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The ultramafic and mafic nodule suite in a tuff-breccia pipe from Cozzo Molino (Hyblean Plateau, SE Sicily)

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ABSTRACT. — Deep-seated ultramafic and mafic nodules occur in a Miocenic tuff-breccia pipe from Cozzo Molino (north-eastern part of the Hyblean Plateau, Sicily). These nodules mainly consist of spinel-lherzolites and websterites. The former show protogranular texture, their mineral assemblage consisting of forsteritic olivine ($mg = 90$), enstatite ($mg = 91$), Cr-spinel ($Cr/(Cr + Al) = 0.3\text{-}0.5$) and Cr-diopside ($Wo_{48\text{-}49}$-$En_{50\text{-}51}$-$Fs_{0\text{-}2}$). The latter consist of coarse equant Cr-diospide and smaller enstatite grains, plus or minus aluminous spinel. Both clino-and orthopyroxene exhibit evident systems of exsolute lamellae. These pyroxenites are believed to derive from the crystallization of a primary liquid intruded into the lherzolites. These two rock-types therefore represent fragments of the Hyblean upper mantle.

The mafic nodules consist of two-pyroxene granulites. They show polygonal granoblastic texture, due to plagioclase grains ($An_{52\text{-}55}$), augite (Wo_{47}-En_{41}-Fs_{12}), bronzite ($mg = 70$), ercynite-type spinel and rare ores. The modal proportions between the plagioclase and the mafic minerals vary greatly even within a single nodule, suggesting that these rocks derive from the static recrystallization of a cm-layered gabbroic intrusion at deep crustal levels.

Key words: Hyblean Plateau, tuff-breccia pipe, nodule suite, upper mantle, lower crust.

RIASSUNTO. — Nella tufo-breccia del diatrema Miocenico di Cozzo Molino (nei pressi di Melilli, Altipiano Ibleo) si hanno diversi noduli ultramafici e mafici di origine profonda. Tra i primi prevalgono di gran lunga le spinel-lherzoliti e spinel-websteriti; le une presentano struttura protogranulare data da olivina Fo_{90}, enstatite ($mg = 91$), spinello cromifero ($Cr/(Cr + Al) = 0.3\text{-}0.5$) e Cr-diopside ($Wo_{48\text{-}49}$-$En_{50\text{-}51}$-$Fs_{0\text{-}2}$). Le websteriti sono costituite da grossi cristalli di diospide cromifero e più piccoli grani di enstatite, con scarse quantità di spinello alluminifero a grana grossa (verde) e plaghe di spinello un po' più cromifero (rossastro). I pirosseni, sia ricchi che poveri di calcio, presentano evidenti strutture lamellari dovute in larga misura ad essoluzioni di fasi pirosseniche complementari e spinello. La struttura di queste rocce varia, gradualmente, dalla cumulitica alla granuloblastica poligonale: pertanto si ritiene che esse derivino dalla parziale ricristallizzazione di pirosseniti magmatiche già formatesi da un liquido «primario» in seno alle lherzoliti: entrambi i tipi di ultrafemiti, quindi, derivano da un livello del mantello superiore ibleo.

I noduli mafici sono dati da granuliti basiche a due pirosseni, ascrivibili al gruppo delle granuliti ad Al-spinello. La loro struttura è granuloblastica poligonale data da plagioclasio $An_{52\text{-}55}$, augite (Wo_{47}-En_{41}-Fs_{12}), bronzite ($mg = 70$) spinello ercinitico e rari solfuri e Fe-Ti ossidi. Poiché le proporzioni tra femici e plagioclasi variano sensibilmente anche in seno allo stesso nodulo, si ipotizza che queste rocce derivino dalla ricristallizzazione statica di una intrusione basica stratificata a cm-layering, in ambiente di crosta profonda.

Parole chiave: Monti Iblei, tufo-breccia, noduli, mantello-superiore, crosta profonda.

Introduction

The north-eastern part of the Hyblean Plateau consists of alternating platform-type sediments, whose age ranges from the Upper Cretaceous to the Lower Pleistocene, and volcanic horizons which represent the pro-

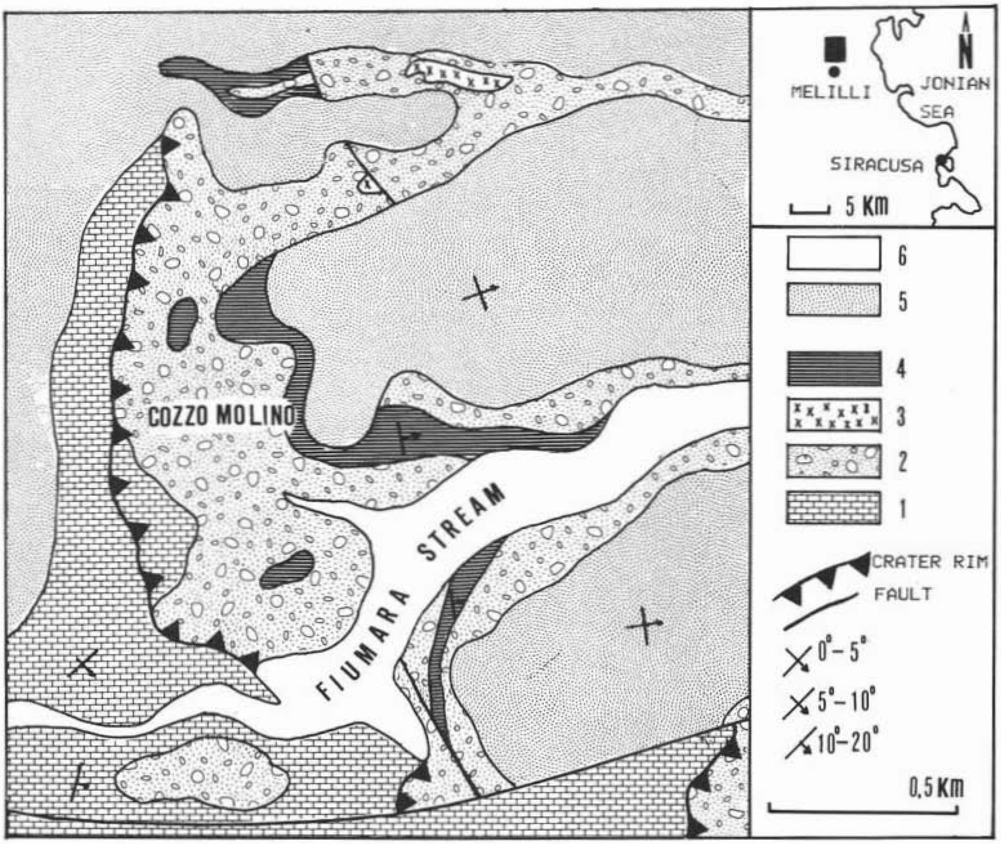

Fig. 1. — Location and geological sketch of Cozzo-Molino tuff-breccia pipe (after CAVALLARO, 1986, modified). Legend: 1) - Miocene shallow-water marine limestones belonging to M.ti Climiti Formation. 2) - Nodule-bearing tuff-breccia. 3) - Biohermes. 4) - Lacustrine sediments: 2, 3, 4 belong to «Carlentini Formation» (Upper Miocene). 5) - Quaternary calcarenites. 6) - Recent fluvial deposits.

ducts of a fissural-type volcanic activity. Basalt are the dominant volcanic lithotypes, with minor differentiates, belonging to both tholeiitic and alkaline suites (e.g. CRISTOFOLINI & BATTAGLIA, 1974).

In a recent paper SCRIBANO (1986) pointed out that most of the alkaline volcanic rocks of this region show a number of deep-seated xenoliths, and reported some harzburgite nodules in a Quaternary basanitoid lava from the northern margin of the Plateau. An ultramafic and mafic nodule suite in a tuff-breccia pipe near the village of Melilli is considered here, in an attempt to contribute to knowledge of the Hyblean lower lithosphere.

Geological setting of the Cozzo Molino Pipe

Pyroclastic flow deposits of Miocene age outcrop in some zones of the northern part of the Hyblean Plateau, and several of their related vents have also been recognized and mapped (CARBONE & LENTINI, 1981; *Carta Geologica del Settore Nord-Orientale dell'Altipiano Ibleo*, 1985). These diatremes often appear as more or less deep hollows, carved into the Miocenic limestone wall rocks by selective erosion (Fig. 1).

Part of one of these tuff-breccia pipes outcrops at Cozzo Molino, two kilometers north of the village of Melilli (Fig. 1). It cuts the Miocenic carbonate horizons and is covered by a thin sheet of varvated lacustrine sediments whose Miocenic age has already been suggested (CARBONE & LENTINI, 1981). This implies the emplacement of a crater lake soon after the end of the eruprive period.

Lastly, transgressive Quaternary calcarenite beds rest on this Miocene age sequence.

Petrographic outlines of the Cozzo Molino tuff-breccia

The studied tuff-breccia consists of polygenetic inequigranular clasts spanning the whole granulometric range for pyroclastic rocks, not exhibiting regular fabric. The essential lava fragments constitute more than 60 vol% of the whole breccia. Their size ranges from lapilli up blocks, the former granulometry being the dominant type.

This lava exhibt a sort of «hybrid» character because ultramafic xenolithis and xenocrysts are more aboundant than the phases crystallizing from the magma. These consist of rare, hour-glass zoned Ti-salite microphenocrysts, often constituting monomineralic clusters. Euhedral olivine microphenocrysts (Fo_{80-87}) also occur, even more rarely than the pyroxene ones. Ti-salite microlaths (often arranged in a fluidal pattern) and opaque micrograins constitute the lava groundmass together with the more or less devitrified glassy fraction. Carbonate amygdales of various sizes are also ubiquitous in this lava.

These reasons clearly suggest that whole-rock chemical composition cannot be crudely used to typify this rock: nevertheless, an attempt was made in this direction both by collecting lava fragments appearing relatively free of coarse grained inclusions and by averaging microprobe spot analyses on the glassy fraction of the lava (Tab. 1). Thus a basanite composition was found following the total alkali/silica classification diagram of Cox et al. (1984). Otherwise, most of the above-mentioned petrologic features (as well as the lack of feldspars and the occurrence of abundant deep-seated inclusions) suggest that the term «kimberlite» (*l.s.*) could also be properly used to tipify this lava, following DAWSON (1980). In this case the whole breccia should be classified as a «kimberlitic tuff-breccia».

TABLE 1

Tuff-breccia «essential» lava fragment composition. Analysis «A»: whole-rock composition with calcite amygdales (see text); analysis «B»: recalculated on calcite-free basic assuming that all loss on ignition consists of CO_2 from calcite; *analysis «C»: averaged microprobe spots on takilite sheaths of nodules (see text). Analysis (A) was performed by XRF, except for MgO (found by AA) and FeO (by titration).* (XRF facilities at Istituto di Scienze della Terra, Catania)

wt%	A	B	C
SiO_2	33.52	42.45	43.77
TiO_2	1.88	2.38	3.58
Al_2O_3	9.65	12.26	14.86
Fe_2O_3	5.40	---	---
FeO	3.52	10.80(*)	11.15(*)
MnO	0.22	0.26	0.09
MgO	10.00	12.75	6.53
CaO	20.15	11.49	15.44
Na_2O	3.45	4.38	2.86
K_2O	0.86	1.10	1.80
P_2O_5	1.65	2.12	ND
L.O.I.	9.73	---	---
TOTAL	100.03	99.99	100.08

(*) All iron as FeO (total).

The ultramafic xenolith suite

General statements

The ultramafic xenoliths occurring in the studied breccia exhibit rounded «nodular» shapes. Their size ranges from 1 to 25 cm and they are usually coated by a 5 to 20 mm takilite sheath (Fig. 2). Most of these inclusions belong to the «Cr-diopside series» (WILSHIRE & SHERVAIS, 1975) and consist of peridotites (mainly spinel-lherzolites) and pyroxenites (mainly spinel-websterites). «Discrete» megacrysts and pyroxenite nodules of the Al-augite series also rarely occur in this breccia, not exceeding 15 (vol%) of total nodule occurrence.

Petrography of the spinel-lherzolite nodules

The spinel-lherzolite nodules occurring in

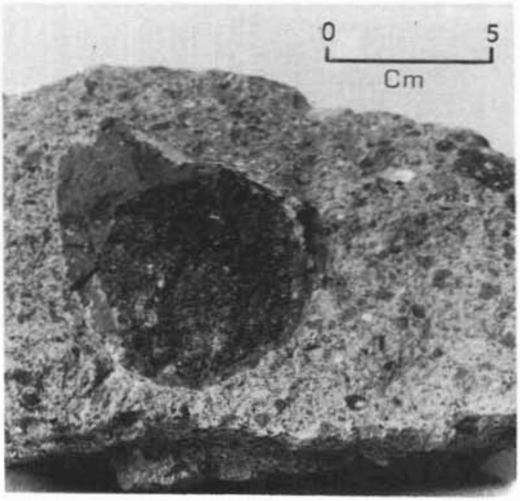

Fig. 2. — Hand specimen of studied nodule-bearing tuff-breccia.

the studied breccia show protogranular texture (MERCIER & NICOLAS, 1975), their minerals often being characteristically interlocked by curvilinear grain boundaries (Fig. 3). Forsteritic olivine and enstatite constitute about 80% of the modal volume (the former ranging between 45 and 60, the latter between 20 and 35 vol%), diopside and spinel represent the rest. The coarse silicate grains, mainly the olivine, show well-developed kink bands and undulose extinction.

Minor textural variations were also observed in these peridotites as, for example, clusters

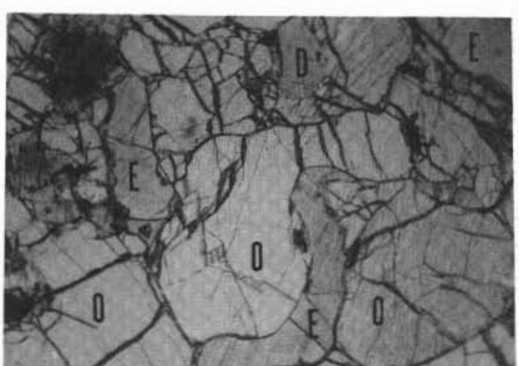

Fig. 3. — Photomicrograph of Cozzo-Molino lherzolite, showing protogranular texture: O = olivine, E = enstatite, D = diopside. *Scale bar = 2 mm. Plane pol. light.*

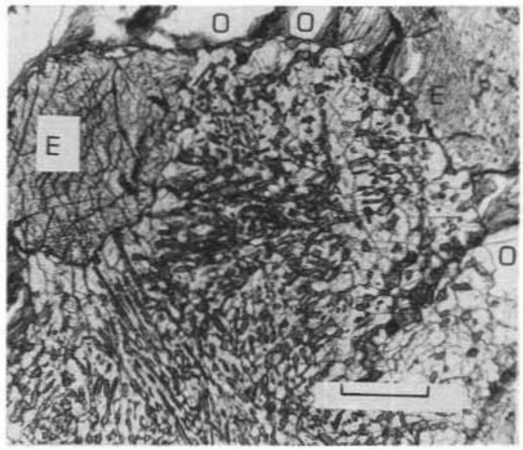

Fig. 4. — Photomicrograph showing «clots» of spongy diospide microcrysts in one of studied lherzolite nodules (see text for explanation). Both enstatite (E) and olivine (O) surrounding clots are more or less resorbed. *Scale bar = 1 mm; plane pol. light.*

TABLE 2

Whole-rock representative analyses of studied nodules. Analysis «A»: lherzolite; «B»: websterite; «C, D»: mafic granulites. All analyses were performed using same methods as analysis «A» in Table 1

Wt%	A	B	C	D
SiO_2	44.11	50.37	48.29	49.05
TiO_2	0.04	0.52	0.33	0.40
Al_2O_3	0.84	4.69	24.82	14.42
Fe_2O_3	2.40	1.82	2.98	5.40
FeO	5.55	1.99	1.43	5.30
MnO	0.18	0.14	0.09	0.00
MgO	41.00	21.40	3.60	7.25
CaO	3.05	17.19	14.62	13.86
Na_2O	0.05	0.63	2.25	2.88
K_2O	0.00	0.00	0.07	0.02
P_2O_5	0.00	0.06	0.06	0.00
L.O.I.	2.78	1.19	1.45	1.42
TOTAL	100.00	100.00	99.99	100.00

TABLE 3

Representative microprobe analyses of olivine grains in lherzolite nodules. Microprobe facilities at «Centro CNR per lo studio delle Formazioni Ignee», Roma

	A	B	C	D	E	F	G
Wt%							
SiO_2	41.98	41.82	41.49	41.66	41.17	41.93	41.74
FeO*	9.20	9.46	9.33	9.43	9.42	9.22	9.45
MgO	48.78	49.15	48.72	49.13	48.94	48.74	48.93
MnO	0.00	0.25	0.21	0.00	0.23	0.17	0.20
Total	99.96	100.68	99.75	100.22	99.76	100.06	100.32
Cations in formula (O=4)							
Si	1.017	1.009	1.008	1.003	1.003	1.015	1.010
Fe*	0.188	0.193	0.192	0.193	0.194	0.189	0.193
Mg	1.779	1.785	1.785	1.791	1.795	1.777	1.783
Mn	0.000	0.005	0.004	0.000	0.005	0.004	0.004
Fo(mol%)	90.4	90	90.1	90.3	90	90.2	90

of unstrained neoblastic subgrains truncating the kink bands of the coarse minerals. «Clots» (up to 3 mm) consisting of mosaics of spongy diopside microcrysts occasionally occur in these rocks, corroding the adjacent enstatite and olivine grains (Fig. 4). The spongy character of this pyroxene probably depends on trapped glass particles (now completely altered) and decrepitated fluid inclusions.

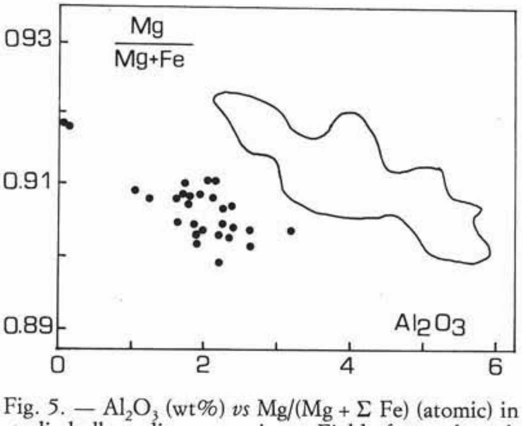

Fig. 5. — Al_2O_3 (wt%) *vs* Mg/(Mg + Σ Fe) (atomic) in studied lherzolite enstatites. Field for «abyssal-peridotite» enstatites was taken from DICK & FISHER, 1984.

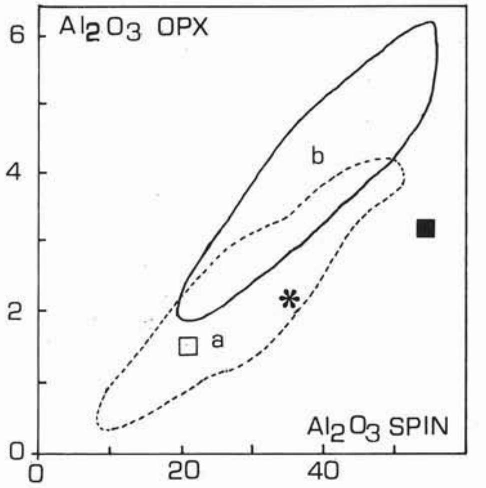

Fig. 6. — Average alumina content (wt%) in coexisting enstatite and spinel in studied lherzolite (asterisk) and websterite (full square). Open square: harzburgite from Scordia (SCRIBANO, 1986). Field «a» (hatched line) encloses «abyssal peridotites»; field «b» «alpine»-types (after DICK & FISHER, 1984).

Mineral chemistry and whole-rock composition of the lherzolites

Microprobe analyses on the lherzolite

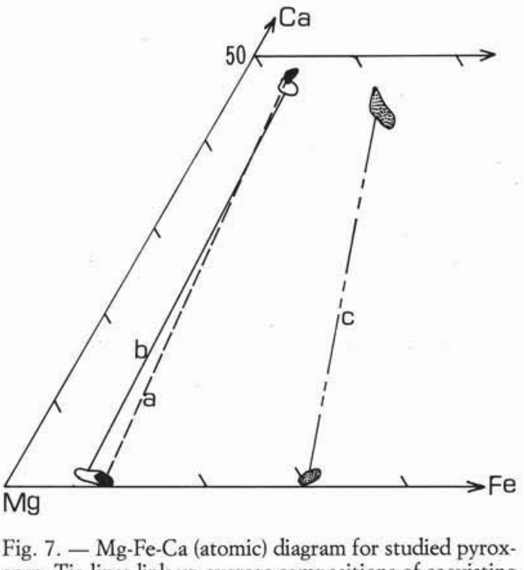

Fig. 7. — Mg-Fe-Ca (atomic) diagram for studied pyroxenes. Tie-lines link up average compositions of coexisting Ca-rich and Ca-poor pyroxenes: «a» represents lherzolite, «b» websterite, «c» granulite pyroxene tie-line.

TABLE 4

Selected microprobe analyses of orthopyroxene in studied lherzolite (A-D), websterite (E-G) and mafic granulite (H-L) nodules. Formulae computed assuming all iron as divalent

	A	B	C	D	E	F	G	H	I	J	K	L
SiO_2	57.12	57.12	57.75	56.98	55.62	55.42	56.42	56.42	56.32	54.04	52.25	53.28
Al_2O_3	1.55	2.24	0.00	1.10	2.81	3.62	3.04	3.51	3.34	2.61	2.24	2.02
FeO*	6.04	6.29	5.67	5.95	6.26	6.26	5.67	5.75	6.13	19.21	19.34	18.93
MgO	33.98	33.52	34.33	33.59	33.67	32.94	33.51	34.05	33.76	23.78	23.93	24.86
MnO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.27	0.49
TiO_2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.31	0.00	0.00
Cr_2O_3	0.45	0.25	0.44	0.28	0.33	0.35	0.39	0.55	0.38	0.00	0.00	0.00
CaO	0.46	0.46	0.67	0.48	0.55	0.47	0.15	0.53	0.44	0.56	0.67	0.43
Na_2O	0.17	0.55	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	99.77	100.43	98.86	98.38	99.24	100.06	99.18	100.81	100.37	100.51	98.70	100.01
Cations in formula (O=6)												
Si	1.964	1,954	2.000	1.983	1.926	1.921	1.944	1.918	1.925	1.955	1.937	1.943
Al(iv)	0.036	0.046	0.000	0.017	0.074	0.079	0.056	0.082	0.015	0.054	0.063	0.057
Al(vi)	0.028	0.045	0.000	0.029	0.042	0.071	0.069	0.060	0.121	0.068	0.036	0.031
Fe	0.173	0.167	0.173	0.185	0.173	0.184	0.176	0.162	0.176	0.597	0.592	0.571
Mg	1.759	1.727	1.790	1.760	1.756	1.719	1.738	1.743	1.737	1.295	1.336	1.366
Mn	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.009	0.015
Ti	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.009	0.000	0.000
Cr	0.012	0.007	0.012	0.008	0.009	0.010	0.011	0.015	0.010	0.000	0.000	0.000
Ca	0.017	0.017	0.025	0.018	0.020	0.016	0.006	0.020	0.016	0.022	0.027	0.017
Na	0.011	0.037	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
$\frac{Mg}{(Mg+Fe^*)}$	0.909	0.904	0.915	0.909	0.905	0.903	0.913	0.913	0.907	0.688	0.688	0.700

*) Iron given as total divalent

olivines show that their $Mg/(Mg + \Sigma\ Fe)$ atomic ratio (= *mg* number) varies between 0.90 and 0.91, 0.903 being the average value. Elements other than Si, Mg and Fe were always below the microprobe detection limit (Tab. 3). The *enstatite mg* number ranges between 0.9 and 0.92 ($\overline{x} = 0.908$), whereas its Al_2O_3 content ranges between 0.0 and 3.0 wt% ($\overline{x} = 2.2$), CaO between 0.1 and 0.7 wt% ($\overline{x} = 0.3$), and Cr_2O_3 from 0.2 to 0.5 wt% ($\overline{x} = 0.35$) (Tab. 4; Figs. 5, 6, 7).

The Cr/(Cr + Al) atomic ratio in the studied *spinel* ranges between 0.3 and 0.5 ($\overline{x} = 0.34$) their *mg* number between 0.56 and 0.63 (Tab. 5, Figs. 6, 8). Analytical results on the *clynopyroxene* show that it is a chromian diopside (Wo_{48-49}-En_{50-51}-Fs_{0-2}) with Cr_2O_3 higher than 0.5 wt% its Ca/(Ca + Mg) atomic ratio being about 0.48, whereas its $(Al + Fe_t + Na + Ti)/(Mg + Cr)$ atomic ratio (= F.I.) varies from 0.30 to 0.45 (Tab. 6; Figs. 7, 9). Moreover, the diopside $(Na\text{-}Cr)/(Al^{iv}\text{-}2Ti)$ ratio suggests that this contains more jadeite than Tschermak's molecule content (Fig. 10).

Concerning the whole rock composition, analysis «A» of Tab. 2 represents the less altered lherzolite nodule analysed here. This

TABLE 5

Representative microprobe analyses of spinel in studied nodules (A-D: lherzolite; E-F: websterite, reddish spinel-type; *G-H: websterie,* green spinel-type; *I-N: mafic granulite). Formulae calculated imposing stoichiometry*

	A	B	C	D	E	F	G	H	I	L	M	N
Wt%												
Al_2O_3	35.21	35.82	34.95	35.92	51.59	50.42	56.92	56.32	45.99	46.97	50.73	4.89
FeO*	19.44	18.12	18.51	18.71	12.71	13.35	11.54	12.53	39.72	39.09	37.40	78.37
MgO	15.55	16.52	15.37	15.28	19.28	19.05	20.35	20.39	10.63	8.89	9.86	2.18
MnO	0.00	0.00	0.00	0.19	0.00	0.00	0.00	0.29	0.16	0.00	0.31	0.38
TiO_2	0.21	0.00	0.00	0.41	0.35	0.32	0.00	0.38	1.37	1.67	1.21	10.55
Cr_2O_3	29.81	27.87	29.30	30.00	15.66	16.24	10.44	8.96	0.30	0.00	0.00	0.42
Total	100.22	99.45	99.00	99.54	99.59	99.38	99.25	99.87	98.17	96.62	99.51	96.79
Cations in formula (O=32)												
Al	9.675	10.093	9.907	9.659	13.007	12.817	14.038	13.992	13.056	13.479	13.897	1.963
Fe(3+)	1.145	1.209	0.996	0.963	0.354	0.469	0.355	0.595	3.587	2.866	2.521	12.792
Fe(2+)	2.640	2.300	2.631	2.701	1.917	1.936	1.661	1.611	4.404	5.083	4.739	9.498
Mg	5.396	5.700	5.369	5.333	6.139	6.116	6.339	6.398	3.811	3.222	3.411	1.105
Mn	0.000	0.000	0.000	0.038	0.000	0.000	0.000	0.052	0.033	0.000	0.061	0.107
Ti	0.037	0.000	0.000	0.072	0.056	0.052	0.000	0.060	0.248	0.305	0.211	2.698
Cr	5.488	5.102	5.429	5.555	2.645	2.766	1.725	1.491	0.057	0.000	0.000	0.113
$\frac{Cr}{(Cr+Al)}$	0.362	0.336	0.354	0.365	0.169	0.177	0.109	0.096	0.004	0.000	0.000	0.054

is consistent with the compositional range for world-wide occurring lherzolites (e.g. KUNO & AOKI, 1970; CARSWELL, 1980). In particular, the studied rock shows close similiarity with lherzolite nodule whole composition occurring in kimberlites (KUNO & AOKI, 1970; DOWSON, 1980) (Fig 11).

Petrography of the websterite nodules

Spinel-bearing websterite nodules were also found in the studied breccia, their modal occurrence consisting of coarse clinopyroxene (60-90 vol%) and less coarse orthopyroxene grains (10-40%) plus or minus spinel and traces of Ni-Fe sulphides and amphibole. Most of the mineral grains are assembled by 120° triple junctions (Fig. 12), whereas in some cases the grain boundaries were irregularly interconnected, resembling a magmatic «adcumulate» texture (WAGER & BROWN, 1968).

These pyroxenes exhibit complex patterns of fine lamellae consisting of both exsolute mineral phase (which are complementary pyroxene and spinel) and polysynthetic twins, the former in some places appearing superimposed on the latter.

Two spinel types occur as accessory minerals: coarse and green, and a smaller, corroded, brownish type. A golden-yellow amphibole also rarely occurs as irregular patches discontinuously rimming the green spinel grains. Interstitial Ni-Fe sulphides are also ubiquitous in these rocks, never exceeding 0.19 of the modal volume.

Mineral chemistry and whole-rock composition of the websterite xenolith

The *clinopyroxene* occurring in these rocks

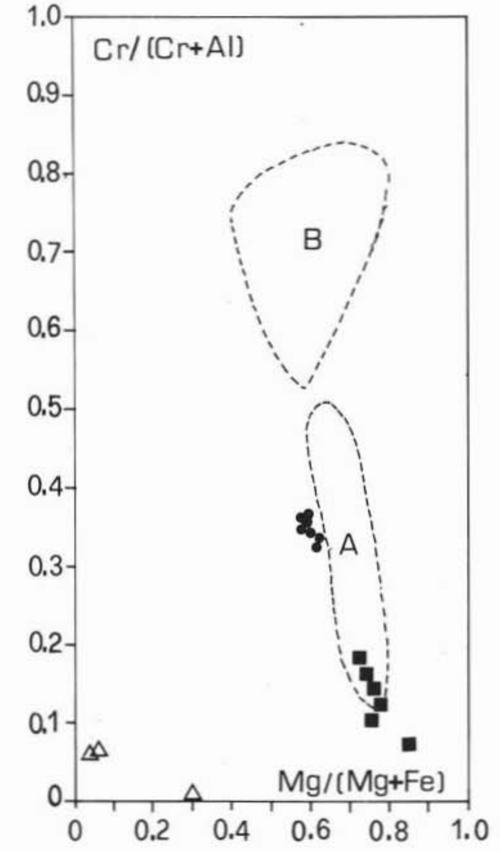

Fig. 8. — Mg/(Mg + Σ Fe) *vs* Cr/(Cr + Al) (atomic ratios) in peridotite (dots), websterite (squares) and mafic granulite (triangles) spinels. Field «a» encloses spinels in «abyssal peridotites», field «b» in the «alpine»-types (after DICK & FISHER, 1984).

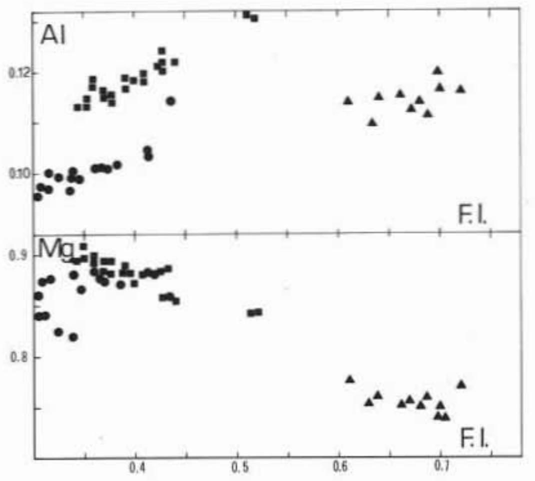

Fig. 9. — Plots of (Al + Σ Fe + Na + Ti)/(Mg + Cr) atomic ratio (= F.I.) *vs* Al and Mg contents (a.u.f.) for clinopyroxenes in studied lherzolite (dots), websterite (squares) and granulite (triangles) xenoliths.

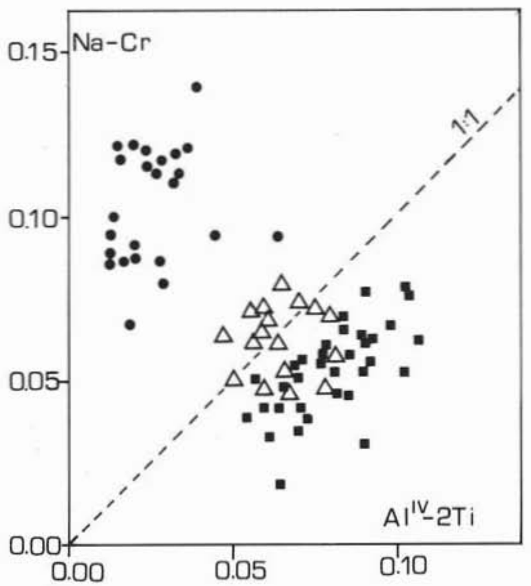

Fig. 10. — (Na-Cr) *vs* (Al_{iv}-2Ti) (a.u.f.) diagram for lherzolite (dots), websterite (squares) and granulite (triangles) clinopyroxenes, showing their jadeiite *vs* Tschermakitic molecule contents.

is a chromian diopside (Wo_{48-50}-En_{48-50}-Fs_{0-2}), its Cr_2O_3 content varying from 0.4 to 0.9 wt% ($\bar{x}$ = 0.63); this has lower silica and slightly higher alumina and titanium contents than the lherzolite diospide (Tab. 6). The diospide of the rock-types may also be distinguished from each other by plotting their F.I. values over their Al contents (Fig. 9) and by emphasizing their different jadeite and Tschermakitic molecule contents (Fig. 10).

The websterite *enstatite*, on the other hand, contains rather less silica (55.4-56.5 wt%) and more alumina (about 4%) than the lherzolite enstatite (Tab. 4). The greyish-green *spinel* is a pleonast type, its Cr/(Cr + Al) atomic ratio varying from 0.07 to 0.11, whereas the same value is about 0.17 in the reddish one. The former type also has a *mg* number of about 0.74, the latter of about 0.72 (Tab. 5; Figs. 6, 8).

The golden-yellow *amphibole* rimming the green spinel is a chromian pargasite (Tab. 7)

TABLE 6

Representative microprobe analyses of clinopyroxenes in studied lherzolite (A-C), websterite (D-G) and mafic granulites (H-K) nodules. Formulae calculated following PAPIKE *et al. (1974)*

	A	B	C	D	E	F	G	H	I	J	K
Wt%											
SiO_2	53.57	54.07	54.20	51.63	51.90	51.63	51.66	50.78	50.77	50.48	50.78
Al_2O_3	2.34	1.93	2.34	4.35	4.12	4.03	4.67	4.02	4.58	3.89	3.57
FeO*	2.75	2.99	2.99	2.59	2.56	2.50	2.59	7.86	7.55	7.84	8.54
MgO	16.34	15.98	16.38	16.21	16.12	16.24	15.61	13.41	13.38	13.51	13.77
MnO	0.18	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.21	0.00	0.00
TiO_2	0.25	0.00	0.00	0.88	0.83	0.74	0.88	0.99	1.02	1.02	0.95
Cr_2O_3	0.76	0.70	0.79	0.74	0.64	0.69	0.47	0.00	0.00	0.00	0.00
CaO	21.40	21.83	21.52	21.95	22.44	22.54	22.42	21.58	21.85	21.43	21.70
Na_2O	1.43	1.56	1.67	1.12	0.84	0.76	0.96	0.67	0.73	0.97	1.00
Total	99.02	99.06	99.89	99.47	99.45	99.13	99.26	99.31	100.09	99.14	100.31
Cations in formula (O=6)											
Si	1.955	1.973	1.957	1.877	1.892	1.888	1.887	1.894	1.877	1.881	1.871
Al(iv)	0.045	0.027	0.043	0.123	0.108	0.112	0.113	0.106	0.123	0.119	0.129
Al(vi)	0.055	0.056	0.057	0.064	0.044	0.062	0.088	0.071	0.077	0.052	0.026
Fe(2+)	0.029	0.030	0.009	0.010	0.044	0.033	0.048	0.217	0.192	0.154	0.142
Fe(3+)	0.055	0.061	0.081	0.069	0.034	0.044	0.031	0.028	0.042	0.081	0.121
Mg	0.889	0.869	0.881	0.878	0.876	0.885	0.850	0.745	0.737	0.750	0.756
Mn	0.006	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.007	0.000	0.000
Ti	0.007	0.000	0.000	0.024	0.023	0.020	0.024	0.028	0.028	0.029	0.026
Cr	0.022	0.020	0.023	0.021	0.018	0.020	0.014	0.000	0.000	0.000	0.000
Ca	0.837	0.853	0.832	0.855	0.876	0.883	0.877	0.862	0.865	0.855	0.857
Na	0.101	0.110	0.117	0.079	0.059	0.054	0.068	0.048	0.052	0.070	0.071
Wo (mol%)	47.70	48.70	48.30	49.04	48.79	49.04	49.42	47.25	48.23	48.35	48.82
En	50.66	49.58	51.14	50.37	48.75	49.15	47.86	41.08	42.39	43.09	43.47
Fs	1.63	1.72	0.56	0.59	2.46	1.81	2.72	11.67	9.38	8.56	7.71

whose *mg* number is 0.85, its K_2O content being 1.2 (wt%) and TiO_2 about 2.4 (wt%).

The whole-rock websterite compositions reflect their rather wide modal variations; nevertheless analysis «B» (Tab. 2) is taken as reasonably representative of the most commonly occurring websterite mode. It fits a hypothetical complex «pigeonitic» pyroxene, whose $mg = 0.91$, $Ca/(Ca + Mg) = 0.36$, F.I. = 0.30.

Discussion on the ultramafic nodules

Lherzolite. The $MgO/\Sigma FeO$ (wt%) ratio of the lherzolite whole rock (= 5.31) fits the «group B» average composition of lherzolite nodules of KUNO & AOKI (1970). The medium degree of depletion of the studied rock is shown by plotting the molar ratios $CaO/(\Sigma FeO + MgO)$ over $(SiO_2 + Al_2O_3)/(\Sigma FeO + MgO)$ (Fig. 13), as this value depends on the pyroxene/olivine modal ratio. The ratio (wt%) $(CaO + Na_2O + Al_2O_3 + TiO_2)/MgO$ (0.097), reported as «basaltic index» by EMBEY-ISZTIN (1978), is also consistent with the above interpretation.

The lherzolite mineral chemistry shows

TABLE 7

Microprobe analyses on yellow amphibole in some of studied websterite nodules (see text). Formulae calculated following Ross *et al. (1969)*

Wt%	A	B	C
SiO_2	43.56	43.22	42.86
Al_2O_3	14.60	14.52	14.19
TiO_2	2.41	2.47	2.58
MgO	17.02	17.43	17.27
FeO*	3.68	3.53	3.86
Cr_2O_3	1.34	1.16	1.19
CaO	11.77	11.68	11.35
Na_2O	3.06	2.88	2.69
K_2O	1.20	1.19	1.19
Total	98.64	98.08	97.18
Cations in formula (O=23)			
Si	6.139	6.126	6.136
Al(iv)	1.861	1.874	1.864
Al(vi)	0.565	0.552	0.531
Ti	0.256	0.264	0.277
Mg	3.576	3.683	3.685
Fe	0.435	0.419	0.463
Cr	0.150	0.130	0.135
Fe (M4)	0.000	0.000	0.000
Ca	1.778	1.774	1.740
Na (M4)	0.222	0.226	0.260
Na (A)	0.614	0.566	0.489
K (A)	0.217	0.216	0.218

TABLE 8

Representative microprobe analyses on plagiocalse feldspars in studied mafic granulite nodules

	A	B	C	D	E	F
Wt%						
SiO_2	53.25	53.53	53.28	53.79	53.79	54.00
Al_2O_3	29.04	29.12	29.37	29.61	28.68	29.18
CaO	10.97	11.37	11.21	11.46	11.02	11.36
Na_2O	5.44	4.89	4.91	5.10	5.33	5.20
K_2O	0.23	0.17	0.14	0.11	0.17	0.17
Total	98.93	99.08	98.91	100.07	98.99	99.91
Cations in formula (O=8)						
Si	2.423	2.428	2.420	2.417	2.443	2.431
Al	1.576	1.575	1.591	1.587	1.553	1.566
Ca	0.540	0.558	0.551	0.558	0.542	0.554
Na	0.485	0.435	0.437	0.449	0.474	0.459
K	0.013	0.010	0.008	0.006	0.010	0.010
An (mol%)	52	55	55	55	53	54

some opposite indications. In fact, the Cr/(Cr + Al) atomic ratios of the spinel ($\bar{x} = 0.34$) suggest that no more than 15% basaltic liquid was extracted from this lherzolite (DICK & FISHER, 1984). This also appears when the studied spinel compositions are compared with those occurring in poorly-depleted «abyssal-type» peridotites (Fig. 8). On the contrary, the studied enstatite compositions shows a significant shift from «abyssal» enstatites (Fig. 7) mainly because the former have lower Al and Ca contents. This should indicate a depletion degree significantly higher than 15% (DICK & FISHER, 1984).

As regards the occurrence of «clots» of spongy diopside microcrysts in some of the studied lherzolite nodules, it must be observed that small glass-bearing microcrystalline blebs are well-known in peridotite nodules. MAALOE & PRINTZLAU (1979) interpreted these blebs as the result of partial melting episodes, noting that all the four lherzolite minerals were resorbed by the formation of the blebs. SCRIBANO (1986) has recently recognized such vitrophyric blebs in harzburgite nodules from the Scordia area (nortern margin of the Hyblean Plateau) consisting of diopside microcryst plunged in a glassy matrix. The similiarity of the diopside «clots» with these «blebs» is evident, except for the larger size of the former and their lower glass/crystalline-selvage proportion. It is noteworthy that «clots» of microcristalline-selvage with sizes very similiar to those studied were described by GHENT et al., (1980) and also interpreted as the result of rapid crystallization of a melt produced by partial melting.

Websterites. Previous authors have pre-

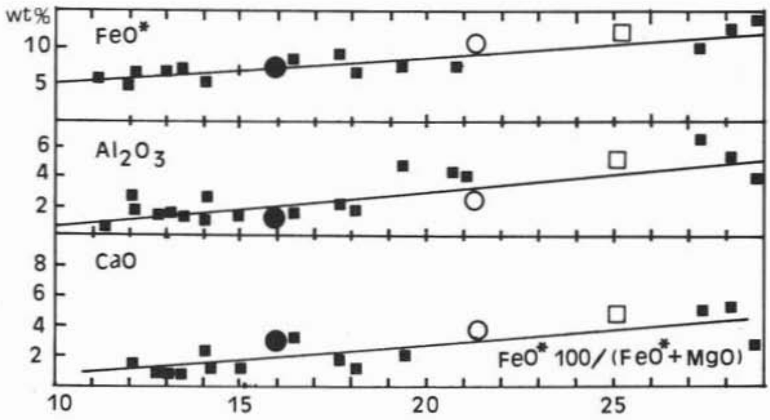

Fig. 11. — Plots of Σ FeO/(Σ FeO + MgO) *vs* CaO, Al_2O_3, Σ FeO (wt%) in studied lherzolite whole-rock composition (full dots) compared to nodule suites from kimberlites (full squares) (after DAWSON, 1980); open circle: primary lherzolite of KUNO & AOKI (1970). Open squares: fertile garnet-lherzolite after DAWSON (1980).

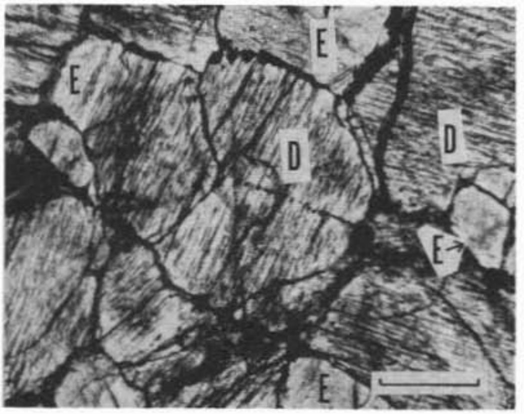

Fig. 12. — Photomicrograph of websterite showing texture of grain boundary equilibrium. Selective alteration marks exsolution lamellae. D = diospide. E = enstatite. *Scale bar = 2 mm, plane pol. light.*

The experimental results of PRESNALL et al. (1978) on the liquid phase relations at the join $CaMgSi_2O_6$-Mg_2SiO_4-$CaAl_2Si_2O_8$ show that, as pressure increases, the forsterite field contracts and the diopside field expands. These authors also note that, at a pressure of 1 GPa, a reaction relation exists in which olivine dissolves as spinel and aluminous diopside crystallizes. Thus, at high pressure, the fractional crystallization of a primary liquid, derived by partial melting of lherzolite, will pro-

sented evidence that early melting in the mantle may result in the formation of spinel-pyroxenites of the Cr-diopside group (e.g. IRVING, 1980; MOUKADIRI & KORNPROBST, 1984; GHENT et al., 1980). This hypothesis is consistent with field evidence in some Alpine-type ultramafic complexes were Cr-diopside websterite dykes are often intruded into the lherzolite (e.g. SINIGOI et al., 1983). These authors also noted the complete lack of olivine in these pyroxenites, consequently suggesting that reaction relationships occur between the liquid and the olivine.

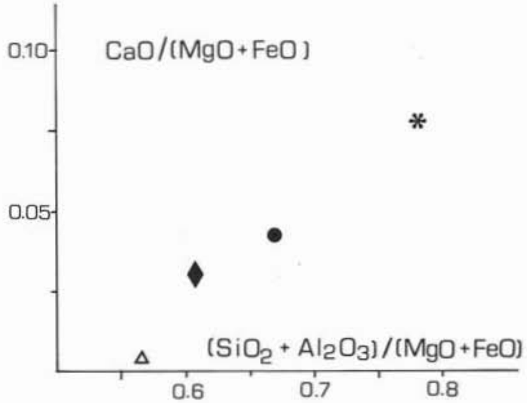

Fig. 13. — Plots of (SiO_2 + Al_2O_3)/(MgO + Σ FeO) *vs* CaO/(MgO + Σ FeO) (molar ratios) in whole-rock composition of studied lherzolite (full circle), harzburgite from Scordia (open triangle: SCRIBANO, 1986), alpine-type peridotites from Ivrea zone (triangle: SINIGOI et al., 1981), Asterisk: undepleted mantle composition after CARTER (1970).

duce spinel-diopside «cumulates» and a residual liquid of tholeiitic composition (which, in the studied case, probably migrated to the upper crust or even to the surface). However, it must be noted that the alumina content of this diopside (PRESNALL et al., 1978) is significantly higher than that occurring in the studied websterites: nor is the already-mentioned Ca-poor pyroxene consistent with the considered experimental results. These discrepancies probably depend on the different composition of the initial liquids and, peraphs, on the sub-solidus re-equilibration of the studied websterites. In fact, it has been pointed out that the whole-rock websterite composition fits a sub-calcic, Al-rich pyroxene: this magmatic primary phase may consequently have led to exoluted Ca-poor pyroxene and spinel at lower temperatures.

The occurrence of pargasitic amphibole is not rare in deep-seated ultramafic xenoliths (e.g. WILSHIRE et al., 1980; IRVING, 1980; EMBEY-ISZTIN, 1976). Several hypotheses have been proposed to account for such occurrences. Most of them imply «pervasive metasomatism» of the mantle by H_2O rich fluids. This is believed to pre-date the incorporation of the ultramafic mineral assemblage by the host magma (e.g. MENZIES & MURTHY, 1980). The mantling of spinel by amphibole, as observed in the studied websterite, perfectly fits the hypothesis of FRANCIS (1976) and BEST (1974) which suggests that the Cr-pargasite derives from reaction of a fluid with spinel and diopside.

Pressure and temperature estimates

Reasonably assuming that all the considered ultramafic nodule compositions can be represented by the CaO-MgO-Al_2O_3-SiO_2 system, recent high-pressure experimental results on this CMAS system are used for estimating equilibrium pressure and temperature *intervals*. However, the *semi*quantitative nature of these estimations must be pointed out, due to the difficulty of correcting for minor elements and also to intrinsic indeterminations and wide error bars of the experimental results in question (e.g. FUJI & SCARFE, 1982).

The lack of garnet and plagioclase in the studied nodules (both lherzolite and websterite) indicates that these were equilibrated within the spinel-peridotite field; this implies a rather wide pressure interval, that is, between, 0.4 and 2.3 GPa (12 < Km depth < 70) (GASPARIK, 1984).

NICKEL et al., (1985) elegantly proposed an empyrical thermometric equation which fits the CMAS system. For natural system this equation cannot be used except for broad indications or qualitative comparisons. The mineral chemistry of the studied lherzolite nodules therefore give temperature intervals between 1100 and 1150 °C and the websterites between 1050 and 1100 °C. It therefore seems reasonable to admit that the lherzolites were equilibrated at temperatures slightly higher than the websterites.

The mafic nodule suite: two-pyroxene granulites

Mafic nodules were also found in the studied breccia. These show granuloblastic texture due to polygonal plagioclase grains and inequigranular ortho-and clinopyroxenes, with green spinel and opaque ores. The modal proportions between the plagioclase and the mafic minerals varies greatly, the Ca-poor pyroxene always being subordinate with respect to the Ca-rich one (Fig. 14).

Plagioclase feldspar exhibits rather homogeneous $An_{54 \pm 2}$ composition, whith very minor potassium content (Tab. 8). *Calcic pyroxene* is an augite (Wo_{47}-En_{41}-Fs_{12}), its Al_2O_3 content being about 4 wt%, $Na_2O = 1\%$, $TiO_2 = 1\%$ (Tab. 6). Fine laths of exsolute orthopyroxene, ilmenite and finer rutile needlets are ubiquitous in these pyroxenes. *Ca-poor pyroxene* shows bronzite composition, its *mg* number being about 0.70 (Tab. 4). *Spinel* is a green ercynite ($Al_2O_3 = 45$-68 wt%, $FeO = 35$-40 wt%) (Tab. 5). Fe-sulphides and Fe-Ti oxides also rarely occur in these rocks, often completely intergrown. Spinel and hyperstene symplectites often occur between the plagioclase

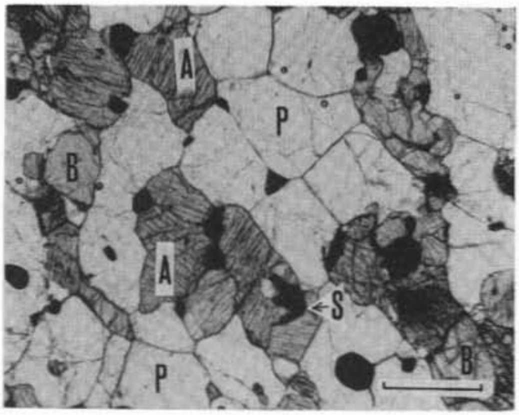

Fig. 14. — Photomicrograph of mafic granulite showing granuloblastic polygonal texture. P = plagioclase. A = augite. B = bronzite. S = dark-green spinel. *Plane pol. light. Scale bar = 2 mm.*

feldspars and ovoidal patches of reddish-brown kelifite-like products.

The whole-rock composition again reflects the modal variations of the rocks (Tab. 2) (see below for discussion).

Discussion on the mafic nodules

The whole-rock composition and mineral chemistry and, generally the texture of the above-described rocks show close similiarity whith the «mafic granulites of the Al-spinel suite» (WILKINSON, 1975) or, more usually, with the «pyroxene granulites» (IRVING, 1974). According to these two authors, the well-developed granuloblastic polygonal texture and very low degree of miscibility shown by the coexisting Ca-rich and Ca-poor pyroxenes indicate protract «post-magmatic» recrystallization.

If the above hypothesis is reasonable, recrystallization represents an isochemical process, the studied whole-rock compositions indicate a «gabbroic» *parentage* with mildly subalkaline affinity: this is shown by plotting the total-alkalis over silica values (e.g. IRVINE & BAGARAR, 1971) and also by the constantly low potassium contents (see Tab. 2) in the studied rocks. The above reported variations of the plagioclase/mafic minerals modal percentages, even within a single nodule, suggest analogies with cm-layering in some mafic intrusions (WAGER & BROWN, 1968).

Experimental results on natural systems very similiar to the studied granulite whole-rock composition (IRVING, 1974) suggest that the lack of garnet in such mineral assemblages indicates an upper pressure limit of about 1 GPa at 1000 °C, the lack of olivine, on the other hand, a lower pressure limit of about 0.5 GPa. This thermobarometric interval gives reasonable indications that the studied rocks derive from deep crustal levels.

Concluding remarks

The lack of true porphyroclastic and other sheared textures in the lherzolite xenoliths from Cozzo Molino, except for the kink bands in some of their minerals, suggest that these rocks steadly «flowed» throughout the upper mantle (GOETZE & KOHLESTEDT, 1973; DARHAM & GOETZE, 1977), not having been involved in any strongly active mantle-diapir.

It is noteworthy that the harzburgite xenoliths occurring in some Quaternary basanitoid lava flows from the Scordia area (about 20 Km NW of the studied zone) show more pronunced deformation features and wider neoblastic zones than the studied lherzolites. Moreover, the spinel occurring in those harzburgites exhibits higher $Cr/(Cr + Al)$ values than that of the studied lherzolites (SCRIBANO, 1986). This, and the bulk compositions of the two considered xenolith types, suggest that the harzburgites from Scordia suffered greater depletion than the lherzolites from Cozzo Molino (Fig. 13).

Mafic granulites, rather abundant in the tuff-breccia of Cozzo Molino, are less represented in the nodule suite of Scordia. Assuming that the time interval from Miocene to Quaternary is too short to produce significant variations in the upper mantle and the lower crust, it seems reasonable that the Hyblean lower lithosphere composition is inhomogeneous. However the development of a satisfactory lithospheric model needs further investigation which, in part, are now in progress.

This paper is part of a research program on deep-seated xenoliths from Hyblean Plateau and Mt. Etna.

REFERENCES

BEST M.G. (1974) - *Mantle derived amphibole within inclusions in alkalic-basaltic lavas*. Jour. Geophys. Res. 74, 512-515.

CARBONE S. & LENTINI F. (1981) - *Caratteri deposizionali delle vulcanoliti del Miocene Superiore negli Iblei (Sicilia Sud-Orientale)*. Geol. Romana, 20, 70-101.

CARBONE S., LENTINI F., GRASSO M. et. alii (1985) - *Carta Geologica del Settore Nord-Orientale dell'Altipiano Ibleo, scala 1:50.000*. Istituto di Scienze della Terra, Universtità di Catania.

CARSWELL D.A. (1980) - *Mantle derived lherzolite nodules associated with kimberlites, carbonatite and basalt magmatism: a review*. Lithos, 13 121-138.

CARTER J.L. (1970) - *Mineralogy and chemistry of the Earth's upper mantle based on partial fusion - partial crystallization model*. Geol. Soc. Am. Bull., 81, 2021-2034.

CAVALLARO F. (1986) - *Rilevamento geologico degli apparati eruttivi di Cozzo Molino e di Vallone Iuso*. Tesina di laurea inedita, Istituto di Scienze della Terra, Catania.

COX K.G., BELL J.D., PANKURST R.J. (1984) - *The interpretation of igneous rocks*. Longmans, London. 450 pp.

CRISTOFOLINI R. & BATTAGLIA M (1974) - *Le manifestazioni basaltiche della zona di Francofonte nel quadro del vulcanismo dell'Altipiano Ibleo*. Boll. Soc. Geol. Ita., 94, 185-207.

DAWSON J.B. (1980) - *Kimbertlites and their Xenoliths*. Springer, Berlin Heidelberg New York. 280 pp.

DICK H.G.B. & FISHER R.L. (1984) - *Mineralogic studies of the residues of mantle melting: abyssal and alpine-type peridotite*. In: Kornprobst J. (Editor), Kimberlites II, the Mantle and Crust-Mantle Relationships. Elsevier, Amsterdam, 303 pp.

DURHAM W.B. & GOETZE C. (1977) - *Plastic flow of oriented single crystals of olivine, I: Mechanical data*. Jour. Geophys. Res. 82, 5737-5753.

EMBEY-ISZTIN A. (1976) - *Amphibolite/Lherzolite composite xenolith from Szigliget, North of the Lake Balaton, Hungary*. Earth and Planet. Sci. Lett. 31, 297-304.

EMBEY-ISZTIN A. (1978) - *On the Petrology of Spinel Lherzolite Nodules in Basaltic rocks from Hungary and Auvergne, France*. Annales Historico-naturales Musei Nationalis Hungarici, 70, 27-44.

FRANCIS D.M. (1976) - *The origin of amphibole in lherzolite xenolitihs from Nuvivak Island, Alaska*. J. Petrol., 17, 357-378.

FUJII T & SCARFE C.M. (1982) - *Petrology of Ultramafic Nodules from West Kattle River, near Kelowna, Southern British Columbia*. Contr. Miner. Petr. 80, 297-306.

GASPARIK T. (1984) - *Two-pyroxene thermobarometry with new experumental data in the system CaO-MgO-Al_2O_3-SiO_2. Contr. Miner. Petr. 87, 73-87.*

GHENT E.D., COLEMAN R.G., HADLY D.G.H. (1980) - *Ultramafic inclusions and host alkali olivine basalts of the Southern Coastal Plain of the Red Sea, Saudi Arabia*. Am. Jour. of Sci., 280-A, 409-527.

GOETZE C. & KOHLSSTEDT D.L. (1973) - *Laboratory study of dislocation climb and diffusion in olivine*. Jour. Geophys. Res. 78, 5961-5971.

KUNO H. & AOKI K.I. (1970) - *Chemistry of ultramafic nodules and their bearing on the origin of basaltic magmas*. Phys. Earth Planet. Int. 3, 273-301.

IRVINE T.N. & BARAGAR W.R. (1971) - *A guide to chemical classification of the common volcanic rocks*. Canadian Jour. Earth. Sci. 8, 523-548.

IRVING A.J. (1974) - *Pyroxene-rich ultramafic xenoliths in the Newer Basalts of Victoria, Australia*. Neus Jar. Miner. Ab., 120, 147-167.

IRVING A.J. (1980) - *Petrology and geochemistry of composite ultramafic xenoliths in alkalic basalts and implications for magmatic processes within the mantle*. Am. Jour. of Sci. 280-A, 389-426.

MAALOE S. & PRINTZLAU I. (1979) - *Natural Partial Melting of Spinel Lherzolite*. J. of Petrol. 20, 727-742.

MENZIES M. & MURTHY V.R. (1980) - *Mantle metasomatism as a precursor to the genesis of alkaline magma-isotopic evidence*. Am. Jour. of Sci. 280-A, 595-622.

MERCIER JC.C. & NICOLAS A. (1975) - *Textures and Fabrics of Upper-Mantle Peridotites as Illustrated by Xenoliths from Basalts*. Jour. of Petrol. 16, 454-487.

MOUKADIRI A. & KORNPROBST J. (1984) - *Garnet and/or Spinel Bearing Pyroxenites in Alkali Basalt near Azrou (Middle Atlas; Marocco): Mantle derived alumina-rich xenoliths related to the «Ariegite-Gropsydite» trend*. In: Kornprobst J. (Editor), Kimberlites II, The Mantle and Crust-Mantle Relationships. P. 179-186. Elsevier, Amsterdam.

NICKEL K.G., BREY G.P. KOGARKO L. (1985) - *Orthopyroxene-clinopyroxene equilibria in the system CaO-MgO-Al_2O_3-SiO_2 (CMAS): new experimental results and implications for the two-pyroxene thermometry*. Contr. Miner. Petr. 91. 44-53.

PAPIKE J.J., CAMERON K. & BALDWIN K. (1974) - *Amphiboles and pyroxenes characterization of the other than quadrilater components and estimates of ferric iron from microprobe data*. Am. Miner. 1746-1782.

PRESNALL D.C., DIXON S.A., DIXON J.R., O'DONNEL T.H., BRENNER N.L., SCROCK R.L., DYCUS D.W. (1978) - *Liquidus Phse Relations on the Join Diopside-Forterite-Anorhite From 1 atm to 20 Kbar: Their Bearing on the Generation and Crystallization of Basaltic Magma*. Contr. Miner. Petr. 66, 190-203.

ROSS M., PAPIKE J.J., SHAW K.W. (1969) - *Exsolution textures in amphiboles as indicators of subsolidus thermal hystories*. Spec. paper Miner. Soc. of Am. 2, 275-299.

SCRIBANO V. (1986) - *The Harzburgite Xenoliths in a Quaternaty Basanitoid Lava near Scordia (Hyblean Plateau)*. Rend. SIMP, 41, 245-256.

SINIGOI S., COMIN-CHIARAMONTI P., DEMARCHI G., SIENA F. (1983) - *Differentiation of Partial Melts in the Mantle: Evidence from the Balmuccia Peridotite, Italy*. Contr. Miner. Petr. 82, 351-359.

WAGER L.R. & BROWN G.M. (1968) - *Layered Igneous Rocks*. Oliver & Boyd, Edinburgh and London, 588 pp.

WILKINSON J.F.G. (1975) - *An Al-Spinel Ultramafic-Mafic Inclusion Suite and High Pressure Megacrysts in an Analcimite and their bearing on Basaltic Magma Fractionation at Elevated Pressures*. Contr. Miner. Petr. 53, 71-104.

WILSHIRE H.G. & SHERVAIS J.W. (1975) - *Al-augite and Cr-diopside ultramafic xenoliths in basaltic rocks from western United States*. In: Ahrens L.H. at alii (Editors); Physics and Chemistry of the Earth, v.9. Pergamon Press, New York. p. 257-272.

WILSHIRE H.G., PIKE J.E.N., MEYER C.E. & SCHWARZMAN E.C. (1980) - *Amphibole rich veins in lherzolite xenoliths, Dish Hill and Deadman. Lake California*. Am. Jour. of Sci., 280-A, 576-593.

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