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CLINOPYROXENITE INCLUSIONS
IN THE TRIASSIC VOLCANIC ROCKS FROM LATEMAR,
PREDAZZO, NORTH ITALY

ABSTRACT. — Ultramafic nodules (clinopyroxenites and spinel-clinopyroxenites) and one high-pressure megacryst from Ladinian volcanic rocks in the Predazzo-Monzoni complex are examined. Chemical, optical and isotopic data are presented about nodules, their clinopyroxenes, one high-pressure megacryst and host rocks. The possible genetic hypotheses are debated on the basis of petrochemical and isotopic data. It is suggested that the nodules are cognate xenoliths produced by crystal settling from an uncontaminated alkali-basaltic magma ($^{87}\text{Sr}/^{86}\text{Sr} = 0.7039$) in a magmatic chamber at a depth of about 15-25 km. in the crust. Then the magma was contaminated ($^{87}\text{Sr}/^{86}\text{Sr} = 0.7052$) during its uprising.

The high-pressure megacryst (Lc) has been produced from the same uncontaminated magma at the boundary crust-mantle or in the upper mantle.

RIASSUNTO. — Vengono esaminati noduli ultrafemici (clinopiroseniti e clinopiroseniti a spinello) ed un megacristallo di alta pressione inclusi in rocce vulcaniche dell'area di Predazzo. Sono forniti dati ottici, chimici ed isotopici su noduli tal quali, su pirosseni separati, su un megacristallo e sulle rocce ospiti. Le possibili ipotesi genetiche sono dibattute sulla base dei dati ottenuti; da tale discussione e confronto risulta che i noduli sono di origine « cognate », prodottisi per « settling » in una camera magmatica posta a 15-25 km. di profondità entro la crosta, da un magma incontaminato a rapporto isotopico $^{87}\text{Sr}/^{86}\text{Sr} = 0,7039$. Du-

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rante la risalita tale magma si è evoluto e contaminato nella roccia ospite a rapporto isotopico $^{87}\text{Sr}/^{86}\text{Sr} = 0,7052$. Il megacrystallo di alta pressione si è originato dal medesimo magma incontaminato al limite crosta-mantello o nella parte superiore del mantello.

Introduction.

Some dikes and necks associated with the Triassic alkalibasaltic volcanism of the petrographic province of Predazzo-Monzoni (Eastern Alps, North Italy) contain ultramafic inclusions. Mention is made of this in Vardabasso (1931), but is restricted to the microscopic description of two samples. Two new occurrences were made by the authors in volcanites crossing the Ladinian calcareous-dolomitic massif of Latemar. These occurrences now permit us to return to this subject as a further step in the interpretation of Predazzo-Monzoni magmatism, object of several studies which have been summarized and presented by Gallitelli and Simboli (1971).

The two outcrops are 3 km. from each other. The first consists of a dike, length 2 m., in Cronton d. Minera region, in the eastern part of Latemar; the second consists of a neck, 15 m. in diameter, in the Lastei della Valsorda region (Fig. 1).

Various kinds of ultramafic nodules have been found in these and others outcrops (Lucchini *et al.*, 1973), but the present study concerns the two main types — clinopyroxenites and spinel-clinopyroxenites — which comprise almost all the findings; research is still being carried out on the remaining types of nodules both in the field and in the laboratory.

Host Rocks.

Petrography.

Microscopic examination of the samples allows the host rocks to be divided into two groups, according to their location in the field.

The Cronton d. Minera rocks display a porphyritic texture with megacrystals ⁽¹⁾ of clinopyroxene, olivine, minor quantities of plagioclases, and more rarely spinels. They are set in a microcrystalline

⁽¹⁾ In this case the term « megacrystal » refers to large crystal, both large xenocryst and large phenocryst.

groundmass made up of violet prisms of titaniferous clinopyroxenes, strips of plagioclases, magnetite granules, spots of chlorite and a few thin sheets of biotite. Among the megacrystals the greatest part is formed by clinopyroxenes ($2V_z = 54^\circ - 60^\circ$, $c \wedge z = 37^\circ - 43^\circ$, diop-

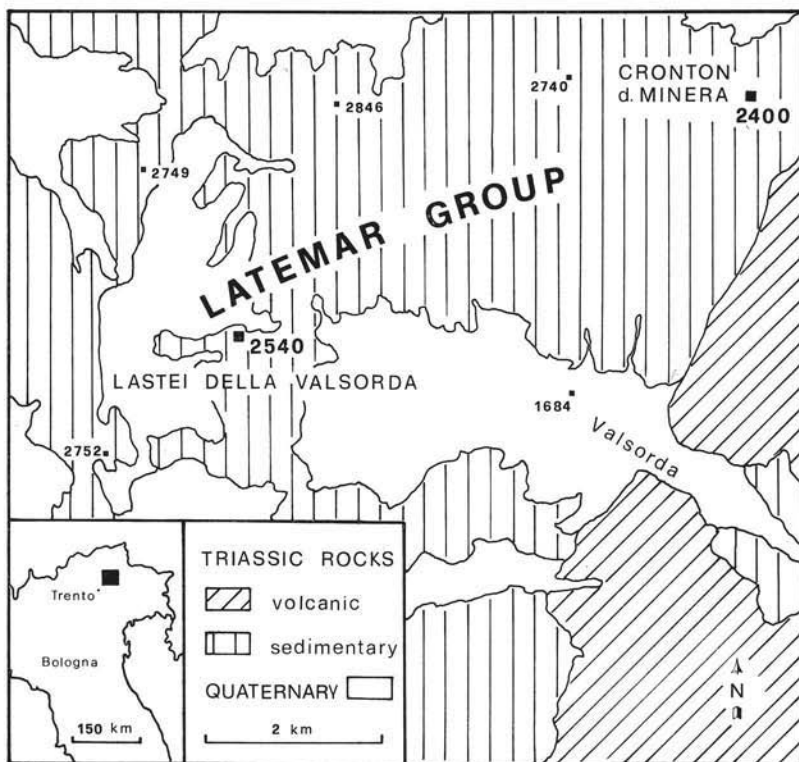


Fig. 1. — Generalized geologic map and occurrences location.

sidic terms). They are irregular in form, often with sinuous edges; they are zoned (a colourless core with distinctive violet rims) and in good condition, but can include small crystals of serpentinized olivines and spinels. The form, sizes, zoning and reaction rims all suggest that these megacrystals probably resulted from nodules, and the use of the terms xenocrysts seems more appropriate.

The olivines ($2V \approx 90^\circ$, F_{088-90}) are subhedral crystals almost totally serpentinized. The size of the crystals varies and often reaches that of the microlites in the groundmass; some crystals include picotite and/or magnetite.

The plagioclases are present both as unaltered subhedral phenocrysts (An_{55}), sometimes gathered into glomeroporphyritic clusters, and as zoned xenocrysts (core An_{85-90} , rim An_{48-50}) irregular in form and very clouded. Quite common among the spinels is a brown type (picotitic term), whose size and colour varies, and which is often rimmed with a corona of magnetite. A rarer type of spinel is the greenish amoeboid one (hercynitic term).

The Lastei della Valsorda host rocks display a porphyritic texture with megacrystals of clinopyroxene ($2V_z = 59^\circ$, $c \wedge z = 43^\circ$) and olivine (F_{088-90}) and rarer spinels, set in a micro- to crypto-crystalline groundmass. This groundmass consists of plagioclases (An_{55}) with an obvious flow texture, violet euhedral titaniferous clinopyroxenes, and opaque oxides. The diffractometric analyses showed that analcime exists amongst the unidentified materials. Among the megacrystals, the clinopyroxenes, olivines and spinels have the same characteristics already mentioned for the Cronton d. Minera rocks, but the size and condition of the olivines is more variable. There are also a few large-sized (cm. 1.5) crystals of pyroxene, which show spinel exsolutions (hercynitic type, $a_0 = 8.135 \text{ \AA}$) lying parallel to (110) of the host (Lc sample).

The presence of several fragments of rocks torn off during the magma rising brings about a marked lack of homogeneity in the samples.

Chemistry.

Five samples were analyzed, three of which (36 - 41 - L) were from Lastei della Valsorda, and two (33 - 111 b) from Cronton d. Minera, in an attempt to cancel the lack of homogeneity in the individual outcrops.

The chemical analyses were carried out according to the different methodologies: SiO_2 , R_2O_3 and H_2O by gravimetric method; Fe_2O_3 and MgO by atomic absorption spectrophotometry; Na_2O and K_2O by flame photometry; MnO , CaO , K_2O , TiO_2 by XRF; FeO by titrimetric method; P_2O_5 by colorimetric method; CO_2 by gasvolumetry.

TABLE 1.

Chemical analyses, C.I.P.W. norms, A.M.S. normative composition of the host rocks.

Wt. %	33	111 b	36	41	L
SiO ₂	44.77	44.24	42.19	43.06	43.32
TiO ₂	1.50	1.71	1.42	1.42	1.37
Al ₂ O ₃	12.00	14.61	14.40	17.87	16.61
Cr ₂ O ₃	n.d.	0.09	n.d.	0.03	0.04
Fe ₂ O ₃	4.73	3.17	3.40	2.23	2.66
FeO	5.36	6.39	5.11	5.77	5.61
MnO	0.15	0.14	0.13	0.15	0.15
MgO	12.54	9.86	7.30	8.10	7.72
CaO	9.47	9.83	13.39	13.10	13.71
Na ₂ O	1.77	1.81	3.47	3.14	3.16
K ₂ O	1.14	1.81	1.14	1.21	1.09
P ₂ O ₅	0.33	0.30	0.31	0.39	0.36
CO ₂	0.38	0.52	2.03	0.88	0.43
H ₂ O ⁺	4.43	4.97	3.99	2.69	3.40
H ₂ O ⁻	1.56	1.13	1.34	0.54	0.76
	100.13	100.58	99.67	100.58	100.39
C.I.P.W. norms					
or	6.73	10.68	6.73	7.12	6.39
ab	14.93	15.30	12.47	6.60	5.45
an	21.41	26.35	20.35	31.08	27.94
di	wo	8.78	7.18	13.04	10.75
	en	6.93	5.14	9.46	7.40
hy	fs	0.84	1.39	2.35	2.47
	en	11.78	2.71	—	—
fo	fs	1.40	0.73	—	—
	fo	8.67	11.62	6.05	8.88
fa	1.15	3.43	1.64	3.26	2.21
mt	6.87	4.59	4.94	3.25	3.87
il	2.84	3.25	2.69	2.69	2.60
ap	0.77	0.71	0.71	0.91	0.84
ca	0.86	1.17	4.62	2.01	0.98
ne	—	—	9.12	10.79	11.50
A.M.S. normative composition					
Plagioclase	37.45	47.48	43.41	47.23	40.80
Sanidine	8.42	12.55	—	—	—
Nepheline	—	—	10.28	13.15	12.50
Clinopyroxene	39.79	23.59	33.19	24.83	36.63
Olivine	8.14	10.02	5.80	9.47	6.09
Magnetite	3.49	2.95	3.14	1.98	2.40
Ilmenite	1.36	2.12	0.66	1.41	0.26
Apatite	0.81	0.59	0.71	0.78	0.74
Calcite	0.54	0.70	2.81	1.15	0.58

Samples 33-111 b : from Cronton d. Minera

Samples 36-41-L : from Lastei della Valsorda

The chemical analyses of the rocks, the C.I.P.W. norms and the AMS calculation (Rittmann, 1965) are presented in Table 1. Based on the diagram (Fig. 2) and the classification criteria suggested by Streckeisen (1967) the host rock at Lastei della Valsorda is an analcime-tephrite, whereas that of Cronton d. Minera is a latite-basalt.

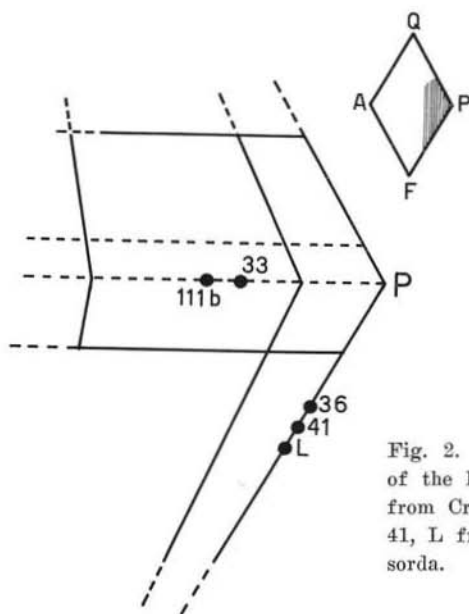


Fig. 2. — Q-A-P-F diagram of the host rocks - 111b, 33 from Cronton d. Minera; 36, 41, L from Lastei della Valsorda.

Clinopyroxenite Inclusions.

Petrography.

In the Cronton d. Minera outcrop the inclusions cover a wide range of shapes and sizes. The shape varies from subspherical to ellipsoidal, from subprismatic to thin tiles. The rims are usually rounded in the larger inclusions becoming angular in the smaller ones. The sizes vary from 25 cm. (max. diameter) to a few centimeters. The colour also varies from bright green to almost black. The elongated inclusions lie with their longer axis subparallel to the direction of the host dike, and are concentrated towards the selvages. Unfortunately it was impossible to locate this trend statistically.

In the Lastei della Valsorda outcrop the inclusions vary within a narrow range of shapes and sizes. Their biggest is 5-6 cm. in dia-

meter and they are usually all of one size with rims ranging from rounded to sharp-edged. Although the host rock is of a prominent flow texture the inclusions are randomly placed. Furthermore, their shapes and sizes could lead to hypothesize their being breccias through disintegration of larger inclusions, a theory which is in accordance with the explosive character of the host rock.

Clinopyroxenites.

Included in this group are the nodules paragenetically alike but different in grain and textural characteristics. Their grain, in fact, varies a great deal from one nodule to another and even within the one nodule, giving it a banded structure. The cumulitic texture, which varies from ad — to mesocumulitic, is obvious in each of these types. In some nodules we can see triple-point textures which, although prevalent to metamorphic rocks (Spry, 1969), could nonetheless be attributed to adcumulitic textures, as has already been seen in the stratiform ultramafic complexes (Wager and Brown, 1968), or to a reaction between the cumulitic phases and the intercumulus material (Giannelli *et al.*, 1972). In some clinopyroxenites the intercumulus phase is still given by clinopyroxene, in others, however, it is given by clusters of chlorite, chalcedony and/or carbonates which may come from trapped liquid, or, in some cases, from olivine. Many nodules, especially the larger ones, are variably cataclasis, with fractures which can break up even individual crystals into many parts. These fractures are usually filled with carbonates and transformation products. The clinopyroxenes ($2V_z = 56^\circ$, $c \wedge z = 39^\circ$, averages of 60 readings, diopsidic terms) vary from subidiomorphic to allotriomorphic, are slightly pale-green coloured, neither twinned nor display exsolution lamellae; chemical analyses are given in Table 2.

Spinel-clinopyroxenites.

These inclusions reach a maximum diameter of 5 cm. The grain size is on average 0.60 mm. (0.20 — 1.40). They have a typical cumulitic texture with clinopyroxenes as their adcumulus phase and spinels as the intercumulus phase. The modal percentages of the single components vary over a narrow range: clinopyroxenes 80-82%, spinels 10-13%, alteration products 7-8%. The clinopyroxenes ($2V_z = 58^\circ$, $c \wedge z = 40^\circ$, averages of 100 readings, diopsidic terms) are allotrio-

morphic, with a slight greenish colouring, neither twinned nor display exsolution lamellae; their chemical analyses are given in Table 2. The black spinels are close to magnetite (magnetite-magnesioferrite, $a_0 = 8.36\text{--}8.37 \text{ \AA}$).

Marginal reactions between nodules and host rock.

The nodules show clear signs of reaction with the host magma. In particular, there is an obvious pinkish-brown zoning which affects the rims of the pyroxenes situated on the edges of the nodules; this phenomenon can also be seen in the clinopyroxenes on the inside of the nodules coming into contact with the magma which has penetrated along the rims of the grains. Host magma aggression can, in a few cases, lead to a complete break-up of the nodules, and the crystals spread over the groundmass clearly show their xenocryst origin.

In these cases the zoning on the rims can be extended or show characteristics similar to those of the groundmass pyroxenes. When the clinopyroxenes have a light-green colouring, a colourless intermediate zone can be seen between the pinkish-brown outside rim and the core. The marginal interaction in some nodules is always shown by an increase in the clinopyroxenes along the rims with the result that they are well-finished and are bigger compared to the inner individual ones.

Chemistry.

Nine clinopyroxenes were analyzed, 6 from clinopyroxenites, 2 from spinel-clinopyroxenites and one high-pressure megacryst (Lc). The samples were chosen on the basis of microscopic examinations of more than 70 thin sections. The chemical analyses and the atomic ratios ($O = 6$) are given in Table 2, while the pyroxene components calculated from the analyses of Table 2 according to the method by Kushiro (1962) are given in Table 3. From the data obtained we can see that there is a homogeneous group of analyses relevant to samples 1,7,34,37,A,C (from clinopyroxenites) and a second group made up of samples 2,41 (from spinel-clinopyroxenites); sample Lc is completely different. The essential difference between the two groups can be reduced to a different Fe tot., and Cr_2O_3 content (ratio 1 : 10) whereas Lc is completely different due to its high Al_2O_3 , TiO_2 and Na_2O

TABLE 2.

Chemical analyses and atomic ratios (0 = 6) of clinopyroxenes.

	1	7	34	37	A	C	2	41	Le
SiO ₂	53.24	51.05	53.82	52.02	53.20	53.08	51.08	47.72	1.595
TiO ₂	0.10	0.12	0.15	0.24	0.49	0.40	0.31	0.49	1.30
Al ₂ O ₃	1.26	1.86	1.66	2.92	2.36	1.61	2.15	6.42	13.83
Cr ₂ O ₃	0.31	0.25	0.22	0.15	0.15	0.13	0.02	0.01	0.01
Fe ₂ O ₃	0.77	1.95	0.66	0.85	—	0.31	2.77	1.03	1.84
FeO	2.17	2.17	1.66	2.67	2.63	3.36	3.65	5.50	5.52
MnO	0.11	0.11	0.05	0.04	0.05	0.07	0.13	0.16	0.11
NiO	0.02	0.02	tr.	tr.	tr.	tr.	0.02	tr.	tr.
MgO	17.36	17.34	17.90	16.88	17.01	16.05	15.85	15.32	13.64
CaO	23.57	22.79	22.84	23.64	24.18	24.03	23.25	22.64	18.83
Na ₂ O	0.21	0.19	0.16	0.28	0.15	0.22	0.19	0.31	0.73
K ₂ O	tr.	0.06	0.02	0.04	0.01	tr.	0.02	0.01	0.08
H ₂ O ⁺	0.94	0.91	0.44	0.72	0.37	0.82	0.61	0.67	1.67
H ₂ O ⁻	0.08	0.16	0.13	0.10	0.14	0.07	0.20	0.60	0.27
	100.10	99.98	99.71	100.55	100.74	100.15	100.25	100.21	100.00
Si	1.956	1.896	1.963	1.906	1.933	1.956	1.898	1.780	1.595
AlIV	0.044	0.104(*)	0.037	0.094	0.067	0.044	0.220	0.220	0.405
AlVI	0.011	—	0.034	0.032	0.034	0.026	—	0.062	0.210
Ti	0.003	0.003	0.004	0.007	0.013	0.011	0.008	0.014	0.037
Fe ⁺³	0.021	0.031	0.018	0.023	—	0.008	0.069	0.029	0.052
Cr ⁺³	0.009	0.007	0.007	0.004	0.004	0.004	—	—	—
Fe ⁺²	0.065	0.067	0.051	0.082	0.080	0.103	—	0.171	0.174
Mn	0.003	0.003	0.002	0.001	0.002	0.002	0.004	0.005	0.003
Ni	0.001	0.001	—	—	—	—	0.001	—	—
Mg	0.950	0.973	0.960	0.922	0.921	0.881	0.878	0.852	0.767
Ca	0.928	0.947	0.892	0.928	0.941	0.949	0.926	0.905	0.761
Na	0.015	0.014	0.011	0.020	0.010	0.016	0.014	0.023	0.053
K	—	0.003	0.001	0.002	—	—	0.001	—	0.004
WXY	2.006	2.036	1.993	2.021	2.005	2.000	2.014	2.061	2.061

Samples 1-7-34-37-A-C: from clinopyroxenites.

Samples 2-41: from spinel-clinopyroxenites.

Sample Le: high-pressure megacryst.

(*) Includes Fe⁺⁴ 0.023 and 0.008 respectively.

TABLE 3.

Pyroxenes components calculated from the chemical analyses of the clinopyroxenes in Table 2 (Mol. per cent).

	1	7	34	37	A	C	2	41	Le
$\text{NaFe}^{+2}\text{Si}_2\text{O}_6$	1.5	1.7	1.2	2.2	—	0.8	1.5	2.2	5.0
$\text{NaAlSi}_2\text{O}_6$	—	—	—	—	1.0	0.8	—	—	0.5
$\text{CaTiAl}_2\text{O}_6$	0.3	0.3	0.4	0.7	1.3	1.1	0.8	1.4	3.6
$\text{CaFe}^{+3}\text{AlSiO}_6$	0.6	1.4	0.6	0.1	—	—	4.5	0.6	—
$\text{CaAl}_2\text{SiO}_6$	2.0	—	4.1	3.6	2.8	2.2	—	6.0	19.9
$\text{CaFe}_2^{+3}\text{SiO}_6$	—	—	—	—	—	—	0.8	—	—
CaSiO_2	44.8	45.8	42.2	43.7	44.9	45.8	42.9	39.9	25.2
MgSiO_2	47.4	47.3	48.8	45.6	45.9	44.0	43.6	41.4	37.2
$\text{Fe}^{+2}\text{SiO}_2$	3.4	3.5	2.7	4.1	4.1	5.3	5.9	8.5	8.6

contents and the lower CaO content. In the Ca-Mg-Fe diagram, Figure 3, the first group falls in the diopside field, the second on the boundary of the field with salite, and Lc in the augite field.

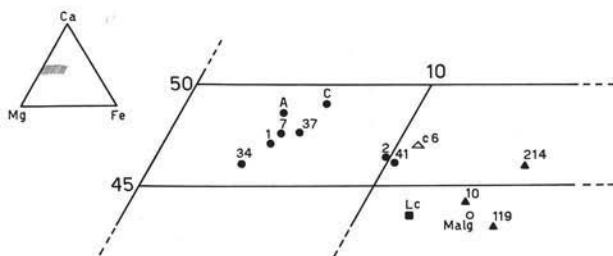


Fig. 3. — Ca - Mg - Fe diagram. Solid circle: epx from nodules (this work); open circle: epx from pyroxenite mass (unp. data); solid triangle: epx phenocrysts in lavas (Lucchini *et al.* 1970); open triangle: epx from ultramafic nodule in camptonite dike (Lucchini *et al.*, 1969); solid square: high - pressure megacryst (this work).

Initial Strontium Isotopic Composition.

For a further investigation on the origin of the ultramafic nodules, the $^{87}\text{Sr}/^{86}\text{Sr}$ initial ratio has been measured on the clinopyroxenes from the nodules and on the host rocks. This kind of determination can be useful, as demonstrated by various Authors (Compston and Lovering, 1969; Stueber, 1969; and others) especially it can be interpreted with other petrochemical parameters. In fact, in a very simple way a different initial $^{87}\text{Sr}/^{86}\text{Sr}$ in respect to the host rock means a different provenance of the nodules (accidental origin); the equality does not help for the accidental origin and is consistent with a cognate one, but finally, as pointed out by Compston and Lovering (1969), more complicated schemes can be envisaged to justify different isotopic compositions with a cognate origin, so that the Sr isotopic composition alone is of poor utility if not connected with the other chemical and petrological data.

Measurements of Rb and Sr were made by the isotope dilution technique using an Atlas CH4 mass spectrometer equipped with an ion multiplier; K was measured by atomic absorption using a Perkin-Elmer spectrophoto-

meter. Sr isotopic composition was determined on unspiked samples using an AEI mod. 503 S mass spectrometer. The obtained values were normalized to the value of sea-water strontium.

The obtained results are shown in Table 4. It is evident that the mean value of initial $^{87}\text{Sr}/^{86}\text{Sr}$ is different from host rocks to the nodules pyroxenes, being significant lower in the last ones; this fact is

TABLE 4.
Rb, Sr contents and Rb/Sr and $^{87}\text{Sr}/^{86}\text{Sr}$ ratios.

Sample	Rb ppm	Sr ppm	Rb/Sr	$^{87}\text{Sr}/^{86}\text{Sr}$ *	$^{87}\text{Sr}/^{86}\text{Sr}$ **
HOST ROCKS					
<i>Cronton d. Minera</i>					
111 a	52	460	0.113	0.7067	0.7057
111 b	42	489	0.086	0.7069	0.7061
<i>Lastei della Valsorda</i>					
LL	68	488	0.138	0.7059	0.7050
L3	73	562	0.130	0.7052	0.7042
L7	167	156	1.107	0.7151	0.7055
CLINOPYROXENITE NODULES					
Cronton d. Minera	2.2	75	0.029	0.7068	0.7068 ²
Lastei della Valsorda	3.2	135	0.024	0.7063	0.7063 ²
PYROXENES					
a) from spinel-clinopyroxenite nodule					
2	1.3	47	0.028	0.7048	0.7048
b) from clinopyroxenite nodules					
7	0.4	85	0.005	0.7032	0.7032
34	1.7	68	0.025	0.7037	0.7037
c) high-pressure megacryst					
Le	3.4	84	0.040	0.7040	0.7040
d) from pyroxenite mass					
Malg.	1.8	55	0.033	0.7058	0.7058
e) from skarn					
Sk	2.2	81	0.027	0.7065	0.7065

* normalized to $^{86}\text{Sr}/^{88}\text{Sr} = 0.1194$

** corrected for 217 m.y.

2 - The higher values of Sr ratios of the nodules if compared to those of their clinopyroxenes are due to veinlets of secondary minerals crossing the nodules, i.e. calcite.

also evident from the Figure 4, in which a 217 m.y. isochron has been drawn (the 217 m.y. age has been chosen on the basis of some unpublished K/Ar age determinations on the Latemar rocks) together with the points relative to the clinopyroxenes from the nodules and from total host rocks. The isotopic results will be commented, taking into account the different genetic hypotheses, together with the geochemical and petrological evidences.

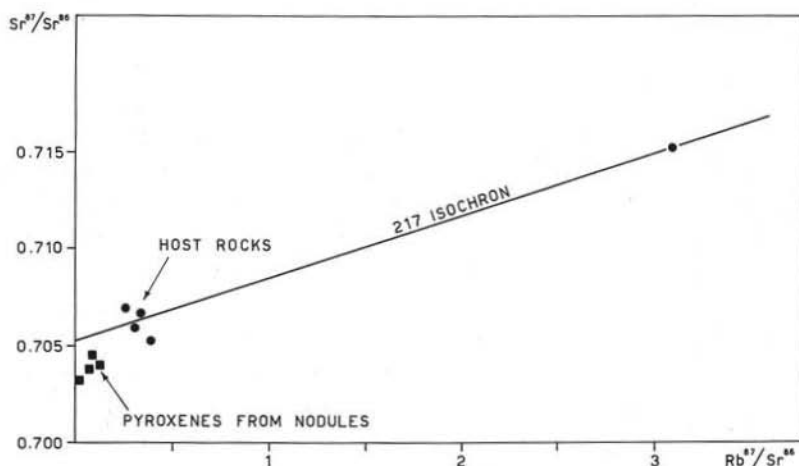


Fig. 4. Isochron line of the Latemar host rocks showing the initial ratio $^{87}\text{Sr}/^{86}\text{Sr} = 0.7052$. Isochron line: 217 ± 25 m.y.

Petrogenesis of the Ultramafic Inclusions.

The study of the ultramafic nodules is of considerable interest because it may provide information on the upper mantle and on the origin of basaltic magma. At present we know of more than 200 places in the world (Forbes and Kuno, 1965) where ultramafic inclusions are found in basaltic rocks. Among the more plentiful nodules we can find the lherzolites often associated with the dunites, harzburgites, wehrlites, pyroxenites or gabbros. The Authors who have taken an interest in the problem of ultramafic inclusions have constructed various hypotheses on their origin in connection with the origin of basaltic magma. The hypotheses can in essence be reduced to 1) xenoliths of the upper

mantle; 2) residues of partial melting of the upper mantle after having produced basalt magma; 3) « cognate xenoliths » both as products of crystal settling from primordial magmas and 4) as products of crystal settling from magmas now known as the host rocks; 5) accidental xenoliths of crustal rocks crossed by the rising magma; 6) reaction of the magma with carbonatic rocks, and particularly as regards the pyroxenite inclusions.

In order to try to explain the origin of the Latemar inclusions and their connection with the host rock we compare the analytic results with those already published in relation to the above-listed hypotheses.

1) *Xenoliths of the upper mantle.*

The Authors prepared to consider the ultramafic inclusions as xenoliths of the upper mantle (Ross *et al.*, 1954; Harris *et al.*, 1967; Ernst, 1965; Aoki and Kushiro, 1968; Kurat, 1971; and others) refer to the well-known spinel-lherzolites inclusions and/or garnet-lherzolites with parageneses given by olivine, orthopyroxene, clinopyroxene, spinel and/or garnet. None of the nodules studied shows any such paragenesis, but Kutolin (1970) admits that there may be pyroxenites in the upper mantle, and accounts for their rarity by the fact that they break-up easily while the host magma is rising to the surface.

These clinopyroxenites, however, are really Cr-diopsidites (Kutolin and Frolova, 1970), which differ considerably from the studied samples from a chemical point of view. However, accepting that the mantle is heterogeneous both vertically and areally (Harris *et al.*, 1967), heterogeneity shown by Jackson and Wright in the Hawaii (1970), a hypothesis could be formed on the origin of the Latemar inclusions as coming from the upper mantle in a pyroxenite shell which is Cr- and Ti-poor. As regards the isotopic composition, the average value obtained is perfectly compatible with an origin of this type (Armstrong, 1968); however if we consider the cumulitic texture and the chemical compositions, this hypothesis is improbable.

2) *Residues of partial melting of the upper mantle after having produced basalt magma.*

If we consider the upper mantle to be composed of both pyrolite (Ringwood, 1966) and websterite — 60% basalt and 40% peridotite (Kutolin and Frolova, 1970) — or similar to the silicate phase of the

average bronzite chondrite (Kuno and Aoki, 1970), it is more probable that, from the partial melting of this upper mantle, we obtain peridotite residues. On this basis, such an origin for the clinopyroxenites under study can be dismissed, even if the low isotopic ratio ($^{87}\text{Sr}/^{86}\text{Sr} = 0.7039$) of the clinopyroxenes would be compatible with this origin.

3) « *Cognate Xenoliths* » as crystal settling from primordial magmas.

Since the *sensu lato* basalt magmas come from the mantle, the ultramafic inclusions, as crystal settling from primordial magmas, should come, at the most, from the crust-mantle boundary, and consequently reflect their chemical-physical conditions. A similar origin was suggested for the series of dunite-wehrlite-eclogite inclusions of Hawaii and other places (White, 1966; Kuno, 1969 *a* and *b*) and also for the well-known high pressure megacrysts contained in the lava (Kuno, 1964; Binns *et al.*, 1970; Frisch and Wright, 1971).

By comparing the chemical compositions of these findings with the pyroxenes of the inclusions studied, this hypothesis is unlikely whereas the megacryst (Lc) shows a clear affinity with these previously mentioned. The isotopic results, however, do not show any differences, and are compatible with an origin in a primitive magma with isotopic ratio $^{87}\text{Sr}/^{86}\text{Sr} = 0.7039$.

4) *Products of crystal settling from magmas which are now known as the host rocks.*

Various types of ultramafic inclusions are ascribed to such an origin ranging from lherzolites to pyroxenites (Frechen, 1948 and 1963), feldspar peridotites (White, 1966), lherzolites (O'Hara and Mercy, 1963; Brotzu *et al.*, 1970; and others). However the majority of researches accept such an origin for the pyroxenite and spinel-pyroxenite inclusions (White, 1966; Aoki, 1968; Aoki and Kushiro, 1968; Aoki, 1970; Kutolin and Frolova, 1970). These last Authors hypothesize such an origin by comparing the chemical and/or textural compositions of the pyroxenite inclusions and their phases with those of a periodotite type. The isotopic data obtained are not compatible with this origin, as there is a significant difference between the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of the host rocks and those of the clinopyroxenes of the inclusions. However the Latemar clinopyroxenites with or without spinel

show a textural and paragenetic affinity with the world clinopyroxenites, and again, the analysed clinopyroxenes resemble one another in chemical composition.

5) *Accidental xenoliths of crustal rocks crossed by the rising magma.*

Some other Authors, including Hamad (1963), Kopecky and Satran (1962), have also attributed such an origin to the ultramafic inclusions. The stratigraphic series in Predazzo region, on the basis of present knowledge, does not include ultramafic masses which are intrusive at depth, nor is there any geological evidence for such. However, in the area studied, there are small pyroxenite masses connected with the intrusive cycle, but their paragenesis and pyroxene composition are quite different from the inclusions. Thus we can exclude this hypothesis; further confirmation is given by the isotopic result obtained from a pyroxene separated from a Predazzo pyroxenite ($^{87}\text{Sr}/^{86}\text{Sr} = 0.7058$) which is clearly higher than that of the inclusions pyroxenes ($^{87}\text{Sr}/^{86}\text{Sr} = 0.7039$).

6) *Inclusions as a reaction of the magma with carbonatic rocks.*

The formation of small pyroxenite masses as a result of the assimilation of carbonatic rocks by silicate magmas is a theory sustained by many Authors, including Tilley and Harwood (1931), Upton (1967); the reaction of a carbonatitic magma on silicate rocks brings about the same result (Upton 1967). As regards the second possibility, in Predazzo region there is no evidence that carbonatitic magmas exist. As regards the first possibility, if we compare the chemical compositions of the pyroxenes of the Latemar inclusions with the diopside pyroxenes from skarns (Deer *et al.*, 1963a; Francis, 1958) we can see a close resemblance in composition. However the obvious cumulitic texture throws doubt on this origin, unless we want to identify the banded structure of some inclusions with the structural reasons for the original carbonatic wall rocks. The isotopic results, however, let us dismiss this hypothesis, as there is a considerable difference between the isotopic compositions of the carbonatic wall rocks $^{87}\text{Sr}/^{86}\text{Sr} = 0.709$ (Borsi *et al.*, 1968) and of one pyroxene ⁽²⁾ from a skarn ($^{87}\text{Sr}/^{86}\text{Sr} = 0.7065$) and that of the pyroxenes of the nodules ($^{87}\text{Sr}/^{86}\text{Sr} = 0.7039$).

(²) Sample Sk from a skarn at Malgola, Predazzo region.

Discussion and Conclusions.

The summary of the possible origins of the clinopyroxenite inclusions, with the petrochemical, textural and isotopic data, lead us to reject all the hypotheses so formed as being unable to explain the origin in full. It must be remembered that in the petrographical region of Predazzo-Monzoni — with an average isotopic ratio $^{87}\text{Sr}/^{86}\text{Sr} = 0.705$ (Borsi and Ferrara, 1967) — some gabbro rocks were found with a

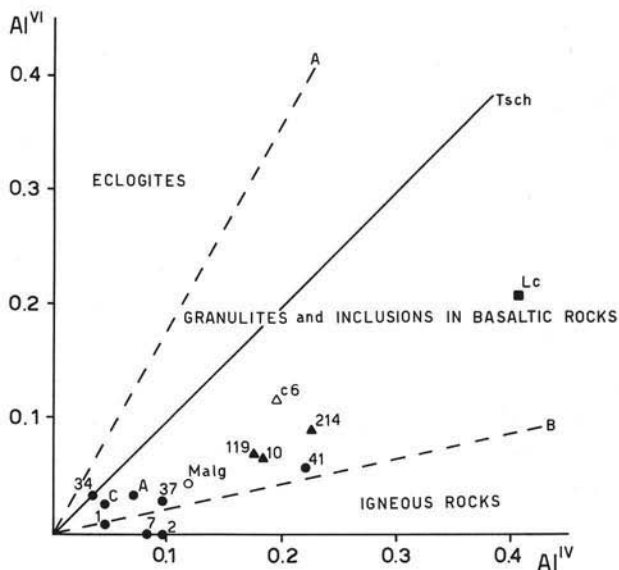


Fig. 5. — Relative proportions of Al^{VI} with Al^{IV} of the clinopyroxenes. Symbols are the same as those for Figure 3.

$^{87}\text{Sr}/^{86}\text{Sr} = 0.7037$ isotopic ratio, associated with several others with a higher isotopic ratio. Such gabbros were assumed as representative of the original magma (Borsi *et al.*, 1968). Therefore a « cognate origin » is probable through settling in a primitive magma ($^{87}\text{Sr}/^{86}\text{Sr} = 0.7039$) which later was contaminated and developed in the host rock ($^{87}\text{Sr}/^{86}\text{Sr} = 0.7052$).

We can now try to determine the physico-chemical conditions in force when the pyroxenite inclusions were forming, if we consider that the chemical composition of the pyroxenes reflect the environmental

conditions of their crystallisation, as shown by several experimental research papers (Boyd and England, 1960; Clark *et al.*, 1962; and others). In particular the relative proportions of Al, in tetrahedral and octahedral site in the clinopyroxenes are related to the P—T conditions of their crystallization, as a high temperature aids the entry of Al in tetrahedral site, whereas the high pressure aids the entry in octahedral site (Thompson, 1947; White, 1964; Aoki and Kushiro, 1968). Aoki and Kushiro (1968) suggested the Al^{IV}-Al^{VI} diagram shown in Figure 5, in which we can distinguish the areas where there are clinopyroxenes of different origin. We can see that it is not only the pyroxenes of the Latemar nodules which fall in the field of the inclusions in basaltic rocks, but also the phenocrysts of lava from the same magmatic region and the Malg. pyroxene from pyroxenite. However the division of Al^{IV}-Al^{VI} does mean different origin conditions, so it seems more reasonable to take the relative proportions of pyroxene components calculated by Kushiro's method (1962) rather than basing it on the partition of one single element.

It has recently been shown that the diopside which crystallizes in the diopside-anorthite system contains the component CaAl₂SiO₆ in solid solution (Hytönen and Shairer, 1961; Clark *et al.*, 1962; and others) and that the quantity in solid solution is in relation to the physico-chemical conditions up to 20 Kbars, at which pressure it appears as an independent phase (Clark *et al.*, 1962). Recent mineralogical and petrological studies show that the components CaAl₂SiO₆ and NaAlSi₂O₆ in the diopside-hedenbergite solid solution series increase as the pressure increases, whereas the molecules CaTiAl₂O₆, CaFe₂SiO₆ and CaFeAlSiO₆ are in relation to the chemical condition of their crystallization (Aoki and Kushiro, 1968; Lovering and White, 1969; Binns, 1969; Aoki, 1970; and others). In particular, by using the diagram suggested by Aoki (1970) produced in Figure 6, we can notice that there is clear separation of the pyroxenes depending on the formation environment. The pyroxene phenocrysts from the lava, and the pyroxene from the pyroxenites, fall within the low-pressure field, whereas the pyroxenes from the nodules, except for two (2 and 7), fall in the high pressure field in a limited area. Samples Lc and c6, the latter coming from an ultramafic nodule in camptonite, also fall in the same field, but clearly separated from the others. By comparing the data from literature with those of the Latemar samples, we can extrapolate

the pressure conditions and, consequently, the origin depth. For pyroxenes containing $\text{CaAl}_2\text{SiO}_6$ in a quantity higher than 5% origin pressures above 5 Kbars are shown (Kuno, 1964; Aoki, 1968; Aoki and Kushiro, 1968; Aoki 1971), from 4% to 11% pressures of 6-7 Kbars (Aoki and Shiba, 1973), from 8% to 13% a depth of 25-35 km (Aoki,

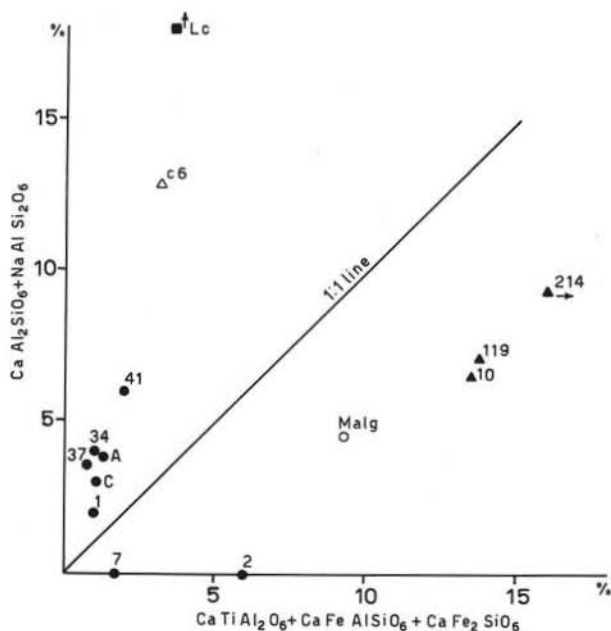


Fig. 6. — Relative proportions of $\text{CaAl}_2\text{SiO}_6 + \text{NaAlSi}_2\text{O}_6$ components and $\text{CaTiAl}_2\text{O}_6 + \text{CaFeAlSiO}_6 + \text{CaFe}_2\text{SiO}_6$ components in clinopyroxenes. Symbols are the same as those for Figure 3.

1968). In the case under study an origin pressure of about 5-6 Kbars, and a depth of about 15-25 km can be hypothesized for the group of pyroxenes from the inclusions (Ca-Tschermak 2%-6%). As regards sample Lc (Ca-Tschermak 19.9%) an origin is hypothesized at a considerably greater depth.

In conclusion, the clinopyroxenite inclusions are « cognate xenoliths » which resulted from cumulitic phenomena in a magmatic chamber at a depth of 15-25 km within the crust from an uncontaminated

magma which, on rising upwards, was contaminated and developed in the host rock. The megacryst Le, although coming from the same uncontaminated magma, formed at the boundary crust-mantle, or in the upper mantle. This is confirmed by the findings of high-pressure megacrysts of Kuno (1964), Aoki (1970), Best (1970), Binns *et al.* (1970) Fritsch and Wright (1971).

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