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PETROLOGY AND GEODYNAMIC SIGNIFICANCE OF THE CALABRIA-LUCANIA OPHIOLITES

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RIASSUNTO. — Studi recenti hanno mostrato che i complessi ofiolitici fanerozoici presentano al loro interno notevoli differenze soprattutto per quanto riguarda i caratteri petrografici e geochimici delle loro sezioni intrusive ed effusive.

La distribuzione degli elementi maggiori ed in tracce, gli andamenti differenziativi, le fasi di liquidus ed il loro ordine di cristallizzazione nelle rocce effusive ed intrusive indicano una corrispondenza dei complessi ofiolitici, da un lato, con segmenti litosferici generati lungo dorsali medio-oceaniche o bacini retroarco ben sviluppati, dall'altro, con associazioni magmatiche formatesi al limite di placche intraoceaniche convergenti (archi insulari, stadi iniziali di apertura di bacini retroarco).

Le ofioliti mesozoiche della Calabria settentrionale e dell'Appennino lucano appartengono a diverse unità tettoniche sovrapposte, interessate da differenti tipi e gradi di metamorfismo.

Nonostante tali differenze tra le varie unità, le caratteristiche petrologiche e geochimiche indicano che tutte le ofioliti studiate possono essere interpretate come un unico originario complesso di ultramafiti di mantello, gabbri cumulitici e basalti tholeiitici ad affinità oceanica, analoghi ai MORB transizionali.

La stretta associazione talora riscontrata tra ofioliti e materiali continentali di bassa crosta (simili a quelli della formazione dioritico-kinzigitica) suggerisce che esse rappresentino relitti di litosfera oceanica formatasi in posizione pericontinentale ed in uno stadio di oceanizzazione embrionale, analogamente a quanto in precedenza proposto per le ofioliti delle unità liguridi esterne dell'Appennino settentrionale.

Tale bacino oceanico dovrebbe essere stato interessato da importanti zone di frattura e faglie trasformi, come suggeriscono le caratteristiche tettonico-metamorfiche delle ofioliti studiate.

Durante la chiusura cretacea del bacino le unità ofiolitiche furono coinvolte in processi di subduzione con sviluppo di paragenesi metamorfiche di alta pressione/bassa temperatura indicanti valori massimi di parziale equilibratura di 6-8 Kb e 350° ± 50° C.

ABSTRACT. — The available petrological and geological data on the Calabria-Lucania ophiolites indicate that they can be considered, like other Western Mediterranean ophiolites, as fragments of the oceanic lithosphere created during the Jurassic opening of the Western Tethyan basin and separating the European and African (Insubrian) continental blocks.

They represent oceanic association of: 1) tectonite spinel-lherzolites, 2) tholeiitic basalts of transitional MORB affinity, 3) gabbroic cumulitic rocks, revealing, on the whole, the closest magmatic resemblance with ophiolites from Balagne (Corsica) and External Ligurides (Northern Apennines).

The magmatic and tectono-metamorphic characteristics of the whole association suggest that the Calabria-Lucania ophiolites may represent lithospheric sections generated at an early oceanic-ridge system (and developed in a pericontinental position), subsequently interested, at least in part, by a tectono-metamorphic evolution in fracture zones.

The Cretaceous closure of this ocean basin took place by undertrusting and subduction processes, with development of high-pressure/low temperature metamorphic parageneses in the ophiolite lithologies indicating maximum values of partial equilibration of 6-8 kb at 350° ± 50° C.

Introduction

Recently important differences have been pointed out among Phanerozoic ophiolites with regard to the geochemical and petrographical characteristics of their extrusive and intrusive sections (MIYASHIRO, 1973, 1975; PEARCE and CANN, 1973; SMEWING et al., 1975; ROCCI et al., 1975; CHURCH and RICCIO, 1977; BECCALUVA et al., 1979, 1980; SAUNDERS et al., 1980; CAMERON et al., 1980; SERRI, 1981).

Athough such differences may sometimes be attributed to physical-chemical variations in a single tectonic setting, recent studies attribute these petrological diversities to ophiolite generation in different original tectonic environments (SUN and NESBIT, 1978; PEARCE, 1975, 1980; BECCALUVA et al., 1979; CRAWFORD et al., 1981).

Particularly evident is the geochemical affinity of some ophiolitic basalts to basalts from mid-oceanic ridges and marginal basins on one hand, and of some other ophiolitic basalts to basalts, basaltic andesites and boninitic types from island-arc setting, on the other (BECCALUVA et al., 1979). This is matched by a parallel and sistematically different crystallization order in lavas and associated plutonic complexes, corresponding to different TiO_2 contents (BECCALUVA et al., 1980; SERRI, 1981), so that the various associations may be classified as high-Ti, low-Ti and very low-Ti ophiolites.

Particularly for the Tethyan realm, significant differences have been demonstrated for the intrusive and volcanic sequences, as well as for mantle ultramafic between Eastern and Western Mediterranean ophiolites (ROCCI et al., 1975; BEBIEN et al., 1975; BECCALUVA et al., 1980). The petrological characteristics of many low-Ti ophiolitic complexes from the Eastern Mediterranean area such as Troodos, Vourinos and Pindos indicate an island-arc/back-arc basin rather than an ocean-ridge original setting (BECCALUVA et al., 1978, 1979, 1980; CAPEDRI et al., 1980). Instead, this latter geodynamic environment has been generally proposed for the high-Ti Western Mediterranean ophiolites (FERRARA et al., 1976; PICCARDO, 1977; BECCALUVA et al., 1975, 1976, 1980; SERRI, 1981; SPADEA, 1979).

In the Calabrian arc, recently considered to be a southern fragment of the dismembered Alpine belt (HACCARD et al., 1972; DIETRICH and SCANDONE, 1972; AMODIO-MORELLI et al., 1976), ophiolites occur in distinct tectonic units. They may, or may not, show *HP-LT* metamorphism and are overthrust by lower continental crust terranes (Diorito-Kinzigitic Formation auct.).

Data on the petrological and geological characteristics of the Calabria-Lucania ophiolites were presented in previous works (HOFFMANN, 1970; DE ROVER, 1972; PICCARRETA and ZIRPOLI, 1975; SPADEA et al., 1979; LANZAFAME et al., 1979 a, DOSTAL et al., 1979). The aim of this paper is to review the salient petrological and geological features of the Calabria-Lucania ophiolites deriving from different occurrences and structural settings, in an attempt to a better definition of their original setting and metamorphism. This should contribute to clarifing some aspects of the tectonic-metamorphic evolution of the southernmost sector of the Alpine chain.

Geological framework

In the Calabrian Arc Tethyan ophiolites crop out discontinuously from the Calabria-Lucania border zone (Lucanian Apennine and Northern Calabria) to Central Calabria (fig. 1). The general ophiolitic sequence consists, in ascending order, of altered ultramafics (mostly mantle tectonites), of gabbro, basalt and chert (AMODIO-MORELLI et al., 1976; LANZAFAME et al., 1979 a).

The ophiolitic lithologies are highly dismembered and occur in several tectonic units which were in the Aquitanian overthrust eastwards on top of the Apennine sedimentary terrains (AMODIO-MORELLI et al., 1976). The ophiolite sedimentary cover includes almost ubiquitous radiolarian chert at the base, overlain by predominant calcareous and argillaceous deposits with abundant terrigenous components. The age of the sedimentary cover is referred to Tithonian-Neocomian. Together with serpentinites the metabasalts represent the predominant rock-type in the ophiolite sequences. The gabbroic complex is poorly represented by very rare Mg-gabbro and Fe-gabbro bodies (these latter are found as fragments in sedimentary breccias), while a mafic sheeted complex is absent. Basaltic dikes occur as scattered intrusions into ultramafics, gabbros and pillow-lavas.

The ophiolitic rocks are included in allochtonous terrains with a different mode of occurrence: as nappes (Northern and Central Calabria), as slices and mélange (Lucanian

Apennine and Northern Calabria), and as olistoliths (Lucanian Apennine).

Based on the occurrence and tectonic position they can be grouped into: 1) *Lower Ophiolite Unit,* composed of mélange and tectonic slices (Frido Unit according to LANZAFAME et al., 1979 a, b) which includes the Diamante-Terranova (pro parte) + Frido

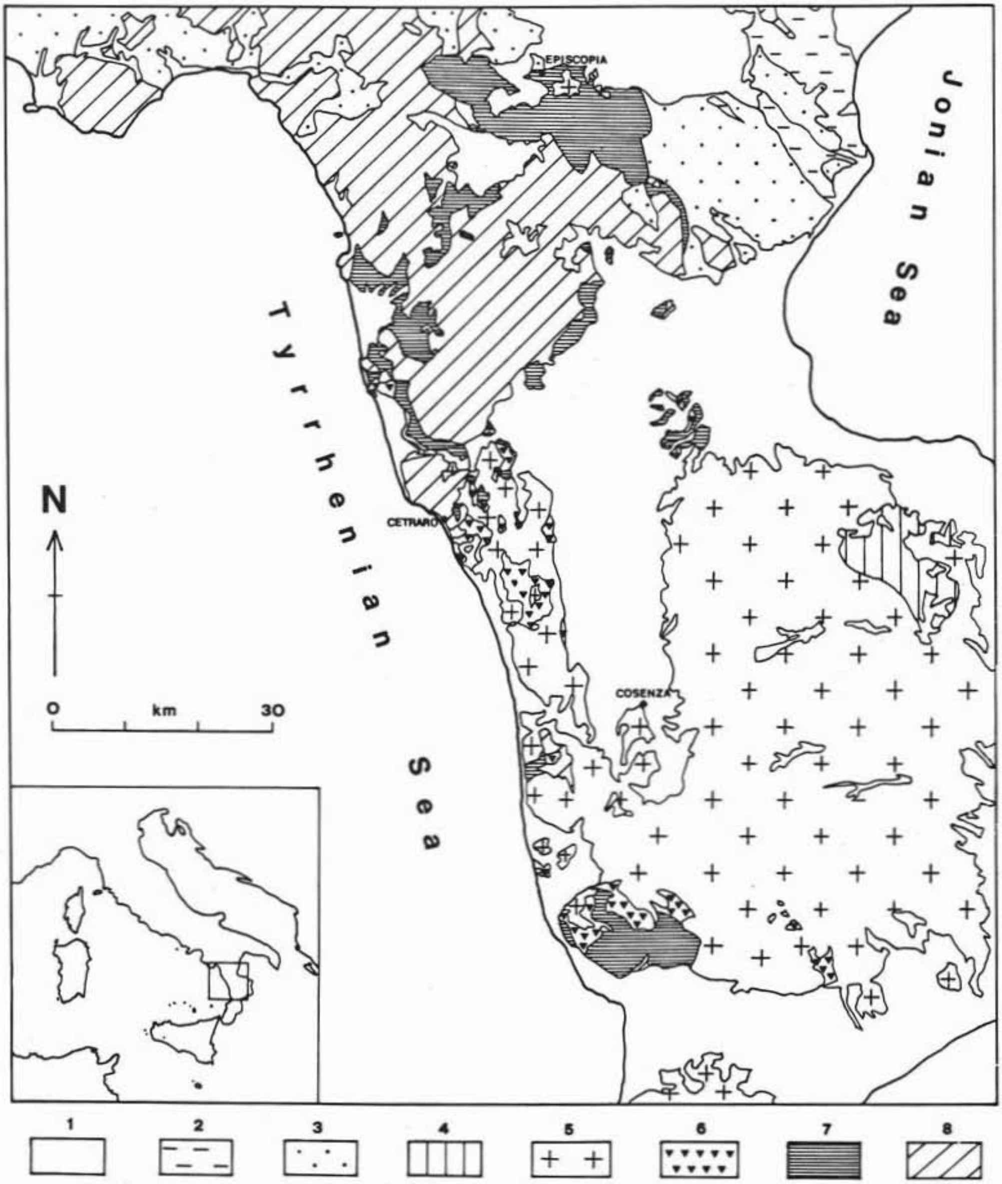

Fig. 1. — Generalized geologic map of the Calabria-Lucania area, Southern Apennines (modified from AMODIO MORELLI et al., 1976 and SPADEA et al., 1980). - 1. Quaternary and Neogene deposits; 2. Sicilide units (Mesozoic-Tertiary); 3. Calabro-lucanian flysch (Late Cretaceous to Miocene) (Cilento Unit of AMODIO MORELLI et al., 1976); 4. Sedimentary cover of continental rocks (Mesozoic); 5. Continental igneous and metamorphic rock units (Paleozoic); 6. Upper Ophiolite Unit (Late Jurassic-Early Cretaceous) (Malvito Unit and Gimigliano Unit of AMODIO MORELLI et al., 1976); 7. Frido Unit (Jurassic-Early Cretaceous) (Diamante-Terranova Unit and Frido Unit of AMODIO MORELLI et al., 1976); 8. Carbonate rock units (Mesozoic-Tertiary).

Unit of AMODIO-MORELLI et al. (1976); 2) *Upper Ophiolite Unit* which comprise the MALVITO and GIMIGLIANO units (pro parte) of DIETRICH and SCANDONE (1972) and AMODIO-MORELLI et al. (1976); 3) *ophiolitic olistoliths*. The ophiolites of the Lower Unit (i.e. Frido Unit), consisting of dominant ultramafic rocks and metabasalts, compose either slices or elements of different sizes in a mélanges with metasedimentary or serpentinitic matrix. The metasedimentary rocks associated with ophiolites derive from calcareous-pelitic sequences, with interbedded quartz-arenites, of Neocomian-Aptian age (Frido Formation of VEZZANI, 1969; Flysch à quartzites of French authors) representing the cover of pillow lavas (LANZAFAME et al., 1979 b).

The Upper Ophiolite Unit, is only about 350 m thick, and consists of predominant metabasalts and capping metasediments which were originally radiolarian chert, pelite and Calpionellid limestone of Tithonian-Neocomian age. This unit is tectonically overlain by the Diorito-Kinzigitic (Polia-Copanello) Unit, which represents the highest tectonic element of the Calabrian Arc (AMODIO-MORELLI et al., 1976).

Olistoliths occur in the Lucanian Apennine and consist of prevalent basaltic pillow-lavas, minor gabbros and serpentinites forming the substratum on which flysch sequences were deposited, probably since Late Aptian.

In the Lucanian Apennine, polymetamorphic rocks from the lower crust, corresponding to hhe Diorito-Kinzigitic Unit, and consisting of granofels, garnet gneiss, and amphibolite are in close association with ophiolites of the Frido Unit. Field and petrographical data indicate that these continental rocks were already associated with the ophiolites at the time of the tectonization and *HP-LT* metamorphism and as far back as the outpouring of the basalt (SPADEA, in press).

Primary petrological features

Basalts

The extrusive basaltic rocks are represented by pillow-lavas and pillows-breccias, and by rare hyaloclastites. The lavas are aphyric and porphyritic basalts (actually metabasalts) mostly olivine-free. Plagioclase phenocrysts occur in all porphyritic types with strongly variable modal abundance (maximum values about 60 % volume), often indicating the intervention of accumulation processes. Basaltic rocks, either aphyric or oligophyric, also occur as dikes within serpentinite and gabbro. Similar dike rocks are intruded into granofels and amphibolite referred to the Diorito-Kinzigitic Unit (LANZAFAME et al., 1978; SPADEA, in press).

In spite of the complex metamorphic effects, the above-mentioned rocks still shown primary features as far as some geochemical characteristics and mineral relics are concerned. Magmatic clinopyroxenes are often still preserved. The chemical mobilization effects are mainly reflected in the high H_2O^+ values as well as in erratic variations of Ca and alkaline elements.

Due to diffused alteration only relatively immobile elements such as Ti, Y, Nb, Zr, P, Cr, REE (HUMPHRIS and THOMPSON, 1978 a, b), and possibly, Mg, Ni, V, Fe, Si and Al (PEARCE, 1975) are used to evaluate the magmatic nature of the rocks.

The basaltic samples show a remarkable chemical homogeneity and geochemical features analogous to those of mid-oceanic ridge basalts (MORB). There are no systematic compositional differences among the rocks of different tectonic units or of different metamorphic facies.

They are characterized by Zr/Y, Y/Nb, Zr/Nb and Ti/Zr ratios in the range of variations shown by mid-ocean ridge and marginal basin tholeiites (PEARCE and CANN, 1973; ERLANK and KABLE, 1976; KAY and HUBBARD, 1978; PEARCE and NORRY, 1979), as indicated by the distribution of the rocks in the PEARCE and CANN (1973) diagrams. An ocean-floor tholeiite affinity is supported by the position of samples in Ti/Cr (PEARCE, 1975; GARCIA, 1978) and Ti/Cr-Ni (BECCALUVA et al., 1979) plots proposed for the discrimination between ocean-floor and island-arc tholeiites (SPADEA, 1979, and in press).

They also share petrographic features with MORB and other high-Ti ophiolitic basalts of pure oceanic affinity, in that they show the crystallization of plagioclase before clinopyroxene which never occurs as phenocryst. In this respect they are strictly comparable to the volcanic sections, or their metamorphic equivalents, of other ophiolites from the Western Mediterranean area, such as Corsica (BECCALUVA et al., 1977; GLOM, 1977), the Alps (BICKLE and PEARCE, 1975; BERTRAND, 1970; MEVEL, 1975; RAITH et al., 1977; LOMBARDO et al., 1978), the Voltri Group (MAZZUCOTELLI et al., 1976; PICCARDO, 1977) and the Northern Apennines (BECCALUVA et al., 1980, and references therein).

It is worth noting, however, that even if they all show a clear ocean-floor affinity, the different ophiolites from the Western Mediterranean area display some differences both in parental magmas and fractionation trends (cf. BECCALUVA et al., 1980).

This is evidenced by the different REE patterns (fig. 2) and ratios between incompatible elements such as Zr/Y, Zr/Nb, Zr/Ti, Nb/Y, P/Y and La+Ce/Y for the various ophiolitic complexes (BECCALUVA et al., 1980).

A relatively wide range of ratios between incomparable elements can also be observed within the Calabrian basalts (fig. 3).

The available REE data on Western Mediterranean ophiolitic basalts generally show flat HREE chondrite-normalized (about 10÷35 times) patterns associated with both slightly positive (Balagne) and negative (Liguria, Alps, Alpine, Corsica) LREE fractionation (fig. 2).

Similarly, the Calabrian basalts have relatively flat chondrite-normalized REE patterns with abundances of heavy REE (HREE) about 12÷22 times those of chondrites, and a slight LREE enrichment comparable to that of Balagne basalts.

These geochemical characteristics, which are different from those of the most commonly LREE depleted oceanic tholeiites, indicate a closer resemblance of Calabria basalts with transitional MORB (SUN et al., 1979). Since incompatible element ratios show little change during the moderate- or high-degree partial melting required to generate ocean-floor type tholeiitic magmas, the above-cited geochemical differences suggest varying degrees of depletion of the source mantle from which the parental melts of the various ophiolite sequences were generated.

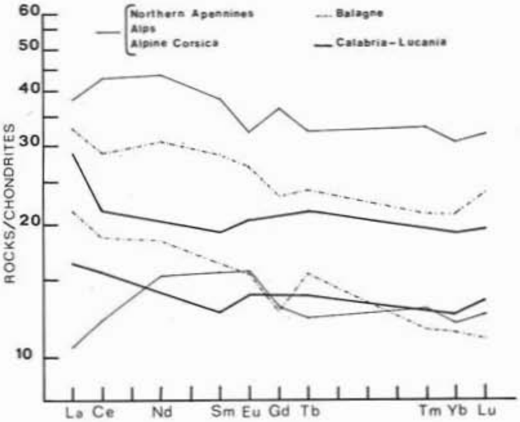

Fig. 2. — Chondrite-normalized REE patterns for Calabria-Lucania metabasalts (after DOSTAL et al., 1979). For comparison REE patterns of ophiolitic metabasalts from Balagne (Corsica), Northern Apennines, Alps and Alpine Corsica are also shown (after VENTURELLI et al., 1981).

Model calculations indicate that the Calabria and Balagne parental magmas could have derived by approximately 15 % equilibrium partial melting of mantle sources with sligthly higher than chondritic Zr/Y and Zr/Ti ratios (fig. 3).

Similar conclusions can be drawn from the Cr-Y and Cr-Ce/Sr diagrams (fig. 4), where the Calabria basalts fit genetic pathways characterized by closed/open system fractionation from intermediate partial fusion degrees.

Low-pressure fractionation in the Calabrian basalts is indicated by variations of all refractory elements, which form an overall tholeiitic trend with increased Ti, Fe, V, Zn, Mn, Sc, and decreased Ni, Cr and Al as the fractionation increases. Zr, Y, Nb, P and REE also increase with the differentiation (SPADEA, 1979; DOSTAL et al., 1979; BECCALUVA et al., 1980). This trend is consistent with fractional cristallization of olivine ± Cr-spinel and plagioclase (which are sometimes still recognizeable as phenocrysts in the metabasalts), later followed by clinopyroxene.

Gabbros

Gabbroic rocks are only a few percent of mafic ophiolites from the Calabria-Lucania area and occur as bodies not exceeding one km³ in volume. Mg-gabbros are cut by fairly abundant mafic dikes, recalling a typical gabbro-diabase association. In some occurrences gabbro with basaltic dikes, previously affected by oceanic metamorphism, represent a substratum on which basalt erupted (LANZAFAME et al., 1978).

Mg-gabbros are coarse-to medium-grained and are composed of saussuritized plagioclase, diopside ± olivine. A clear layering, shown by variations in texture and mineral composition, suggests a cumulitic origin. The

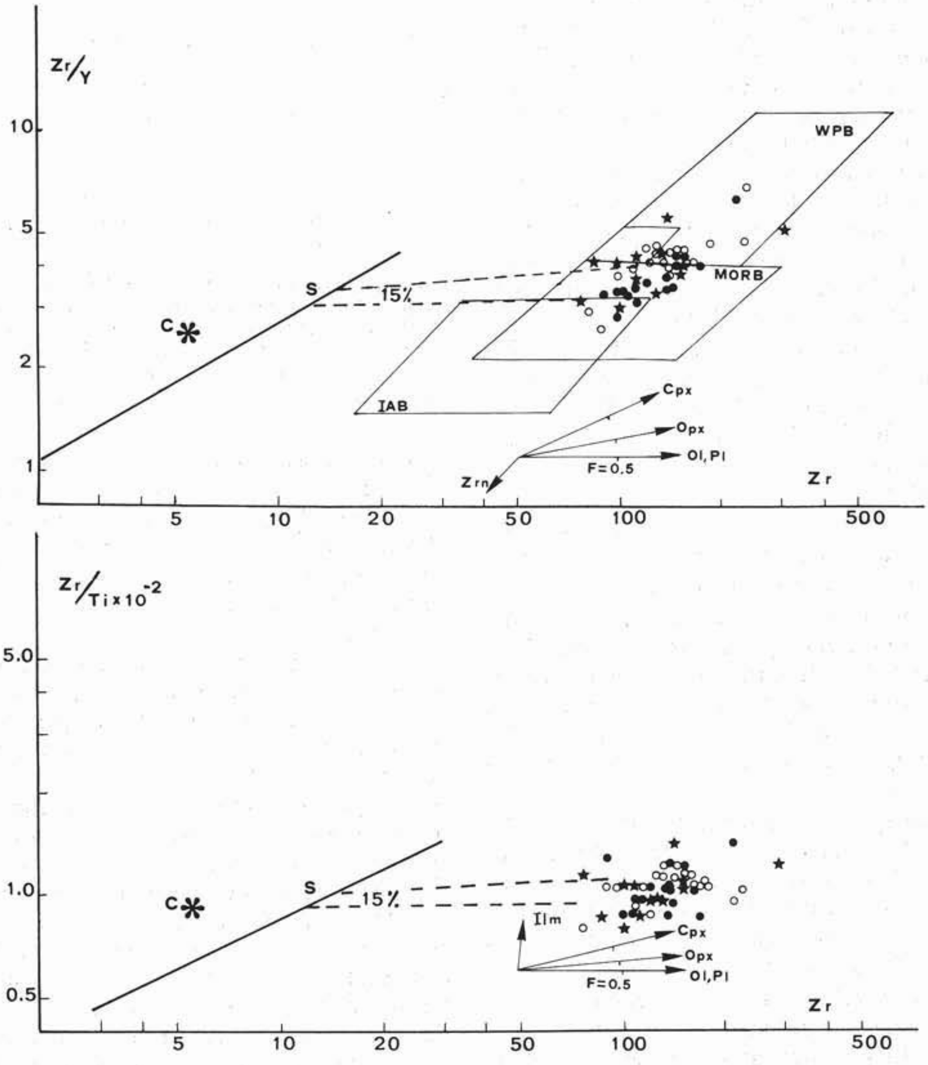

Fig. 3. — Zr/Y and Zr/Ti vs. Zr plot for Calabria-Lucania metabasalts with different metamorphic facies: prehnite-pumpellyite = ●; lawsonite-albite = ○; blueschist and greenschist = ★; samples with plagioclase accumulation are not shown (data after SPADEA, 1979). Dashed lines indicate non modal batch melting (cf. SHAW, 1970) trends and degrees (figures) for the inferred ophiolitic parental magmas from hypotetical sources chemically and mineralogically similar to mantle lherzolites of Western Mediterranean ophiolites (BECCALUVA et al., 1981). The source for Calabrian basalts as been modelled as follows: S = Ol 0.60, Opx 0.20, Cpx 0.16, Sp (Spinel) 0.04 and the assumed eutectic composition: Ol 0.15, Opx 0.15, Cpx 0.40, Sp 0.30. The modelled vectors indicate fractional cristallization of olivine (*Ol*), plagioclase (*Pl*), orthopyroxene (*Opx*), clinopyroxene (*Cpx*), ilmenite (*Ilm*) and zircon (*Zrn*); $F = 0.5$ liquid fraction. Partition coefficients and distribution fields of basalts from different tectonic settings are after PEARCE and NORRY (1979): *IAB* = island-arc basalts, *MORB* = mid-oceanic ridge basalts, *WPB* = within-plate basalts. Asterisk shows chondrite composition.

high MgO and low content of residual elements such as Ti, P, Zr and Nb are compatible with those rather undifferentiated terms of a cumulitic series where the adcumulus processes bring about the expulsion, to a great extent, of the original intercumulus liquid (table 1). Fe-rich gabbros occur as fragments of sedimentary breccia in the Frido Unit. In spite of advanced metamorphism (in the glaucophane schist facies), primary cumulitic textures and mineral assemblages are still recognizable in these rocks. Their chemical composition (table 1) is characterized by high Fe, Ti and P contents, reflecting the nature and proportion of cumulus phases, and by a general increase in residual elements indicating higher extent of original intercumulus liquid (meso- and ortho-cumulate textures).

On the whole the gabbroic rocks have chemistry and fractionation trends comparable to those of gabbroic intrusives from other Western Mediterranean ophiolites (fig. 5) and from the modern oceanic crust (MIYASHIRO et al., 1970; KAY et al., 1970; MELSON and THOMPSON, 1970; ENGEL and FISHER, 1975).

Both Mg- and Fe-rich types may be interpreted as cumulates generated from oceanic tholeiite magmas by separation of olivine, plagioclase and pyroxene during early stages (Mg-gabbros), later accompanied by Fe-Ti oxide and apatite (Fe-gabbros).

Mantle ultramafic

Serpentinized ultramafic occur in the Lucanian Apennine as large bodies (up to 300 m in tickness). Minor bodies and scattered lenses are also presenr in the Northern and Central Calabria.

In most occurrences they are serpentinized lherzolites containing relicts, often well-

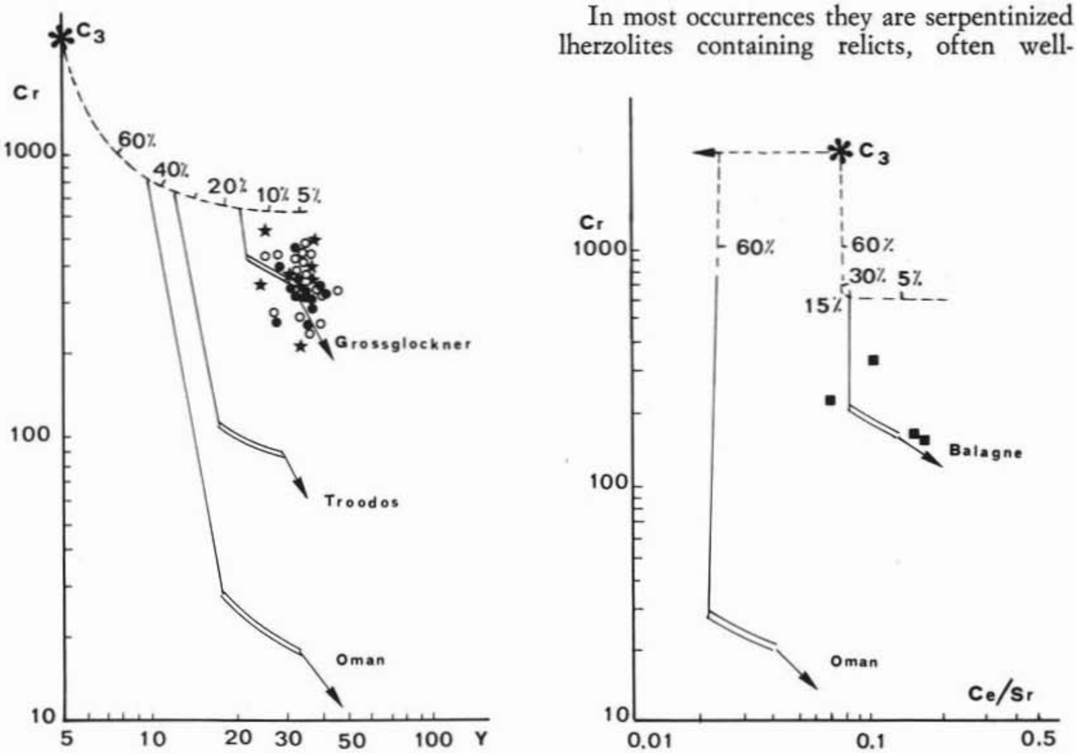

Fig. 4. — Cr vs. Y and Cr vs. Ce/Sr plots as modelled by PEARCE (1980) tor derivation of ophiolitic parental magmas by different partial melting degrees (figures) from C_3 chondrite source. Closed and open system fractional crystallization trends are indicated by single and double lines, respectively. For Calabria-Lucania metabasalts in Cr vs. Y plot data and symbols are as in fig. 3; in Cr vs. Ce/Sr plot data are from DOSTAL et al., 1979. Note the close resemblance of Calabrian ophiolitic magmatism, both in partial melting degree and fractionation trends, with other Western Mediterranean ophiolites like Grossglockner and Balagne.

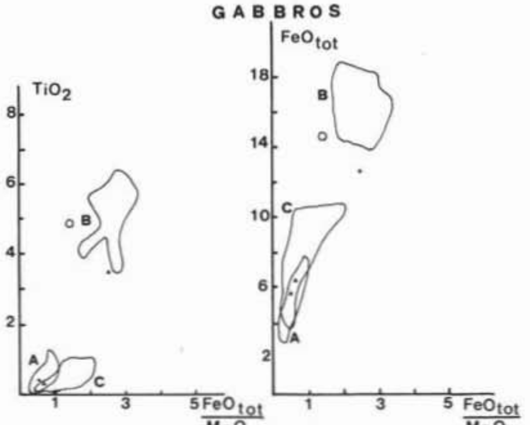

Fig. 5. — TiO_2 and $FeO_{tot.}$ vs. $FeO_{tot.}/MgO$ diagrams for volcanites and gabbros from Calabria-Lucania ophiolites (▲). *Gabbros*: A = Mg-gabbros, B = Fe-gabbroids from Northern Apennines and Corsica ophiolites; C = gabbroic rocks from Vourinos and Troodos ophiolites (after BECCALUVA et al., 1980). *Volcanites*: A = volcanites from Northern Apennines and Corsica ophiolites; B = volcanites from Vourinos and Troodos ophiolites (after BECCALUVA et al., 1980). For comparison, fractionation trends for abyssal tholeiites (C), Skaergaard liquid (D) and island-arc tholeiite suites of Macauley Island-Kermadecs (E), Miyake-Jimalzy-Bonin (F) and Tofua-Tonga (G) are also shown (after MIYASHIRO, 1975).

preserved, of diopside and chromite. Relict olivine may sometimes be found. Completely bastitized orthopyroxene is often recognizable in rocks still containing fresh diopside. On the basis of relict minerals and tectonite texture most ultramafic can be attributed to primary mantle lherzolites.

Rare serpentinized dunites, harzburgites and websterites are represented as centimeter-sized bands within the main lherzolitic masses (LANZAFAME et al., 1978).

The bulk rock chemistry (table 1) of the Calabrian mantle lherzolites is indistinguishable from that of comparable peridotites of other Western Mediterranean ophiolites (cf. BECCALUVA et al., 1980).

Metamorphic evolution

General aspects

The different metamorphic evolution of the Calabria-Lucania ophiolites provides a criterion for a major classification.

A first order subdivision can be made considering the presence of high-pressure metamorphism. This metamorphism related to an early underthrusting has been extensively recognized in the Pennine zone of the Alps, where it is known as an Eo-Alpine event (DAL PIAZ, 1974), and in the Alpine Corsica (OHNENSTETTER et al., 1975).

Ophiolites affected by high-pressure metamorphism occur typically in mélange and slices of the Lower Ophiolite Unit in the Lucanian Apennines and Northern Calabria, and compose, pro parte, the Upper Ophiolite Unit in Northern and Central Calabria. They are considered to be of Alpine affinity and to testify a provenance from a subducted part of the ocean crust (DIETRICH and SCANDONE, 1972).

A second major group is characterized by weak metamorphism, without penetrative deformation, unrelated to high-pressure conditions. Typically, this group is represented by spilitized pillow-lavas which either compose, pro parte, the Upper Ophiolite Unit in Northern and Central Calabria, or are included as olistoliths in Late Cretaceous deposits in the Lucanian Apennines. These ophiolites were considered to be of Liguride affinity (DIETRICH and SCANDONE, 1972). Their metamorphism probably developed mainly in an oceanic environment.

The chronology of the metamorphic and tectonic events in which the ophiolites were involved can be inferred from stratigraphical relations within different members of the suite and with different flysch sequences. Few radiometric ages have recently been reported (BECCALUVA et al., 1981) which indicate extensive isotopic re-equilibration during Oligocene-Early Miocene times.

A first metamorphic event, markedly poly-

TABLE 1

Analyses of ophiolitic and related rocks from the Calabria-Lucania area (Southern Apennines): metabasalts grouped according to metamorphic facies (average values, standard deviations, with number of samples in brackets, are reported); metagabbros (Mg- gabbro and Fe-gabbro), serpentinized ultramafics (largely serpentinized and completely serpentinized lherzolite, respectively), and basaltic dike rocks intruded in lower continental crust terranes

Lithotype	Metabasalt								Mg-Gabbro		Fe-Gabbro	Lherzo-lite	Serpentinite		Basalt dike
Met. Facies	PR-PP		LAW-AB		GL-SCH		GR-SCH		PR-PP	PR-PP	GL-SCH				PR-PP
	$\bar{x}$(18)	±σ	$\bar{x}$(37)	±σ	$\bar{x}$(9)	±σ	$\bar{x}$(7)	±σ	x(1)	x(1)	x(1)	x(1)	x(1)	x(1)	$\bar{x}$(2)
SiO_2 (wt%)	49.38	2.23	47.62	2.08	45.38	2.25	46.65	2.02	48.60	48.20	44.89	40.04	40.63	38.04	47.27
TiO_2	1.99	0.41	1.75	0.64	1.84	0.46	2.02	0.72	0.37	0.41	3.51	0.11	0.11	0.08	1.28
Al_2O_3	16.37	1.11	18.66	3.12	16.93	1.99	16.38	2.40	17.93	15.90	10.49	3.06	2.82	2.48	16.16
FeO_{tot}	10.72	1.71	9.71	3.25	10.57	1.79	10.86	2.20	6.38	5.70	12.61	7.39	7.51	6.91	10.28
MnO	0.20	0:08	0.16	0.05	0.18	0.04	0.18	0.04	0.14	0.12	0.20	0.19	0.15	0.08	0.17
MgO	5.87	2.03	5.50	1.88	6.38	1.75	7.18	1.47	9.72	11.00	4.93	34.42	33.67	39.08	9.45
CaO	6.21	3.32	7.63	2.38	9.50	2.22	8.18	1.94	8.41	10.24	12.73	1.25	0.20	---	7.88
Na_2O	4.01	1.44	3.29	1.50	2.42	0.89	2.34	1.10	1.57	2.44	3.10	---	---	0.02	3.28
K_2O	0.79	0.98	0.55	0.59	0.86	0.90	0.96	1.28	2.47	1.61	1.73	---	---	0.02	0.12
P_2O_5	0.22	0.06	0.20	0.08	0.20	0.05	0.25	0.08	0.02	0.02	1.19	---	0.01	0.01	0.21
L.I.	4.25	1.32	5.35	1.34	5.53	1.52	4.43	0.53	4.10	4.06	2.56	12.97	14.05	12.51	3.50
Ni (ppm)	110	61	91	29	115	49	104	72	149	134	59	1840	1710	2150	214
Cr	336	50	355	74	322	135	272	142	796	158	66	2760	---	2560	456
V	339	50	287	113	338	86	280	8	---	184	241	67	81	81	185
Ba	52	18	44	30	63	55	337	314	---	---	278	27	24	---	53
Sr	154	89	205	124	209	123	214	135	66	60	342	4	7	13	85
Rb	12	18	9	12	16	16	18	32	17	18	39	---	---	---	7
Zr	131	28	122	41	118	32	143	69	17	19	254	4	4	---	109
Nb	6	5	7	5	6	6	6	7	1	2	110	---	---	---	6
Y	34	4	29	7	33	6	37	26	14	7	25	2	2	---	25

phasic, took place in oceanic environment and developed at first in peridotite and gabbro, before the eruption of stratigraphically overlying pillow-lavas. A second phase affected the whole ophiolite sequence and is characterized by spilitic alteration of the pillow-lavas. This early metamorphism can be ascribed to the Jurassic-Early Cretaceous, the earliest Cretaceous minimum age being indicated by the distribution of the metamorphism in sediments on top of the sequence.

The subsequent metamorphic event related with early displacement by subduction is considered at least synchronous, or even older (pre Upper Albian) (HACCARD et al., 1972; SPADEA in press), with that of the Eo-Alpine event, for which a Late Cretaceous age (100÷60 Ma) is known by extensive radiometric dating.

Later episodes of Alpine metamorphism are related to the main phases of the Apennine orogeny, which occurred in Middle Tertiary (Oligocene-Miocene) and Miocene times (OGNIBEN, 1969, 1973; HACCARD et al., 1972; AMODIO-MORELLI et al., 1976).

Oceanic metamorphism

Evidences of alteration related with ocean-floor metamorphism prior to early tectonism are displayed in few cases within the Calabria-Lucania ophiolites. As in most ophiolitic rocks, in fact, the dominant oceanic metamorphism is of low- to very low-grade and took place without apparent deformation, making its distinctions from later low-grade orogenic metamorphism difficult. Furthermore, in the higly dismembered ophiolites of the Calabria-Lucania area the criterion of recognizing an oceanic metamorphism on the basis of the high gradient inferred by the vertical distribution of mineral assemblages cannot usually be applied.

Nevertheless, alteration of higher grade than spilitization can, in some cases, provide clear evidence of oceanic metamorphism.

One instance is represented by gabbro, intruded by basaltic dikes and stratigraphically overlain by pillow-lavas, which composes olistoliths exposed in few sections of the Lucanian Apennines (LANZAFAME et al., 1978). The gabbro and associated basalt show a complex multiphase retrograde (from middle- to low-grade) metamorphism, unlike the overlying pillow-lavas (as well as dikes intruded in the latter) which were affected only by spilitization.

In metagabbro, assemblages consisting of cummingtonite followed by brown and green hornblende, and subsequently by actinolite are displayed, which suggest a recrystallization under amphibolite, followed by greenschist facies conditions. Earlier alteration is occasionally testified by recrystallization of diopside followed by development of reddish hornblende, which could indicate initial high-grade, quasi-magmatic conditions. The metabasaltic dike rocks display only amphibolite and greenschist facies assemblages (LANZAFAME et al., 1978).

Another favorable circumstance occurs in cases of close association (in mélange zone) of basic rocks affected by rodingitic alteration with development of different mineral assemblages. One group of rocks displays typical rodingitic assemblages dominated by diopside and hydrogarnet which are overprinted by younger ones including pumpellyite as major phase. Widespread pumpellyte and no relic of older metasomatic assemblages characterize another group of rodingitized basic rocks (SPADEA, in press). There are indications that rodingitic alteration, and consequently serpentinization, occurred both before and after the tectonic displacement of the peridotite bodies. The older process, during which the diopside-hydrogarnet pair crystallized, very likely took place in an oceanic environment.

High-pressure metamorphism

High-pressure/low-temperature assemblages developed during an early subduction event are generally well preserved without extensive overprinting, particularly in the northern area (Lucanian Apennine), where aragonite is widespread in metasedimentary rocks of the Frido Unit (SPADEA, 1976; LANZAFAME et al., 1979 b; SPADEA, in press).

Ophiolites and associated sedimentary rocks display different features of the high-pressure metamorphism, either in the degree of recrystallization, or in the composition of the associated minerals in similar primary lithotypes, or in deformation. Two main groups of high-pressure rocks can be distinguished and be arranged in a blueschist facies series as defined by TURNER (1981).

A first group includes typical blueschist metabasites with glaucophane-lawsonite and also containing various Na-pyroxenes, crossite, phengite, pumpellyite, albite and sphene.

A second group of *HP-LT* rocks consists of prevalent metabasalts and capping metasediments: mineral assemblages are dominated in the former by albite-lawsonite-chlorite (plus pumpellyite, epidote, and ubiquitous sphene). Blue amphiboles and sodic pyroxenes rarely occur, and are mainly represented by Mg-riebeckite and aegirine-augite, respectively.

In terms of facies classification the two group of high-pressure rocks are referred to the blueschist (or glaucophane schist facies according to DE ROEVER, 1972), and to the lawsonite-albite facies, respectively. Detailed reports have been published on the mineralogy and petrology of these meta-ophiolites, particularly of metabasites (basalt, dolerite, and rare gabbro: HOFFMANN, 1970; DE ROEVER, 1972; DE ROEVER et al., 1974; PICCARRETA and ZIRPOLI, 1975; SPADEA et al., 1979).

Mineral assemblages and textures of rocks referred to both the lawsonite-albite and blueschist facies indicate that the dominant *HP-LT* metamorphism was polyphase and was overprinted by a younger metamorphism under lower pressure conditions. The latter attained greenschist facies during its climax.

The polyphase character of the high-pressure metamorphism is clearly shown by zoning of blue amphiboles and Na-pyroxenes, and by textural relations of Ca-silicates (lawsonite, pumpellyite, and epidote).

Widespread mineral assemblages developed in lawsonite-albite facies metabasites include

TABLE 2

Mineral assemblages developed during HP/LT metamorphism (under lawsonite-albite and glaucophane schist conditions and during a late event (mostly under greenschist facies conditions) in metabasites and metasedimentary rocks of the Calabria Lucania area (Southern Apennines)

LITHOTYPES	METAMORPHIC FACIES		
METABASITES	LAW-AB	GL-SCH	GR-SCH
ALBITE	———	- - -	———
LAWSONITE	———	———	
PUMPELLYITE	———	- - -	
EPIDOTE	- - -	- - -	———
OMPHACITE/JAD-AEG		———	
AEGIRINE-AUGITE	- - -	- - -	
GLAUCOPH/CROSSITE		———	
CROSSITE/MG-RIEBECK	- - -		
ACTINOLITE			———
CHLORITE	———	- - -	———
WHITE MICA	- - -	- - -	- - -
METASEDIMENTARY ROCKS			
QUARTZ	- - -	- - -	———
ALBITE	- - -	- - -	- - -
PHENGITE	———	———	- - - ? - -
PARAGONITE	- - -	———	
CHLORITE	———	———	- - -
ARAGONITE		———	
ANKERITE	- - -	———	- - - ? - -
CALCITE	- - -		———

as major phases:

a) albite-chlorite ± lawsonite ± pumpellyite ± epidote;

b) albite-chlorite ± Mg-riebeckite ± aegirine-augite;

with ubiquitous sphene, and phengite, calcite and hematite as possible additional minerals (DE ROEVER, 1972).

Besides variations in mineral composition, strong differences in metamorphic textures are displayed, as a result of variable deformation.

Metabasites with blueschist assemblages include either pervasively recrystallized, massive or more or less deformed rocks, or partly recrystallized rocks in which magmatic textures and minerals can survive. They consist mostly of:

c) lawsonite ± pumpellyite-glaucophane-crossite ± albite ± phengite ± chlorite;

d) lawsonite ± pumpellyite-jadeite/aegirine-aegirine/augite-glaucophane-crossite ± albite ± phengite ± chlorite;

e) lawsonite-omphacite-jadeite/aegirine ± chlorite ± albite.

Sphene is a common additional phase, and sporadic aragonite, represented by relict forms, occurs (HOFFMANN, 1970).

A group of poorly recrystallized metabasites, mostly with a basaltic parentage occurring within the Frido Unit from the Lucanian Apennines closely associated to metasedimentary rocks with widespread aragonite, displays typical blueschist assemblages, but mainly in small quantities, with aragonite as a possible additional component.

Metabasites consisting of dominant albite and chlorite, with small amounts of lawsonite and/or pumpellyites, and in places of aragonite, are common within the Frido Unit in the same area. They can be considered either as representative of transitional conditions between lawsonite-albite and the blueschist facies, or be assigned to the lawsonite-albite facies according to TURNER (1981).

Mineral assemblages displayed by metabasites of lawsonite-albite and the blueschist facies are compared in tab. 2. Assemblages developed during a late metamorphic event, which are qualitatively similar in both groups of high-pressure rocks, are also reported. The overall differences between metabasites of the two high-pressure facies are also reflected in the composition of both blue amphiboles and sodic pyroxenes, as emphasized by DE ROEVER (1972) and DE ROEVER et al. (1974). Pertinent chemical data are plotted in figs. 6 and 7.

Some *P-T* constraints on the conditions of the high-pressure metamorphism are provided by the occurrence of lawsonite and aragonite, by the composition of blue amphiboles and sodic pyroxenes, and by the coexistence of albite and quartz. Estimated conditions for the lawsonite-albite facies metamorphism are fluid pressure between 3 and 4.5 kb, and temperature in the 250° ÷ 350° C range. For transitional conditions to blueschist facies, higher pressure (above 5 kb) and probably lower temperature can be estimated by the occurrence of aragonite and the absence of glaucophane. For blueschist facies metamorphism pressure between 6 kb and 8 kb, and a possible temperature range in the order of 350° ± 50° C can be inferred.

Summary and conclusions

The available petrological and geological data indicate that the Calabria-Lucania ophiolites may be considered as fragments of the oceanic lithosphere developed during the

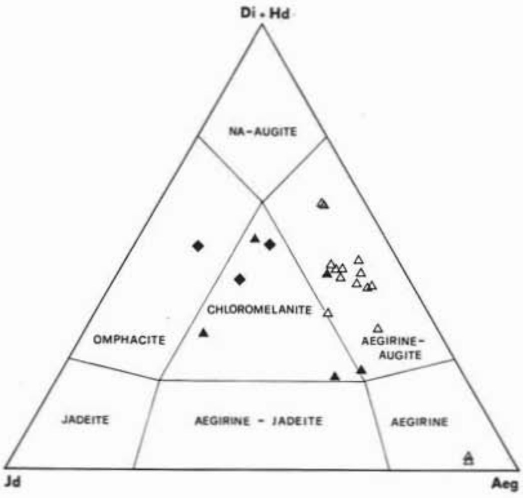

Fig. 6. — Composition of Na-pyroxenes, in terms of the molar proportions of end-members diopside+hedenbergite-jadeite-aegirine, occurring in lawsonite-albite facies metabasalt (△) and in blueschist facies metabasalt (▲) and metagabbro (♦) from the Calabria-Lucania area (Southern Apennines). Data from HOFFMANN (1970); DE ROEVER (1972); SPADEA et al. (1979); SPADEA (unpublished).

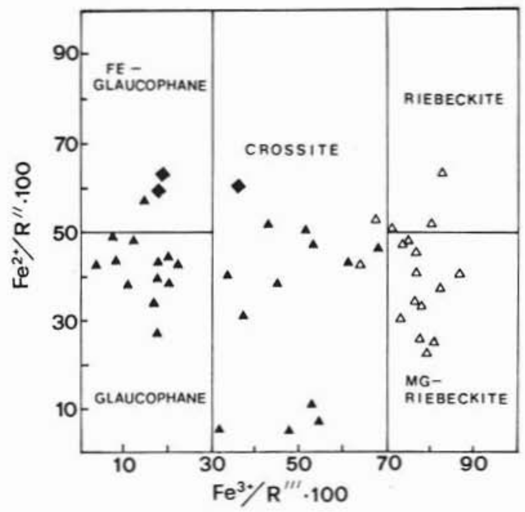

Fig. 7. — Composition of Na-amphiboles, in terms of $Fe''/Fe'' + Mg + Mn \cdot 100$ vs $Fe'''/Fe''' + Al + Ti \cdot 100$, in metabasalt and metagabbro from the Calabria-Lucania area (Southern Apennines). Data from HOFFMANN (1970); DE ROEVER (1972); DE ROEVER et al. (1974); SPADEA et al. (1979); SPADEA (unpublished).

Jurassic opening of the Western Tethyan basin and separating the European and African (Insubrian) continental blocks.

They represent oceanic associations consistuted by: 1) mantle ultramafic generally showing a spinel-lherzolitic character; 2) oceanic tholeiitic basalt similar to transitional MORB, evolving by fractional crystallization towards ferrobasaltic compositions; 3) gabbroic rocks produced by cumulus processes, at various fractional crystallization stages, from oceanic tholeiite magmas.

In this regard they are similar and have the same significance of the other ophiolitic complexes from the Western Mediterranean area, and reveal the closest resemblance, as far as the magmatic characteristics are concerned, with those of Balagne and External Ligurides. Their basaltic sequences, in fact, show an affinity with undeplepted tholeiites of transitional MORB type from External Ligurides and Balagne.

All the data on the Western Mediterranean ophiolites indicate that after initial rifting episodes (Middle Triassic to Early Jurassic), continental fragmentation and development of multiple deep seaways took place (SCANDONE, 1975), which later evolved to ridge segment/fracture zone systems (PICCARDO, 1977; BECCALUVA and PICCARDO, 1978; BECCALUVA et al., 1980). This was apparently related to separation of Africa from North America, and its eastward motion with respect to the Euroasiatic plate (DEWEY et al., 1973) which produced large scale tensional and transcurrent effects within the epicontinental and newly-formed oceanic domains.

As it has been suggested for the analogous sequences from the External Ligurides and Balagne (BECCALUVA et al., 1980), basalts from the Calabria ophiolites might represent the activity of an early oceanic-type magmatism developed in a pericontinental position, very close to the new continental margins. This hypothesis can also account for the abundance of terrigenous sediments covering ophiolitic basalts, which require a nearby continent (LANZAFAME et al., 1978), and their primary association with continental crust terranes prior to the tectonic-metamorphic evolution during orogeny (LANZAFAME et al., 1979 a; SPADEA, in press).

Since there is no contrasting geological or petrological evidence, it is conceivable that this oceanic basin never reached a well-developed stage, resulting in a narrow deep seaway with remnants from continental crust margins. Moreover, the fact that 1) the brecciation of ophiolitic along with continental material, 2) the serpentinization of the mantle lherzolites and 3) the oceanic metamorphism in gabbros occurred, in some places, before oceanic basalts extrusion and dikes emplacement, indicates early tectonism and similar characteristics to those of oceanic fracture zones as pointed out for some Northern Apennines ophiolites (cf. ABBATE et al., 1972; GALBIATI et al., 1976; BECCALUVA et al., 1980; SERRI, 1980). Such a tectonic environment could also account for the lack of a complete sheeted dike and gabbro complex, and for the general considerably reduced thickness of the ophiolitic sequences with respect to normal oceanic crust.

Therefore the Calabria-Lucania ophiolites may represent lithospheric sections generated at an early ocean ridge system, later interested, at least in part, by a subsequent tectonic-metamorphic evolution in fracture zones and, eventually, by injection of new oceanic melts at the intervening ridge/transform intersections. An oceanic/pericontinental pattern, strongly affected by both divergent and transcurrent movements, with development of short ridge segments and important fractures and leaky transform zones (cf. CRISTENSEN and SALISBURY, 1975), should have characterized the original geodynamic environment of the Calabria-Lucania ophiolites.

Before the end of Early Cretaceous the closure of this ocean basin took place by convergence, underthrusting and consumption of the oceanic lithosphere, which might have been subducted for a short time, due to its restricted extension. The age of the early *HP-LT* metamorphic episode is considered to be post-Aptian and pre-Late Albian, based on stratigraphical evidence (HACCARD et al., 1972; SPADEA, in press).

Pertinent metamorphic assemblages indicate partial equilibration at different pressure conditions, reaching maximum values of $6 \div 8$ kb at $350° \pm 50°$ C. The widespread blueschist assemblages and the largely incomplete equilibria attained suggest a high rate of consumption, resulting in a rapid decrease of the geothermal gradient and the establishment of the blueschist facies stability conditions. The subsequent exhumation, which occurred extensively without overprinting and obliterating the high-pressure assemblages, may also have occurred at high rates. This implies, according to the model proposed by DRAPER and BONE (1981) an early tectonic emplacement of the high-pressure terrains.

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