1.869	1.835	1.768	1.848
Na	0.322	0.308	0.269	0.296	0.270	0.277	0.298	0.554	0.289
K	0.122	0.113	0.142	0.141	0.124	0.147	0.133	0.056	0.115
F	0.037	0.037	0.038	0.037	0.037	0.029	0.038	0.032	0.033
OH	2.250	1.889	2.099	2.177	2.101	1.976	1.951	2.238	1.543
T	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000
C	4.998	5.000	5.000	5.000	5.000	4.986	5.000	5.000	5.000
B	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000
A	0.179	0.340	0.227	0.231	0.223	0.293	0.322	0.469	0.362
(OH)	2.287	1.926	2.137	2.214	2.138	2.005	1.989	2.270	1.576
mg^*	0.640	0.653	0.595	0.609	0.639	0.586	0.597	0.753	0.564

TABLE 1 (*segue*)

Sample	P2	P3	P19	P20	P21	QD10	P4	P5	P6	P7
SiO_2	45.90	44.57	45.01	45.13	45.06	45.51	46.96	46.66	46.96	47.62
TiO_2	1.08	1.43	1.14	1.05	0.95	0.75	1.15	1.17	0.96	0.83
Al_2O_3	8.43	9.20	9.94	9.19	9.62	9.01	7.55	8.20	7.60	7.52
Fe_2O_3	4.71	5.00	5.01	4.89	3.95	4.02	2.38	2.12	2.16	1.19
FeO	13.18	14.06	13.44	13.89	15.35	15.03	16.72	16.29	16.39	17.03
MnO	0.54	0.62	0.51	0.59	0.62	0.68	0.76	0.62	0.70	0.68
MgO	11.18	9.84	10.09	10.36	9.10	9.60	9.40	9.72	9.79	9.87
CaO	11.28	11.67	11.28	11.25	11.53	11.45	11.67	11.62	11.68	11.53
Na_2O	1.01	1.15	1.04	1.00	0.96	0.80	0.80	0.85	0.80	0.80
K_2O	0.47	0.60	0.49	0.41	0.75	0.69	0.60	0.49	0.60	0.50
F	0.07	0.08	0.06	0.07	0.07	0.08	0.07	0.07	0.06	0.06
H_2O^+	2.24	1.81	2.02	2.30	1.90	2.06	2.07	2.07	2.22	2.24
	100.10	100.08	100.05	100.21	99.93	99.80	100.20	100.02	99.96	99.93
O≡F	0.03	0.03	0.02	0.03	0.03	0.03	0.03	0.03	0.02	0.02
Total	100.07	100.05	100.03	100.18	99.90	99.77	100.17	99.99	99.94	99.91

Numbers of atoms on the basis of 24(O,OH,F)

|										
Si	6.771	6.676	6.674	6.682	6.758	6.811	7.005	6.956	6.990	7.073
Al^{IV}	1.229	1.324	1.326	1.318	1.242	1.189	0.995	1.044	1.010	0.927
Al^{VI}	0.236	0.301	0.411	0.286	0.458	0.400	0.333	0.396	0.324	0.390
Ti	0.120	0.161	0.127	0.116	0.107	0.084	0.129	0.131	0.107	0.093
Fe^{3+}	0.523	0.563	0.559	0.544	0.445	0.453	0.267	0.238	0.241	0.134
Fe^{2+}	1.626	1.761	1.666	1.720	1.925	1.880	2.085	2.031	2.040	2.115
Mn	0.067	0.078	0.064	0.074	0.078	0.086	0.096	0.078	0.088	0.086
Mg	2.457	2.196	2.229	2.284	2.033	2.140	2.088	2.159	2.171	2.184
Ca	1.781	1.861	1.786	1.768	1.837	1.810	1.850	1.827	1.854	1.822
Na	0.289	0.335	0.299	0.286	0.279	0.232	0.231	0.245	0.231	0.230
K	0.089	0.115	0.093	0.078	0.144	0.131	0.115	0.093	0.114	0.094
F	0.033	0.038	0.028	0.033	0.033	0.038	0.033	0.033	0.029	0.029
OH	2.202	1.808	1.997	2.271	1.900	2.057	2.059	2.058	2.203	2.218
T	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000
C	5.000	5.000	5.000	5.000	5.000	5.000	4.998	5.000	4.971	5.000
B	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000
A	0.188	0.391	0.234	0.156	0.306	0.216	0.196	0.198	0.199	0.148
(OH)	2.235	1.846	2.025	2.304	1.933	2.095	2.092	2.091	2.232	2.247
mg■	0.602	0.555	0.572	0.570	0.514	0.532	0.500	0.515	0.516	0.508
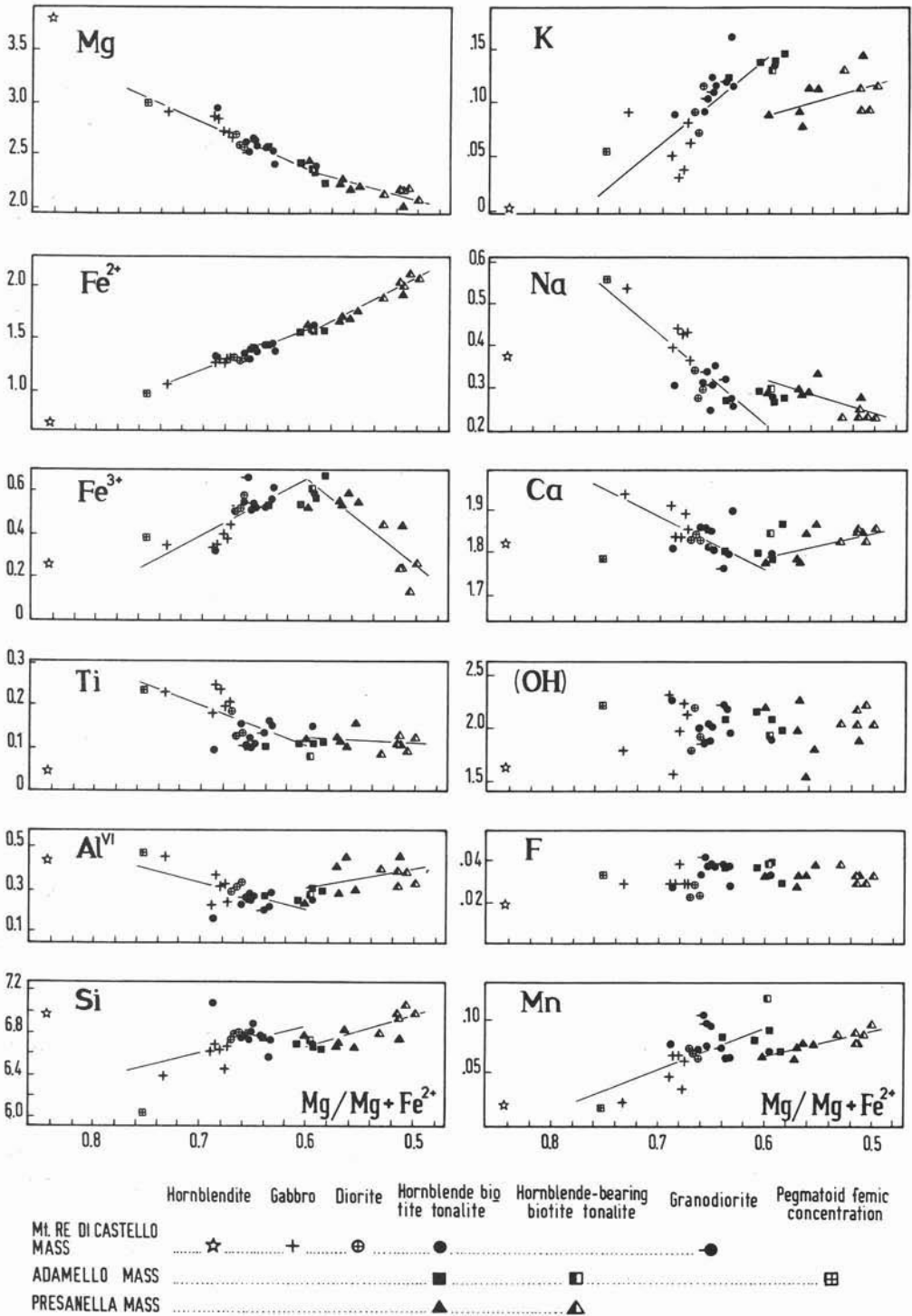
Fig. 2. — Mg/Mg+Fe²⁺ ratios *vs.* atom numbers from wet analyses. Best lines are drawn through the representative points of amphiboles from M. Re di Castello mass (except RC30) and Presanella mass respectively.

TABLE 2

Microprobe analyses of the amphiboles from Adamello Massif

Sample	RC30B	RC30G	RC30C	RC26B	RC26G	RC26C	RC28B	RC28G	RC22B
SiO_2	44.2	46.2	52.5	45.2	48.8	53.7	43.8	47.2	45.1
TiO_2	1.65	0.37	0.15	1.61	0.19	0.35	2.00	1.11	2.17
Al_2O_3	13.3	11.1	5.7	8.1	4.8	1.65	10.8	7.4	9.2
FeO^{*}	8.4	9.9	8.5	14.3	15.9	9.9	14.6	13.8	13.6
$Fe_2O_3^{**}$	2.5	2.9	2.5	3.3	3.7	2.3	3.7	3.5	4.2
FeO^{**}	6.2	7.3	6.3	11.3	12.6	7.8	11.3	10.7	9.9
MnO	0.15	0.22	0.23	0.57	0.43	0.55	0.33	0.24	0.58
MgO	16.3	16.5	19.0	13.0	13.2	18.1	12.6	14.0	13.4
CaO	12.2	11.5	11.7	11.5	11.7	11.7	11.6	11.6	11.4
Na_2O	1.99	1.69	0.26	1.22	0.14	0.00	1.75	1.09	1.40
K_2O	0.28	0.30	0.14	0.32	0.23	0.04	0.35	0.37	0.34
Total	98.8	98.1	98.5	96.1	95.8	96.2	98.2	97.2	97.7

Numbers of atoms on the basis of 23(0)

	RC30B	RC30G	RC30C	RC26B	RC26G	RC26C	RC28B	RC28G	RC22B
Si	6.275	6.605	7.329	6.756	7.292	7.722	6.428	6.923	6.608
Al^{IV}	1.725	1.395	0.671	1.244	0.708	0.278	1.572	1.077	1.392
Al^{VI}	0.501	0.475	0.266	0.183	0.137	0.002	0.297	0.202	0.197
Ti	0.177	0.040	0.016	0.181	0.022	0.038	0.220	0.122	0.239
Fe^{3+}	0.268	0.313	0.263	0.372	0.416	0.249	0.409	0.386	0.463
Fe^{2+}	0.736	0.872	0.735	1.412	1.574	0.938	1.386	1.312	1.213
Mn	0.018	0.027	0.027	0.072	0.055	0.067	0.041	0.030	0.072
Mg	3.448	3.514	3.951	2.894	2.938	3.877	2.754	3.058	2.924
Ca	1.855	1.761	1.749	1.841	1.872	1.802	1.824	1.823	1.789
Na	0.547	0.469	0.070	0.354	0.041	0.000	0.497	0.310	0.398
K	0.051	0.055	0.025	0.061	0.043	0.006	0.065	0.069	0.063
T	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000
C	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000
B	2.000	2.000	2.000	2.000	2.000	1.979	2.000	2.000	2.000
A	0.601	0.526	0.102	0.370	0.098	0.000	0.495	0.312	0.358
mg^{*}	0.824	0.801	0.843	0.672	0.651	0.805	0.665	0.700	0.707

(continua)

* FeO value based on electron microprobe value for Fe.   ** Fe_2O_3 and FeO partitioned according to the ratio found by wet analysis in the same sample. Total is for partitioned Fe_2O_3 and FeO values. $mg^* = Mg/Mg + Fe^{2+}$.

« Common hornblende » is the prevailing end-member. It is associated with variable amounts of pargasite or edenite, and often tschermakite too. The sum of common hornblende plus tschermakite end-members always exceeds that of edenite plus pargasite end-members, with the exception of specimens CAB, RC 27, RC 26 and RC 28.

From the calculations of the above end-members, an excess of $(Na + K)$ in A site sometimes remains, and, owing to the relationships between Al^{iv} and $(Al^{vi} + Fe^{3+})$, this cannot be used to obtain edenite, pargasite or alkali amphibole end-members. Within the limits of experimental error, all other cations are completely consumed. This

TABLE 2 (segue)

Sample	RC22G	RC5B	RC5G	RC5VG	P2B	P2G	P7BG	P7G
SiO_2	45.8	45.4	45.7	44.4	46.8	45.8	46.5	47.0
TiO_2	1.18	1.77	0.84	0.76	1.08	0.87	1.09	0.65
Al_2O_3	7.6	8.4	8.0	8.7	7.7	8.0	7.4	7.0
FeO^*	16.6	15.7	17.1	18.4	15.8	18.5	18.9	19.4
$Fe_2O_3^{**}$	5.1	4.7	5.1	5.5	4.3	5.0	1.2	1.3
FeO^{**}	12.0	11.4	12.4	13.4	12.0	14.0	17.8	18.2
MnO	0.76	0.53	0.73	0.73	0.43	0.61	0.73	0.85
MgO	12.0	12.7	11.7	10.5	12.7	10.8	10.2	10.0
CaO	11.3	11.1	11.2	11.3	10.4	10.5	10.8	11.2
Na_2O	0.80	1.11	0.98	0.51	0.86	1.00	0.75	0.49
K_2O	0.46	0.59	0.53	0.67	0.39	0.43	0.52	0.56
Total	97.0	97.7	97.2	96.5	96.7	97.0	97.0	97.3

Numbers of atoms on the basis of 23(O)

	RC22G	RC5B	RC5G	RC5VG	P2B	P2G	P7BG	P7G
Si	6.828	6.700	6.814	6.719	6.935	6.863	7.018	7.090
Al^{IV}	1.172	1.300	1.186	1.281	1.065	1.137	0.982	0.910
Al^{VI}	0.164	0.161	0.220	0.270	0.279	0.276	0.334	0.335
Ti	0.133	0.197	0.094	0.086	0.120	0.098	0.123	0.073
Fe^{3+}	0.571	0.521	0.571	0.625	0.479	0.563	0.136	0.147
Fe^{2+}	1.495	1.407	1.546	1.695	1.486	1.754	2.246	2.295
Mn	0.096	0.066	0.092	0.094	0.054	0.077	0.093	0.109
Mg	2.664	2.792	2.599	2.367	2.804	2.411	2.293	2.247
Ca	1.804	1.754	1.788	1.831	1.651	1.685	1.746	1.809
Na	0.231	0.317	0.283	0.147	0.247	0.290	0.219	0.143
K	0.088	0.112	0.100	0.129	0.073	0.083	0.100	0.109
T	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000
C	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000
B	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000
A	0.246	0.327	0.293	0.244	0.193	0.237	0.290	0.267
$mg^{\blacksquare}$	0.641	0.665	0.627	0.583	0.654	0.579	0.505	0.505

excess $(Na+K)_A$ is observed in amphiboles with $(OH+F)$ less than the theoretical value of 2. This would suggest that substitution of oxygen for $(OH+F)$ in (OH) sites is necessary in order to balance the excess $(Na+K)$ in A site (DEER et al., 1963). In some cases, however, after calculations, we obtained remains of Si, Al^{iv}, Ca, $(Mg+Fe^{2+}+Mn)$; their proportions exactly correspond to the edenitic end-member but there is no $(Na+K)$ in A site for obtaining it. This fact suggests a substitution of $(H_3O)^+$

for $(Na+K)$ in A site, which corresponds to an « edenite » end-member of the type $(H_3O)^+Ca_2Mg_5(AlSi_7)O_{22}(OH)_2$. Alternatively, the substitution of Al^{iv} for Si in the edenite end-member, lacking $(Na+K)$ in A site may be balanced by $(OH+F)$ substituting for oxygen in (O) site.

It is noteworthy that the greater the charge defect in A sites, the greater the excess of $(OH+F)$ over the value of 2. This is shown by the good negative correlation between $(Na+K)_A$ and $(OH+F)$ (fig. 4).

Similar correlations were also noted by JAN & HOWIE (1982) for the amphiboles of Swat-Kohistan.

A further suggestion for substitutions between anions is given by the correlations also including $(Al^{vi} + Fe^{3+} + 2Ti)$ and $(Al^{iv} + Na_B)$. In the plot $(Na + K)_A + (Al^{vi} + Fe^{3+} + 2Ti)$ vs. $(Al^{iv} + Na_B)$ where the calcic amphiboles should lie along a diagonal line with a $1:1$ slope, the analysed amphiboles show a more or less marked deviation from linearity: the points above the diagonal line correspond to amphiboles with $(OH + F) < 2$; the opposite holds true for the points lying below it. The very good correlation between

distinctly lower in amphiboles from gabbros and bi*-tonalites than in other rock-types (see also fig. 2). Lower proportions of Fe^{3+} generally correspond to higher values of Al^{vi}.

According to JAN & HOWIE (1982), the mutual relationships between Al^{vi}, Ti and Fe^{3+} are responsible for the color and absorption intensity of the amphiboles. Comparison between the colors of the analysed amphiboles as a function of the above elements are consistent with the conclusions of the quoted Authors. The dashed line in the plot of fig. 6 a separates the brown amphiboles (below) from the green ones (above) and corresponds to that proposed by JAN &
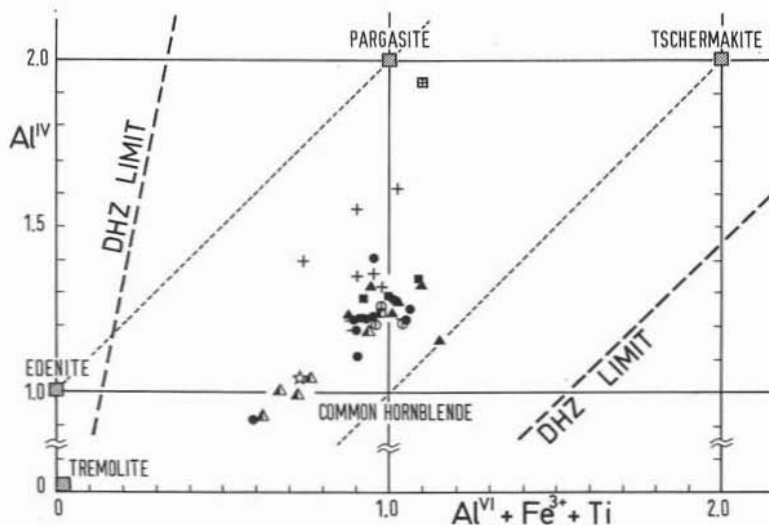

Fig. 3. — Plot of Al^{iv} vs. $(Al^{vi} + Fe^{3+} + Ti)$ of amphiboles of Adamello Massif (adapted from DEER et al., 1963). Symbols as in fig. 2.

$(OH + F)$ and the ratio $(Na + K)_A + (Al^{vi} + Fe^{3+} + 2Ti)/(Al^{iv} + Na_B)$ of fig. 5 indicates the compensating mechanism through that the electrostatic neutrality is achieved.

These data emphasize the importance of the $(OH + F)$ variation in influencing the total chemical composition of amphiboles. The extent of $OH + F$ (and Al^{iv}) compositional range is seen from the variation of A site $(0.57 \div 0.15)$ and of total $Al^{vi} + Fe^{3+} + 2Ti$ $(1.33 \div 0.69)$.

The relations between Al^{vi}, Fe^{3+} and Ti are shown in fig. 6. The highest Ti values are observed in amphiboles from gabbros. No significant variations in Ti are seen among amphiboles from other lithologies. Fe^{3+} is

HOWIE (1982). Absorption intensity seems related to absolute amounts of $Fe^{3+} + Ti$. In fact, the amphiboles with marked absorption either in brown from gabbros or in green from tonalites (RC 1, RC 2, RC 4, RC 5, P 3) also have the highest values of $(Fe^{3+} + Ti)$; conversely, the pale brownish or sludge-green amphiboles of the bi*-tonalites showing weak absorption (P 4, P 5, P 6, P 7) also have the lowest values of $Fe^{3+} + Ti$. These data agree with the results of JAN & HOWIE (1982), but do not require that absorption intensity is significantly depending on the Fe^{2+}/Mg ratio.

Fig. 6 b, $(Al^{vi}$ vs. $Fe^{3+})$ shows a tentative boundary between the brown and green

amphiboles at a value of 0.45 atoms of Fe^{3+}. Moreover even the green amphiboles mostly have lower Al^{vi} than the brown ones the role of Al^{vi} on amphibole color seems difficult to define. There are in fact green amphiboles with high Al^{vi} (e.g., QD 10, P 21, P 19, P 1) and also some brown amphiboles with low Al^{vi} (e.g., RC 29, RC 26). From a comparison of data from table 1 and fig. 2, we believe that the major role on amphibole color is played by Ti and Fe^{3+}.

In order to evaluate the chemical variations produced by zoning, we analysed by microprobe zoned crystals from the following rocks (tab. 2):

RC 30 (hornblendite): strongly zoned crystals with brown core and brownish-green mantle, bordered by a pale green to colorless rim.

RC 28 (hornblende gabbro): strongly zoned crystals with brown core and brownish-green rim.

RC 26 (hornblende-clinopyroxene gabbro): brown amphibole with narrow green rim. Also contains pseudomorphs
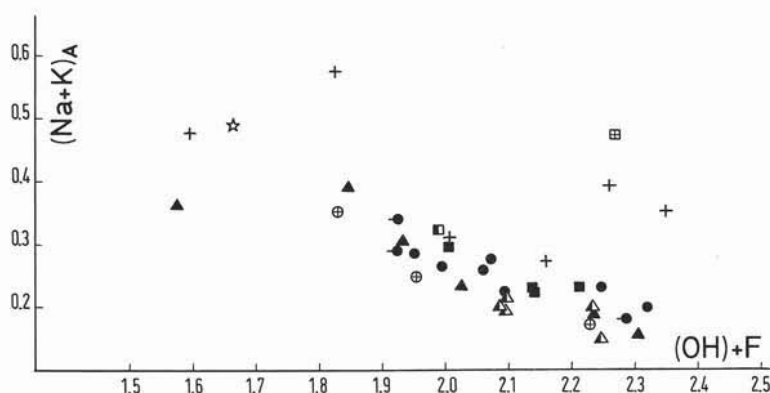

Fig. 4. — Relationship between (OH + F) and $(Na + K)_A$ in amphiboles of Adamello Massif. Symbols as in fig. 2.

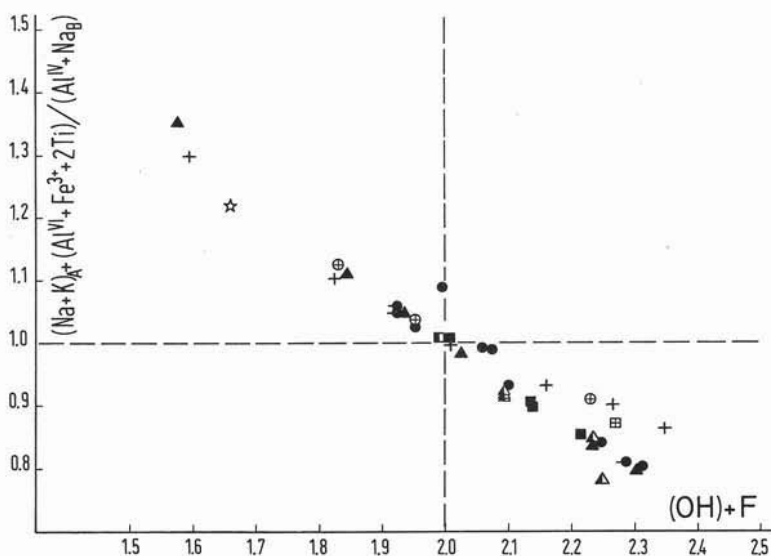Fig. 5. — The linear correlation between cationic ratios $(Na + K)_A + (Al^{vi} + Fe^{3+} + 2Ti) / (Al^{iv} + Na_B)$ and anionic substitution. Symbols as in fig. 2.
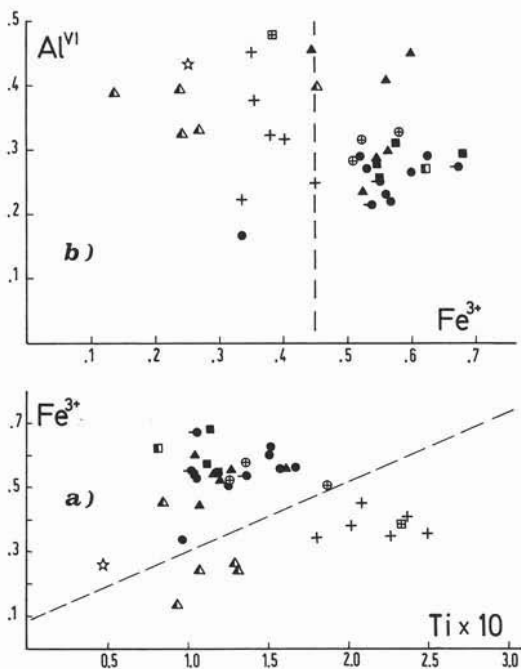
Fig. 6. — Plot of Ti (*a*) and Al^{vi} (*b*) *vs.* Fe^{3+} atom numbers in amphiboles from Adamello Massif. Symbols as in fig. 2.

of colorless amphibole after clino-pyroxene.

RC 22 (pyroxene-bearing hornblende quartz-diorite): brown cores mantled by brownish-green borders.

RC 5 (hornblende biotite tonalite): greenish-brown core mantled by deep green border. A small green unzoned crystal was also analysed.

P 2 (biotite hornblende tonalite): greenish-brown core mantled by deep emerald green border.

P 7 (hornblende-bearing biotite tonalite): pale pink or brownish core mantled by pale green border.

Plots of Si *vs.* mg ratios (fig. 7) indicate that the field of compositional variations within single crystals is similar to that covered by the ensemble of amphiboles from all the different rock-types (fig. 2). Some extension up to actinolite field is due to the effect of deuteric alterations which produce

thin rims either of actinolitic hornblendes (RC 26G, RC 30C) or actinolite pseudo-morphosing clinopyroxene (RC 26C).

The following points can be underlined:

a) the observed compositional range from the cores to the rims of the amphiboles is broader in the mafic and ultramafic rocks than in rocks of intermediate composition; in its turn, the amphibole in the diorite shows a compositional range larger than in rocks of tonalitic composition;

b) Si content usually increases, and Ti, Na decrease from the brown cores to the green borders. The amphibole from tonalite P 2 is an exception;

c) mg values of the amphiboles tends to be nearly constant from the core to the border in the mafic and ultramafic rocks. Similar behaviour is also shown by the hornblende of bi*-tonalite P 7. In the amphiboles from other rocks (quartzdiorite and tonalite), the transition from core to border is marked by a decrease in mg. Comparatively, hornblendes of most gabbros, diorites and tonalites *l.s.* have compositional ranges similar to those displayed by the corresponding zoned hornblendes.

The observed crystallochemical features of the Adamello amphiboles may be summarized as follows.

1. - They are mostly Mg-hornblendes which tend to be rich in pargasite and/or tschermakite in some gabbroic rocks; patches or rims of actinolitic hornblende or late-generation actinolite, linked to recrystallization effects in subsolidus, are also found.

2. - Substitutions occur in all the crystallographic sites:

a) in *T* site Si varies between 6.1 and 7.1, most values falling between 6.6 and 6.8 (fig. 2);

b) in *C* site bivalent ions fall around a value of 4.0 (4.3 in the amphiboles of the bi*-tonalites). Between Mg and (Fe^{2+}+Mn) there is an excellent negative correlation and mg ratio decrease with decreasing Al^{iv} (fig. 2). For tri-quadrivalent ions the largest substitutions Al^{vi} ⇆ Fe^{3+} are observed in rocks other than gabbros; in the latter amphiboles show the highest Ti contents (fig. 6);

c) in *B* site, Ca averages 91 % of the population; the rest is Na or Na+Mn. Fe^{2+} is present in CAB and in those six amphiboles displaying the highest $(Na+K)_A$ values and $(OH+F) < 1.9$ (fig. 4);

d) in *A* site K has a subordinate role, mainly in the amphiboles from gabbroic rocks (fig. 2);

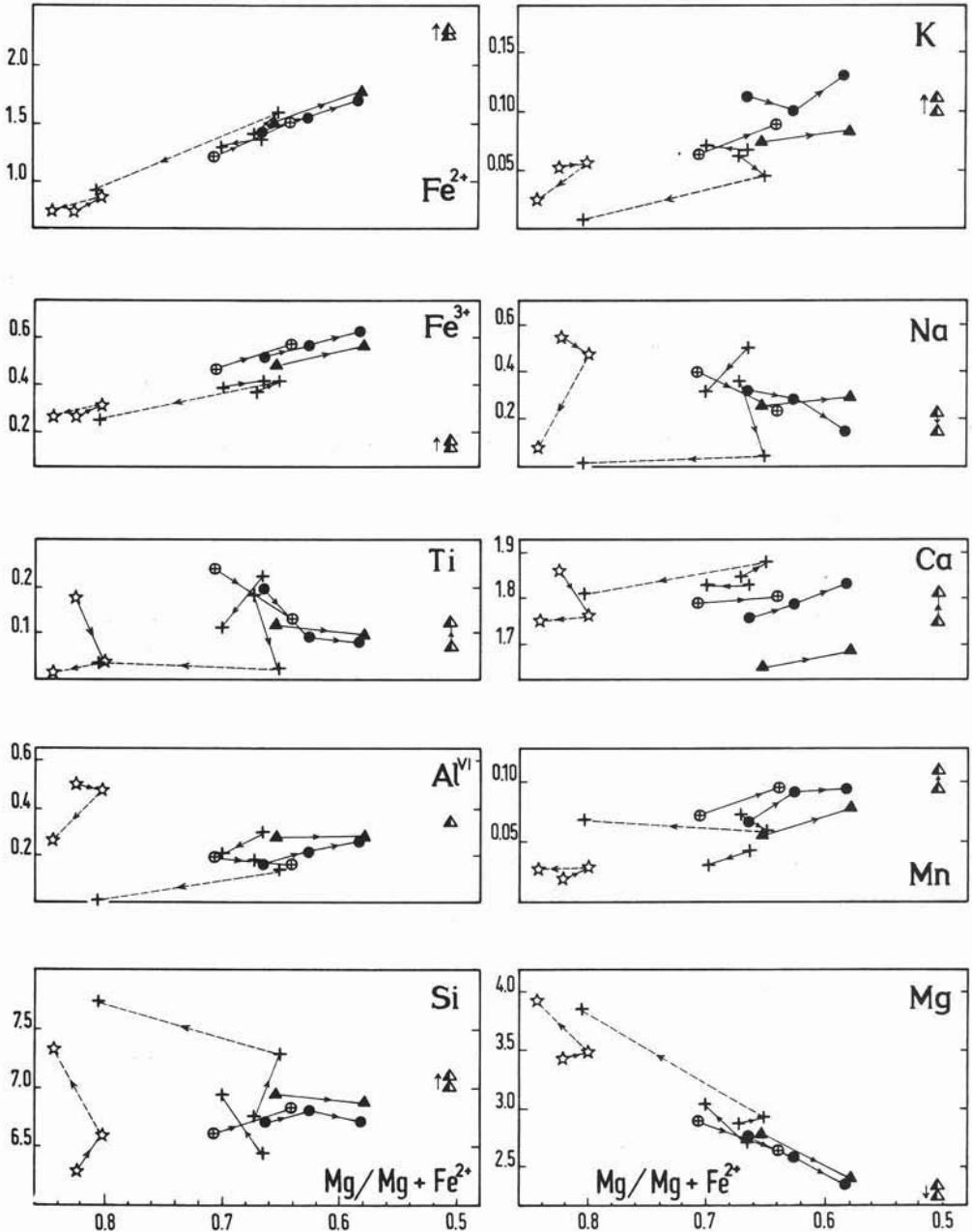*e*) in OH site the $(OH+F)$ sum may be far from the theoretical value of 2, ranging

Fig. 7. — Mg/Mg+Fe²⁺ ratio *vs.* atom numbers of zoned amphiboles (microprobe analyses). Solid lines join compositions of the cores (brown) with those of the rims (green); arrow follows trend from core to rim: dashed lines join the latter with outer deuteric rim (colourless). Symbols as in fig. 2.
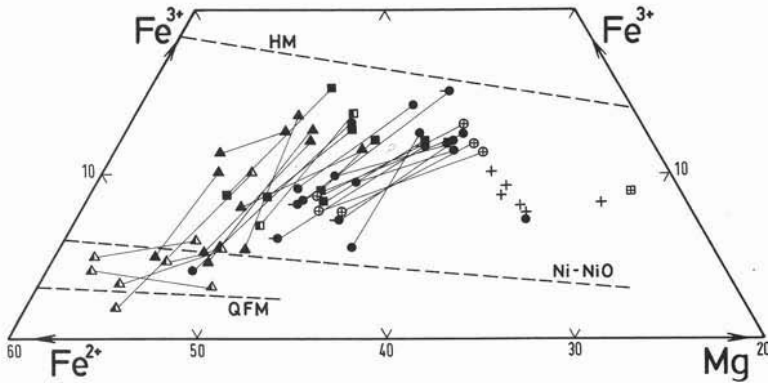
Fig. 8. — Plot of amphiboles and biotites of Adamello Massif in Fe^{3+}-Fe^{2+}-Mg diagram of WONES & EUGSTER (1965): tie line indicates coexisting pairs. Biotites always show higher Fe^{2+}/Mg ratio and lower Fe^{3+} value of coexisting amphiboles. Symbols as in fig. 2.

from 1.6 to 2.3, due to replacement such as $(OH+F) \leftrightarrows O$.

3. - The charge unbalancing due to substitutions of tri- and quadrivalent ions for bivalent ions in C site, of Na for Ca in B site, and to the presence of $(Na+K)$ in A site is only partially equilibrated by $Al^{iv} \leftrightarrows Si$ replacement. Electrostatic neutrality is achieved through the anionic substitution $(OH+F) \leftrightarrows O$. These compensating mechanisms are suggested by the fact that $(Na+K)_A$, $(Al^{vi}+Fe^{3+}+2Ti)$ and their sum are positively correlated with Al^{iv} and negatively with $(OH+F)$. Since Al^{iv} and $(OH+F)$ do not turn out to be significantly correlated, it may be deduced that both more or less independently influence (or are influenced by) the various cationic groupings. Moreover, by means of the calculation of the idealized end-members, a deficit or excess of $(Na+K)_A$ may be identified which can be balanced precisely by anionic substitutions such as $(OH+F) \leftrightarrows O$.

4. - Compositional variations of the zoned crystals are coherent with those shown by whole amphibole with decreasing mg (figs. 7 and 2).

5. - Some chemical peculiarities, such as the Fe^{3+} contents and the Fe^{3+}/Ti ratio (fig. 6 a) justify the differences in color and pleochroism already used by BIANCHI et al. (1970) as criteria discriminating between the amphiboles of the various igneous masses.
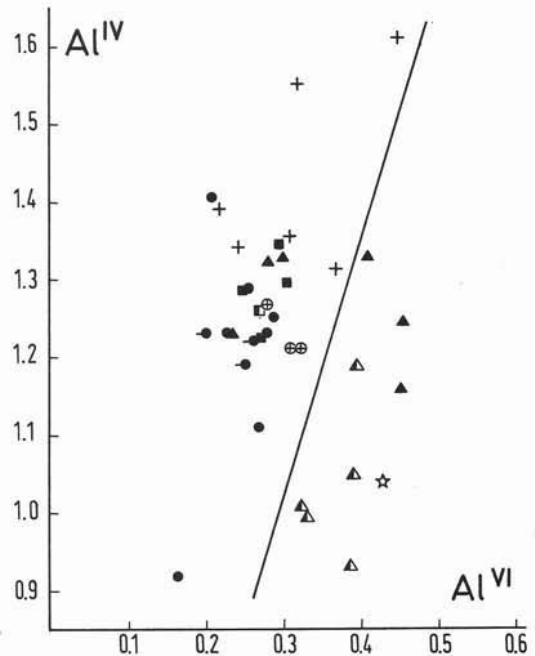

Fig. 9. — Plot of Al^{iv} vs. Al^{vi} of amphiboles from Adamello Massif: solid line of 3.3 ratio is after FLEET & BARNETT (1978). Symbols as in fig. 2.

Concluding remarks

The above ensemble of compositional features allows us to draw some conclusions regarding our aims.

From inter-element correlations against mg, a quite continuous trend in found, in which the amphiboles of each of the three igneous masses occupy definite portions without substantial overlap (fig. 2).

In the composite mass of M. Re di Castello, the mg values, decreasing from the gabbros to diorites and tonalite-granodiorites, follow a fractionation trend, although this is not precisely defined. In fact, the line in fig. 2 is a compromise due to the marked dispersion of some representative points (RC 27, RC 30, RC 11), probably indicating different fractionation processes (cumulus?) or other effects: thus, for example, the pargasitic hornblende RC27 (mg = 0.73) comes from a rock which, in composition and texture, seems to correspond to a primitive gabbro (CALLEGARI E., pers. comm.). Effects of late reequilibration must also be borne in mind for RC 30, and probable contamination by nearby carbonatic sediments for RC 11.

The trend of the Presanella amphiboles in fig. 2 is peculiar: except for the Mg and Fe contents, the hornblendes from tonalites do not show important compositional differences with respect to those from the tonalites of the other masses. Vice versa, the hornblendes of the bi*-tonalites show more Si, Fe^{2+} and Al^{vi}, and less Mg and Fe^{3+}, with minimum values of mg. This means that, with respect to those of Re Castello, the Presanella amphiboles define trends which are shifted or inverted; the trends of the bi*-tonalites, in particular, show a «special» position in the various chemographical representations.

It is interesting to note that the variations of Mg/Fe ratios in the three masses correlate with those already found for the coexisting biotites in the same rocks (DE PIERI & JOBSTRAIBIZER, 1983). However, inside each mass, variations in the Mg/Fe ratio of the amphibole, with respect to those of biotite, turn out to be more sensitive in recording lithological variations.

It is well known that the composition of amphiboles may be influenced both by chemistry and by the physical conditions of the magma in which they crystallize. On the basis of the data in the literature regarding amphiboles from different plutonic complexes, it is not easy to ascertain whether the influence of the various intensive parameters $(T, fH_2O, fO_2, \text{etc.})$ is greater than that of bulk chemistry or vice versa. However, the cases of non-correlation between amphibole composition and lithology (DE ALBUQUERQUE, 1974) seem to be quite limited.

According to our data, a relation undeniably exists between the crystal chemistry of the amphiboles and the composition of their host rocks: we refer to unpublished analytical data and published analyses (CALLEGARI, 1963; BIANCHI et al., 1970) on similar rocks from the same localities.

On this basis, we have observed that, along the sequence of gabbros, diorites and tonalites, both amphibole and host-rock show antipathetic variations for Fe and Mn and sympathetic ones for Si, Al, Mg, Ti, Na and K and for mg values.

In particular, the close dependence between the mg values of the amphibole and the host-rock allow us to give petrological significance to the well-diversified position assumed in fig. 2 by the amphiboles of the three masses. Various Authors have discussed the relations between the mg of the amphibole and the apparent differentiation of the gabbro-granite sequence (LARSEN & DRAISIN, 1950; BEST & MERCY, 1967; KANISAWA, 1975; CAWTHORN, 1976; MURAKAMI, 1977; OBA et al., 1977; KATO et al., 1977). According to CAWTHORN (1976), the mg value $(Mg/Mg+Fe^{2+})$ of whole rock may be used as a temperature indicator and « with differentiation both temperature and mg value are expected to fall; hence the lower the mg value the lower the likely temperature of crystallization ». Following this, we made a preliminary investigation of fractionation factors between amphiboles and bulk rock compositions for various oxides against mg values of the whole rock. In this way we observed:

a) the mg parameter of the rock discriminates the field of the M. Re Castello rocks from that occupied by the Presanella rocks, the latter being characterized by lower mg values. The resulting discrimination conforms to that indicated by the mg values of the amphiboles in fig. 2;

b) the values of the fractionation factors (X MeO Amph/X MeO rock) of MgO and

FeO increase with decreasing mg (temperature), while those of TiO_2 and Na_2O tend to fall.

All these data agree well with the conclusions of CAWTHORN (1976), and confirm some systematic variations between the composition of the amphibole and the host-rock.

It should be noted, in any case, that the mg variations of the amphibole are relatively more marked in the tonalites - bi*-tonalites of the Presanella mass than in the more differentiated gabbro-granodioritic sequences of M. Re Castello. This suggests that additional factors may influence mg values of amphiboles: *temperature, fO₂, total pressure and fluids.*

As regards temperature, reference may be made not only to the above-mentioned relations between temperature and mg of the whole rock, but also to the experimental data of HELZ (1973), SPEAR (1976) and many field observations (see TANAKA, 1980; JAN & HOWIE, 1982).

Accordingly, the portions of Al^{iv}, Ti and Na of the amphiboles decrease with temperature.

On this basis, the data of figs. 2, 3, and 7 suggest higher crystallization temperatures for the amphiboles of the gabbros with respect to those of the tonalites, in particular those of the bi*-tonalites showing the lowest mg values.

On this respect we must bear in mind that, in the amphiboles studied, decreasing Al^{iv} is accompanied by a reduction in the Mg/Fe^{2+} ratio and thus in their thermal stability (see WONES & GILBERT, 1982; figs. 3-4).

The influencing role of the oxygen fugacity may be advisaged on the oxidation state of the Presanella amphiboles. They have a nearly constant iron content (Fe_{tot} 2.2-2.4 atoms); however, Fe^{2+} in amphiboles from tonalites ranges between 1.6 and 1.8, while that from bi*-tonalites is between 2.0 and 2.1. More reducing crystallization conditions may therefore be deduced for the latter, in agreement with the small oxidation ratios both of the co-existing biotites (fig. 8) and the host-rocks ($Fe_2O_3/Fe_2O_3 + FeO =$ 0.16÷0.06), which significantly are substantially devoid of opaque minerals. This is consistent also with the decreasing of Fe^{3+} compensated by Al^{vi}.

Since in the amphiboles Al^{vi} is believed to be partially dependent also on T and P, variations of the octahedral population must be interpreted bearing in mind both the influence of bulk chemistry and the control exerted by the various intensive parameters.

An example of multiple control by environmental factors may be shown by the behaviour of Al^{vi} and Fe^{3+}, whose amounts seem to be independent of Al_{tot} and Fe_{tot} (fig. 2). Fig. 6 *b* shows the representative points of the amphiboles of the gabbros and bi*-tonalites side by side: in the other representations they often appear opposed. If high Al^{vi} due to proportionality with Al^{iv} is to be expected in the amphiboles of the gabbros (HELZ, 1973; LEAKE, 1965, 1971), this reason certainly cannot be invoked for those of the bi*-tonalites, in view of their low Al^{iv} contents. Taking into account the competitive effect between Al^{vi} and Fe^{3+} (fig. 2), it is immediately apparent that Al^{vi} is high due to the scarcity of Fe^{3+} in the latter; but this explanation is not valid for the amphiboles of tonalites P 1, P 19 and P 21 which, with equal Al^{vi}, are among the richest in Fe^{3+}. Interestingly, these three amphiboles come from rocks which, as bi*-tonalites, are foliated (fig. 1); instead, amphiboles from corresponding massive tonalites (P 2, P 3, P 20) show smaller quantities of Al^{vi}. Thus, a pressure-dependent effect on Al^{vi} seems to come to the fore. Apart from the fact that all the Presanella rocks represent the deepest part of the Adamello Massif, it should be remembered that some Authors (FLEET & BARNETT, 1978) believe that relatively high Al^{vi} *vs.* Al^{iv} may reflect a pressure effect. As shown in fig. 9, all and only, the above-mentioned amphiboles show Al^{iv}/Al^{vi} ratios less than 3.3, the value proposed by FLEET & BARNETT as an approximate limit for unaltered igneous Ca-amphiboles. We may be dealing here with a question of pressure linked to fluid circulation, since the latter is documented both by recementing of cataclastic structures and by the finding of accessory tourmaline in the foliated facies of Presanella (BIANCHI et al., 1970). This conclusion also seems to agree both with the excess of (OH + F) in their amphiboles and particularly in the coexisting

biotites (DE PIERI & JOBSTRAIBIZER, 1983) and also with recrystallization phenomena of K-feldspar with high triclinicity (JOBSTRAIBIZER et al., 1983). The influx of fluids may cause the abrupt fall in the Fe^{3+} of the amphibole (and associated biotite), probably linked to their reducing effect.

At present, it is difficult to judge whether this effect is subject to possible external influences (carbonaceous schists of the cover?) ([1]) or wheter it is mainly controlled by the activity ratio aH_2O/aH_2 of the dissolved fluids.

In its turn, the latter may be conditioned by differential losses of H_2 and H_2O and by interaction of these with the components of the melt, particularly with the Si-O-Si bridges whose number increases as differentiation proceeds (MUELLER, 1971).

However, reducing effects may be noticed in the relations between the oxidation ratio (o.r.) of amphibole and parent rock. In effect, if we plot the Fe_2O_3/Fe_2O_3+FeO values of the rock against those of the respective amphibole (and biotite), we see quite good positive correlation up to values of 0.3; for higher values (0.3-0.5) the o.r. of the amphibole tends to decrease, while that of biotite remains stationary and in any case always remains under that of the amphibole (see fig. 8). However, at the lower values of o.r. typical of the bi*-tonalites, the amphibole is in competition only with the biotite and both show very similar values between themselves and the host-rock, while at values between 0.2 and 0.3 the amphibole shows greater o.r. than its host-rock, compensating for the lower values expressed by the biotite. In the gabbros, where mica is lacking, the lowering of the o.r. of the amphibole with respect to its host-rock reflects strong competition with magnetite, in accordance with petrographic observations which show higher modal quantities of the oxide. These facts suggest what the role of fO_2 could be in controlling the composition of ferro-magnesian minerals both directly and through precipitation of competitive phases.

The overall data illustrated here lead to the conclusion that the Adamello amphiboles show compositional dependence on bulk chemistry, temperature, fluid pressure, oxygen fugacity, and mineral assemblages. These effects overlap; only comparative analysis of the hornblendes of the various igneous units of the eruptive complex allows us to identify the influence of the various parameters. Most of them express a model of magmatic crystallization in which compositional factors linked to modes of fractionation may cooperate with physical parameters dependent on intrinsic features (X, T of the original magma) and occasional conditions (depth of emplacement, interaction with non-cognate fluids). We believe a certain amount of caution must be used in interpreting the composition of the hornblendes in petrological terms, especially in magmatic sequences where the minerals are zoned, as in our case, since the different parts of the crystal may reflect very different equilibrium conditions. Observations on zoned crystals are relevant here, since they show the wide variation range found in amphiboles from basic rocks and their progressive reduction as differentiation proceeds.

It is easy to foresee that the fractionation on residual liquids is more efficaceous in basic than in acidic rocks. In the NE Presanella rocks, the compositional differences between cores and rims, although clear under the microscope, in reality turn out to be very limited. An interpretation of the patchy zoning in these amphiboles would be of particular interest, since they may be connected to subsolidus reequilibration.

([1]) The Presanella rocks are embedded in the schists of the South-Alpine basement, while the other plutonic masses were uplifted to more superficial levels, sometimes crossing the Permo-Mesozoic cover.

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