**Zeitschrift:** Schweizerische mineralogische und petrographische Mitteilungen = Bulletin suisse de minéralogie et pétrographie

**Band:** 53 (1973)

**Heft:** 3

**Artikel:** Jadeite-Bearing metagranites l.s. and related rocks in the Mount Mucrone Area (Sesia-Lanzo Zone, Western Italian Alps)

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**DOI:** https://doi.org/10.5169/seals-41389

# Jadeite-Bearing Metagranites l. s. and Related Rocks in the Mount Mucrone Area (Sesia-Lanzo Zone, Western Italian Alps) *)

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With 9 figures and 1 table in the texte, and 2 plates

**Summary**

In the Mt. Mucrone area (inner central portion of the Sesia-Lanzo zone) there are relics of a granitic to quartz-dioritic stock, having sharp contacts with a pre-granitic foliated complex, consisting of mesozonal two-micas-K-feldspar-paragneisses.

Granitic and foliated rocks have suffered a complex high-pressure-low-temperature metamorphism, marked by the blastesis of minerals such as jadeite (and other Na-pyroxenes like omphacites, chloromelanites and aegirine-augites), zoisite, garnet and phengitic micas.

A petrographical study has shown that at least four metamorphic stages have been involved:

1st stage: development of jadeite-quartz-zoisite-assemblage after plagioclase, and of garnet-white-mica-assemblage after biotite. The latter reaction can be detected in all phases of the transformation, and has led to the growth of typical corona textures (garnet rims around biotite).

2nd stage: development of poorer and poorer jadeite pyroxenes (omphacites to chloromelanites), followed by the occasional appearance of aegirine-augite in equilibrium with albite. Glaucophane (rarely observed) presumably formed towards the end of this stage.

3rd stage: abundant development of phengitic micas (mainly after jadeite, K-feldspar and biotite relics), albite and titanite.

4th stage: appearance of very fine-grained greenish (or brown-greenish) biotite flakes, both in the rock and the veins, in association with carbonates, green amphibole and clinozoisite. This stage must probably be referred to the thermal effect of the Tertiary stock outcropping in the nearby Cervo Valley.

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*) Work carried out with the financial support of the Italian National Research Council (C.N.R.).

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Among the original contributions of the present study the following are of note: the first occurrence of pure jadeite in the Sesia-Lanzo zone; the very intimate intergrowth of jadeite with quartz; the occurrence in the same rock of several Na-pyroxenes; the garnet stability over the whole range of high-pressure metamorphism.

Experimental data on the stability of Na-pyroxenes and phengitic micas suggest that the Mt. Mucrone rocks initially underwent a pressure of at least 10 Kb, roughly corresponding to a lithostatic load of 35 km. The ensuing mineral evolution can be explained either assuming unloading or a modest temperature increase or the combined action of both parameters.

**Riassunto**

Nell'area del M. Mucrone (settore interno della Zona Sesia-Lanzo) sono stati trovati relitti di un ammasso granitico fino a quarzodioritico, con rapporti discordanti nei confronti di una serie scistosa pregranitica con caratteri mesozonali, costituita da paragneiss ad una o due miche e K-feldspato.

Le rocce granitiche e quelle scistose hanno subito un evento metamorfico di alta pressione e bassa temperatura, messo in evidenza dallo sviluppo di minerali quali: giadeite (ed altri pirosseni alcalini quali omfaciti, cloromelaniti ed egirinaugiti), zoisite, granato, miche bianche (fengiti).

Lo studio petrografico ha permesso di ricostruire la complessa serie delle trasformazioni metamorfiche, successive all'intrusione dei graniti, riducibili nei seguenti stadi:

1° stadio. Sviluppo di giadeite + quarzo + zoisite da preesistente plagioclasio, e di granato + fengite da biotite. Quest'ultima reazione è documentata in tutte le fasi della trasformazione e porta allo sviluppo di caratteristiche strutture coronitiche (orli di granato su biotite).

2° stadio. E' caratterizzato dallo sviluppo di pirosseni alcalini, progressivamente più poveri in molecola giadeitica (omfaciti fino a cloromelaniti) ed infine dalla comparsa di egirinaugite in equilibrio con albite (per il settore esaminato, unico caso di coesistenza fra alcali-pirosseno e albite).

3° stadio. Appare generalizzato lo sviluppo di fengite ed albite, che si formano a spese sia dei pirosseni alcalini (esclusa l'egirinaugite) che del feldispato potassico e dalla comparsa di titanite al posto del rutilo.

4° stadio. E' caratterizzato dalla comparsa di biotite verde o verde-bruna microlamellare, sia nella massa della roccia, che nelle fratture, in associazione con carbonati, anfibolo verde e clinozoisite.

Quest'ultimo stadio è probabilmente riferibile ad un effetto termico collegato con l'intrusione terziaria del vicino plutone della Valle del Cervo.

Fra i contributi originali sono da ricordare: la prima segnalazione di giadeite nella Zona Sesia-Lanzo; la sua intima compenetrazione, alla scala micro- e submicroscopica, con quarzo; la presenza di più pirosseni alcalini nella stessa roccia; la stabilità del granato attraverso tutto l'intervallo del metamorfismo di alta pressione.

La ricostruzione petrografica degli eventi metamorfici, vista alla luce dei dati sperimentali sulla stabilità dei pirosseni alcalini e delle fengiti, consente di indicare che le rocce di quest'area sono state sottoposte inizialmente a pressioni minimali di 10 Kb, corrispondenti grosso modo ad un carico roccioso di circa 35 km.

La successiva evoluzione minerogenetica implica variazioni nei fattori P–T: essa si può spiegare vuoi con uno sgravio di pressione, vuoi con un moderato aumento di temperatura, o con l'azione combinata dei due fattori.

## INTRODUCTION

The Mt. Mucrone area lies at the head of the Oropa basin (Biella). It belongs to the central innermost portion of the Sesia-Lanzo zone, which is better known as the "eclogitic micaschist" formation[1]). This formation mainly consists of omphacite and/or glaucophane-bearing phengitic micaschists often including nodules, lenses, or masses of glaucophanitic eclogites or glaucophanites (NOVARESE, 1929; 1931).

These micaschists and their associated eclogites have been studied by several authors. The best account is still that of BIANCHI and DAL PIAZ (1963). Detailed examination of the eclogites may be found in VITERBO-BASSANI and BLACKBURN (1968) and in an unpublished thesis by MARTINOTTI (1969). The eclogitic micaschists and the associated rocks of the Sesia-Lanzo area have been studied by BIANCHI, DAL PIAZ and VITERBO (1965), while the age of the metamorphism has been dealt with by BIANCHI and DAL PIAZ (1963), DAL PIAZ, GOSSO and MARTINOTTI (1971), HUNZIKER (1970) and ERNST (1971). Recent papers on the minerals of rocks belonging to the eclogitic micaschist formation, including data from other areas, are due to CALLEGARI and VITERBO (1966), MONESE, OGNIBEN and VITERBO (1967), OGNIBEN (1968), FIORENTINI POTENZA and MORELLI (1968), and FIORENTINI POTENZA (1969). The eclogitic micaschist formation also includes granitoid orthogneiss masses, that locally display a massive texture (metagranites) as first noted by FRANCHI (1902).

The present paper deals with a metagranite mass, outcropping at Mt. Mucrone, previously examined in a thesis by one of the writers (MAFFEO, 1969). The results of this earlier work have been re-examined, extended and improved in the present paper.

## GEOLOGICAL OUTLINE

A little stock of granitoid rocks outcrops within the eclogitic micaschist formation, in the Mt. Mucrone area, well known for its widely distributed eclogites (among the finest in the whole Sesia-Lanzo Zone). These massively structured granitoid rocks extend for about 0,5 $km^2$ around the Colle del Limbo[2]) on the ESE face of the mountain. The granitoid stock consists of clearly massive portions (the area of which is usually no more than a few

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[1]) The term "eclogitic micaschists" (micascisti eclogitici) was proposed by A. STELLA (1894) for the Na-pyroxene-glaucophane-garnet-quartz-micaschists, with interbedded eclogite layers or lenses, widespread in the Orco valley. This term was then used with a formational meaning by S. FRANCHI, V. NOVARESE and A. STELLA in the sheets M. Rosa (29), Varallo (30), Ivrea (42) and Biella (43) of the Geological Map of Italy.

[2]) Sheet Lilianes 42 I NE of the Italian Military Geographic Institute.

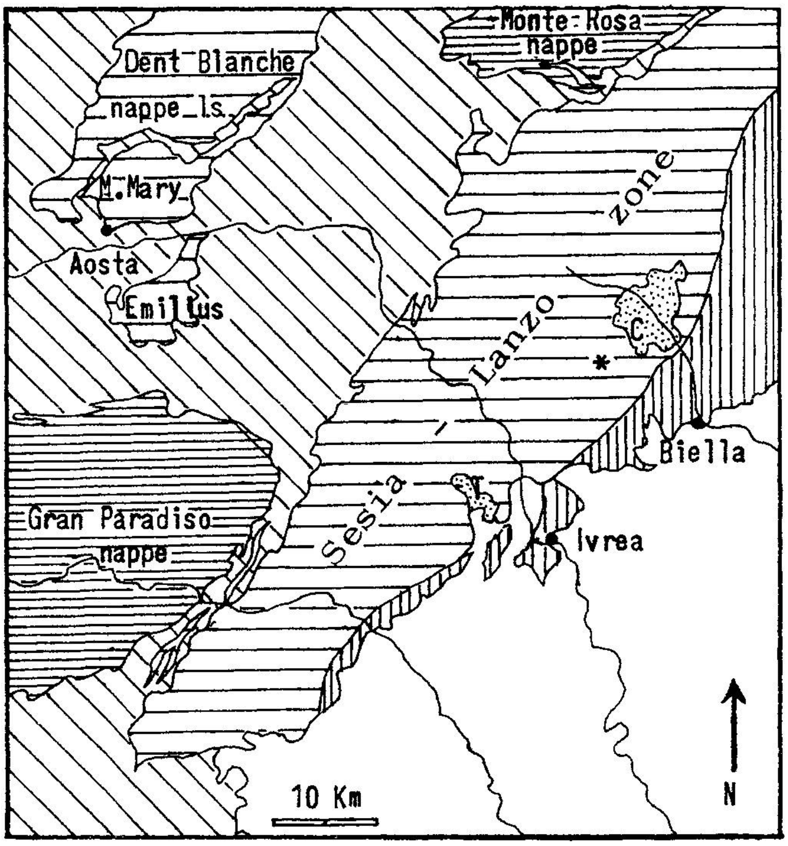


Fig. 1. Simplified structural map showing the location of the Sesia-Lanzo zone in the central part of the North-western Alps. Sesia-Lanzo zone and related nappes; horizontal wide ruling; Gran Paradiso and Monte Rosa nappes; horizontal close ruling; Pennidic Mesozoic: oblique ruling; Southern Alps; vertical ruling; Tertiary plutonic stocks; spotted: T = Traversella mass, C = Cervo valley mass. Asterisk indicates the Mt. Mucrone area.

hundred square metres), separated by bands with a slightly foliated structure. The massive portions are typically "granitic" – looking and contain biotite, quartz and centimetre-size K-feldspars. The existence of abundant primary relics (see below) warrants the use of the term *metagranites l. s.;* the gneissose forms, with quartz eyes elongated on the foliation planes, can be referred to as *granitic orthogneisses.* At its periphery the mass gradually tapers off to increasingly gneissose forms, so that no clear boundary with the surrounding eclogitic micaschists can be determined.

The original relations between the metagranitic mass and the surrounding rocks were discordant as can be deduced from the presence of angular inclusions, with clear signs of residual foliation (Fig. 2), in both the metagranites and the orthogneisses. A similar picture was described by Franchi (1902) at the Colle della Vecchia, a few km to the NW (between the upper Cervo and Lys valleys).

Fine-grained rocks with an apparently massive texture, microscopically classifiable as *quartz-garnet-pyroxene-fels,* are occasionally observed both

Fig. 2. Angular block of foliated rock (upper) enclosed in metagranite (lower). Southeastern side of the Mt. Mucrone.

Fig. 3. Blastomylonite bands crossing massive metagranite. The inner light layer is composed of pink zoisite. Eastern wall of the Mt. Mucrone.

inside the mass and along its contact. These rocks are locally injected by metagranitic apophyses and their contacts are always sharp. These elements suggest their hornfelsic character, though the absence of relics of foliation cannot be explained.

The metagranitic mass is crossed by numerous and narrow bands, mylonitic in aspect, now recristallized (*blastomylonites:* Fig. 3). These rocks have the same constituents as and gradually blend into the metagranites. The microscope shows that their virtually constant pink innermost part primarily consists of zoisite.

## PETROGRAPHY

### Metagranites lato sensu

Our description is of a typical sample collected at the foot of the E wall of Monte Mucrone, where the original igneous fabric is best preserved. The rock is pale-grey and has a massive structure and medium-grained granular texture, in which one can recognize quartz, biotite and potassic feldspar (up to 2 cm).

The microscope shows a virtually unaltered hypidiomorphic texture, with automorphic plagioclases (Fig. 4) (now pseudomorphically replaced by a microgranoblastic aggregate of minerals), large interstitial quartz and/or K-feldspar grains and well developed biotite flakes. The primary assemblage is completed by white mica and by accessory minerals.

High magnification reveals in most garnets a darker core filled with very small *rutile* needles.

The biotite changes not only into garnet but also into *white mica* (Figs. 5 and 6) usually in the form of small flakes without preferred orientation or

Fig. 4. Monte Mucrone metagranite (SL 137). Well preserved relics of the original granitic texture. The plagioclase laths are completely replaced by the high-pressure jadeite + quartz + zoisite assemblage. The clear groundmass is still preserved orthoclase. 35 × – Plane polarized light.

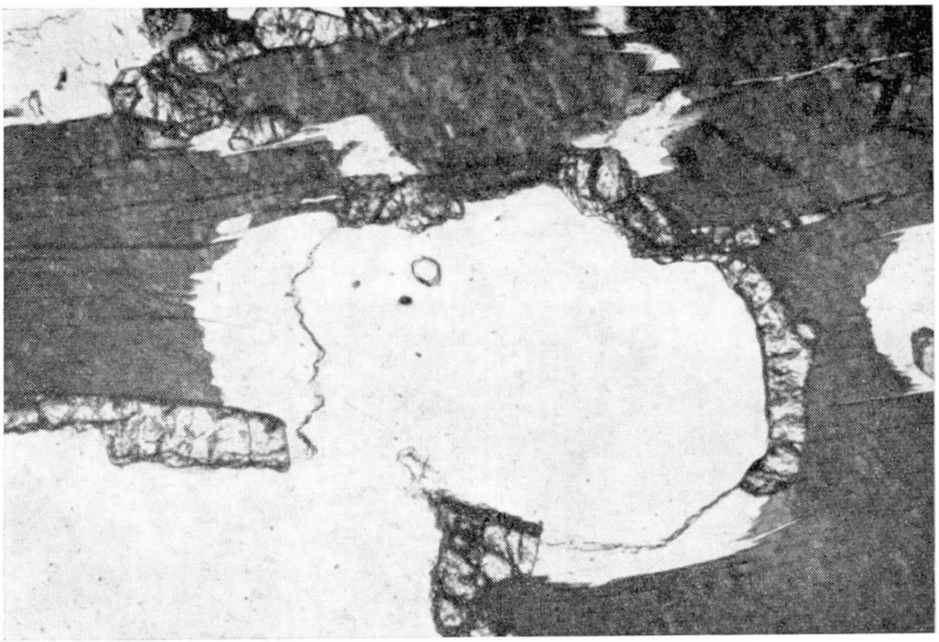

Fig. 5. Mt. Mucrone metagranite (SL 40). Detail of textural relationships along the biotite boundaries. In the early stage of the high-pressure metamorphism rims of garnet and/or white mica develop at the expense of biotite. This reaction occurs at the same time as the plagioclase replacement by the jadeite-zoisite-quartz-assemblage. 130× – Plane polarized light.

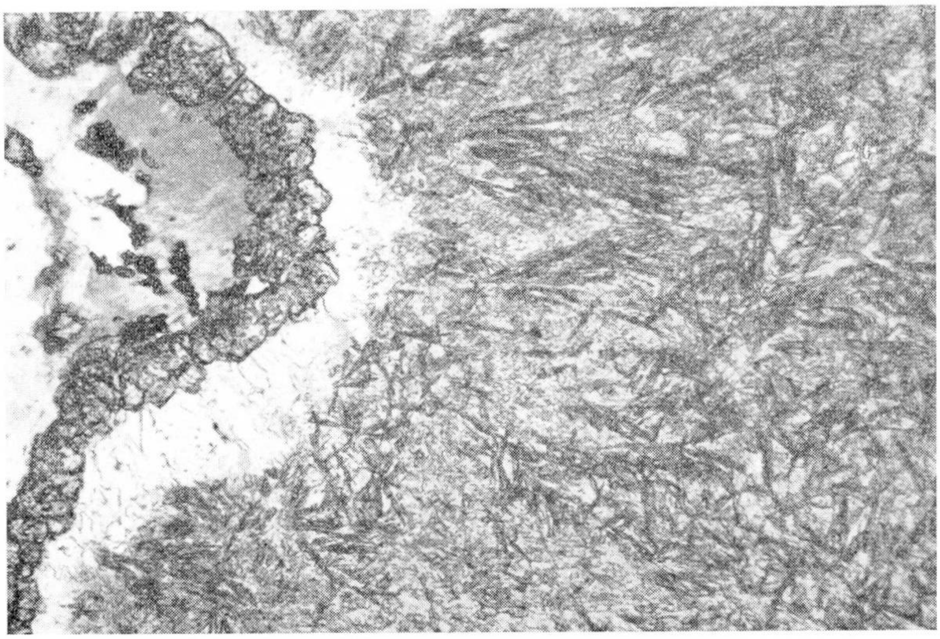

Fig. 6. Mt. Mucrone metagranite (SL 40). Detail of textural relationships at the original boundary biotite-plagioclase. Plagioclase (right) is transformed into a fine-grained assemblage of jadeite + quartz + zoisite; the latter mineral forms the visible fine needles. Biotite (left), partially replaced by white mica (± rutile), is continuously rimmed by a garnet corona. A clear, zoisite-free, rim of white mica develops between garnet and the pseudomorphs after plagioclase. 120× – Plane polarized light.

more rarely as homoaxial overgrowths. This transformation is mostly localized at the periphery of the biotite flakes or along kink-bands.

The *original plagioclases* are completely transformed into an aggregate of dirty brown minerals, the relief of which is considerably higher than that of quartz (Fig. 4). Since it is impossible to identify them with the microscope, X-ray diffraction analysis was used. This revealed an assemblage of *jadeite + zoisite + quartz*, with the first mineral predominant.

No original plagioclase relics are found, but the quantity of zoisite microlites, although varying, is always such as to suggest andesine as the parent plagioclase.

*Jadeite* xenoblasts form the groundmass of the aggregate-pseudomorphs. The refraction index ($n_\beta = 1.660 \pm 0.002$) and the (221) interplanar spacing ($d_{221} = 2.918$ Å) shows that its composition agrees with that of pure end-member $NaAlSi_2O_6$ (ESSENE and FYFE, 1969). This fits in well with the optic axial angle values ($2\ V_\gamma = 70$–$73°$).

The *zoisite* crystals form very fine interwoven tufts, that stand out from the jadeitic groundmass because of higher relief (Fig. 6).

The third pseudomorph component, *quartz*, is usually identifiable only with the highest magnifications, because it forms tiny *vermicular inclusions in jadeite* about 1.5 micron in diameter.

A very fine-grained *rim of white mica intimately intergrown with quartz* is

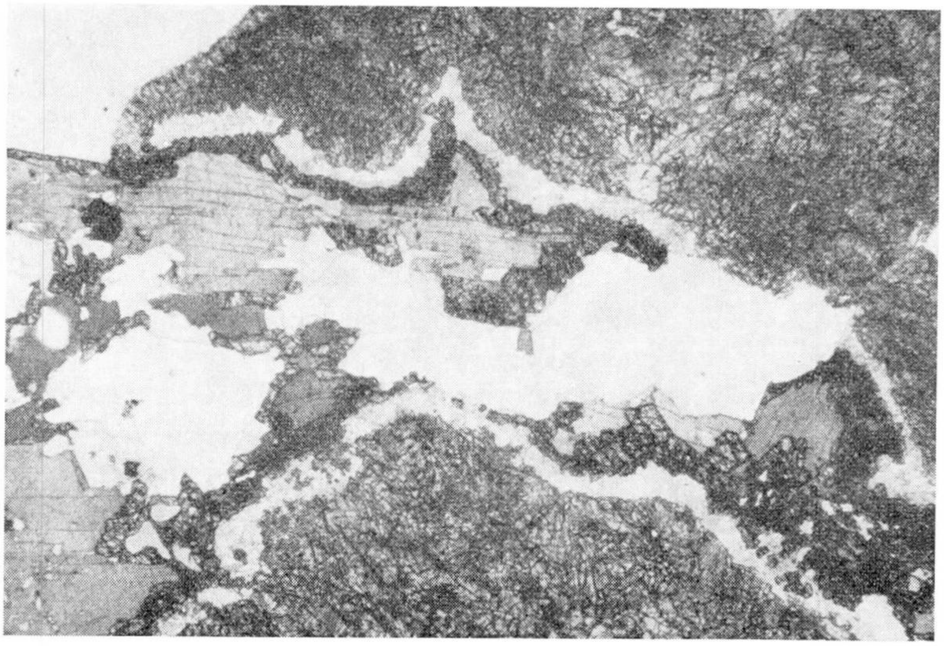

Fig. 7. Mt. Mucrone metagranite (SL 3). Rims of garnet and/or white mica around relict biotite flakes. The dark gray areas are jadeite + zoisite + quartz pseudomorphs after plagioclase; white areas: quartz grains. Note the continuous clear rims of white micas along the boundary between garnet coronas and the pseudomorphs after plagioclase. These micaceous rims are typically absent where the pseudomorphs are in contact with quartz grains. 35 × – Plane polarized light.

normally observed all along the boundary of the pseudomorphosed plagioclases against the garnet coronas (Figs. 6 and 7). The absence of this white-mica rim from the garnet-quartz boundary shows that its genesis is in some way connected with the biotite-plagioclase pair. Similar rims were also observed at the contact between biotite and potassium feldspar.

It is remarkable that vermicular quartz is not found in the jadeite very near (1–2 mm) the quartz-mica rims.

The inherited accessories include large, elongated and typically pleochroic *allanite* prisms, abundant *apatite* in stumpy crystals, small zircons and occasional *ore minerals*.

According to the quantitative relationships among the original minerals these rocks can be classified as granodiorites (Streckeisen, 1967). Considering the present metamorphic imprint and the abundance of textural and mineralogical relics, we can define them as *metagranodiorites*. Other samples from the Mt. Mucrone area display a total or almost total absence of K-feldspar, suggesting a composition intermediate between that of *grano-* and *quartz-diorites*.

Microscopic examination of many other massive and faintly foliated samples reveals no substantial departure from the rocks described above. Variations are however noted in the following:

a) Grain size, particularly in jadeite and zoisite, less commonly in garnet. Jadeite occasionally appears as clearly distinguishable granoblasts associated with single zoisite prisms. The associated quartz crystals, being a

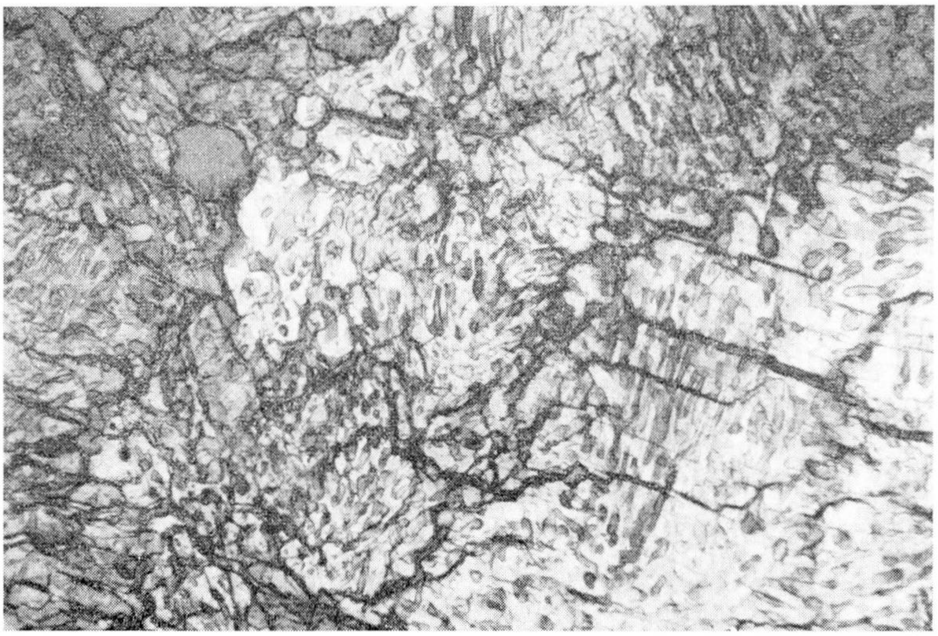

Fig. 8. Mt. Mucrone metagranite (SL 53). Vermicular intergrowth between jadeite and quartz: similar textures (but on a much smaller scale!) are commonly observed in the pseudomorphs after plagioclase. 130 × – Crossed polars.

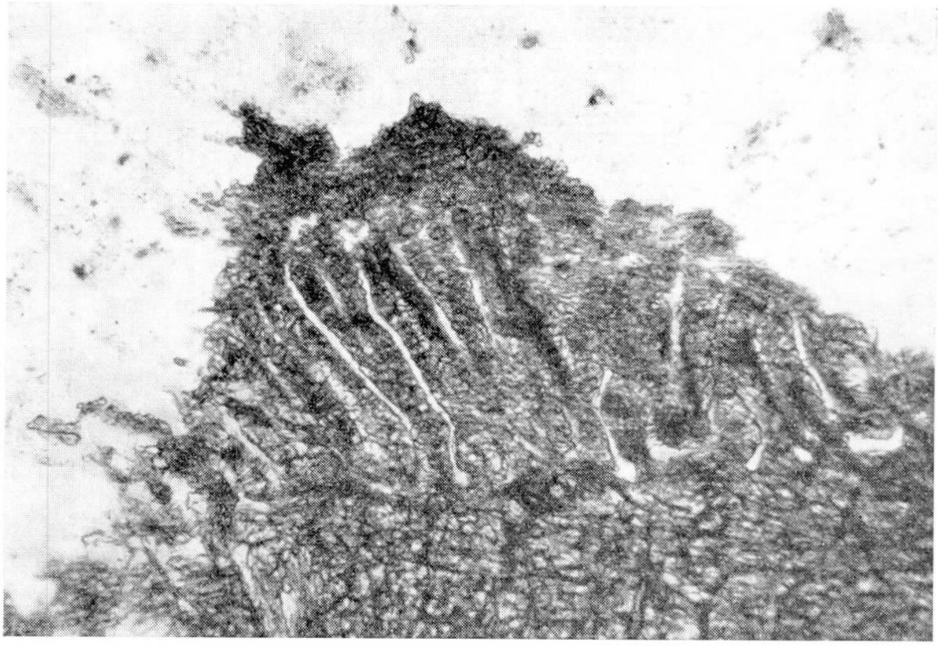

Fig. 9. Mt. Mucrone metagranodiorite (SL 139). Relic of an original myrmekitic intergrowth between orthoclase (white) and an old plagioclase, now entirely replaced by the high-pressure jadeite + quartz + zoisite assemblage. 145 × – Plane polarized light.

product of this reaction, also become larger and larger as jadeite grain size increases, and form vermicular micro-intergrowths with the pyroxene (Fig. 8).

b) Potassium feldspar features. Besides the predominant orthoclase, microcline is occasionally found. Relics of *myrmekitic intergrowth* have been sometimes observed at the boundaries with plagioclase; the plagioclase component of the myrmekite is, however, transformed into jadeite (Fig. 9).

c) Presence of a second alkali-pyroxene. Locally, especially where the rocks show a slightly foliated structure, a second Na-pyroxene (chloromelanite) begins to appear. Its optical and textural features are the same as those of the similar Na-pyroxene found in the orthogneisses (see below).

d) Textural features of the quartz crystals. In some samples the large igneous quartz grains appear to have recrystallized into a granoblastic-polygonal aggregate. Both types of quartz are however present in most cases.

e) The intensity of a late metamorphic stage giving rise to the albite-white-mica-clinozoisite-assemblage (described in more detail further on). It is present in all metagranitic rocks and follows the main stages characterized by Na-pyroxene development.

**Granitic to quartz-dioritic orthogneisses**

Owing to the scarcity of K-feldspar these rocks are slightly different from metagranites. In this respect, they resemble the abundant metaquartzdiorites of the nearby Cervo valley. Macroscopically they are greenish, with lenticular quartz eyes between one millimetre and one centimetre long, elongated along the foliation planes.

Microscopic analysis of a variety of samples leads to a picture that is essentially similar to that of the metagranites. Three points however are to be noted:

a) An almost complete transformation (with the same character as observed in metagranites) of the original biotite into garnet + phengite ± chloromelanite aggregates (Figs. 3–4, Pl. I). Garnet is generally present as typical coronas and occasionally as isolated blasts. Phengite appears in a "parquet" aggregate inside the garnet corona and is commonly associated with xenoblasts of greenish chloromelanitic pyroxene[3]) (Figs. 3 and 4, Pl. I). Biotite relics are observed sporadically inside these domains, this being the rule when distinct jadeite blasts are still present. Garnet is found either in mosaic textured associations or as single crystals inside finely interlocking white micas. In this case it often displays a planar internal texture marked by tiny rutile inclusions. A second generation garnet, contemporary with the chloromelanite, seems to be present occasionally as a rim around the first one.
b) Quartz lenses, elongated along the foliation planes and consisting of sometimes deformed polygonal aggregates, are also typical of these rocks.
c) Chloromelanite is widespread either in characteristic corona textures, that are typically situated along the quartz-biotite boundary (Figs. 1 and 2, Pl. I), or in the above mentioned associations with phengite. It occurs mostly in the rocks that display a more advanced transformation of jadeite into albite + white-mica and of biotite into garnet + white-mica. In the initial stage chloromelanite forms rims essentially along the boundary quartz-micas (biotite and/or white-mica after biotite); in a next stage, when biotite has almost completely disappeared, chloromelanitic pyroxene grows as individual grains intimately associated with white micas. From the observed facts it can be inferred that *chloromelanite has formed mainly from the biotite, whereas jadeite develops at the expense of the plagioclase. In any case the chloromelanitic pyroxene is younger than the jadeite because the former is rimming the latter.* Moreover, veins filled with chloromelanite + white-mica are found cutting the jadeite-bearing assemblages (Fig. 1, Pl. II).

These successive transformations may have been influenced by structural control. In this connection, it can be noted that chloromelanite is rarely observed in the metagranites, while it is very common in the gneissose types.

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[3]) The pyroxene has been determined as chloromelanite by the $n_\beta = 1.695–1.710$ and $d_{221} = 2.965$ Å (Essene and Fyfe, 1967).

Furthermore a later transformation is widespread in these rocks, similar to, but more advanced than that observed in metagranites. Typical is the albite + white-mica assemblage replacing jadeite.

Where white mica predominates the replacement of jadeite is complete; where on the contrary, the albite is predominant, the replacement develops in a mesh-like pattern, finally producing a characteristic kind of "nebulitic" albite, usually untwinned. The original needles of zoisite are still preserved.

Two reasons suggest that this latter transformation is later than the soda-pyroxene stages. Albite was never found in stable assemblage with chloromelanite, the latter being, on the contrary, in paragenesis with white mica, both in the rock and in the veins.

The rare associations between these two minerals are always marked by the presence of an intervening reddish alteration rim. In the only case of direct contact, in fact, chloromelanite has a "corroded" appearance, while the albite, clearly derived from potassic feldspar, is probably later.

Only the white mica deriving from jadeite is found in contact with quartz; on the other hand, the phengites deriving from biotite are always separated from quartz by a chloromelanite rim. These relationships suggest the later growth of the white mica deriving from jadeite.

The instability of the quartz-jadeite pair is shown by the appearance of extremely thin aegirine-augite + albite rims (Fig. 4, Pl. II) between the two minerals. Aegirine-augite[4]) forms very fine subparallel needles on the quartz side, while albite is developed against the jadeite. Thin aegirine-augite rims are occasionally developed around chloromelanite. This phenomenon is much more widespread in the Monte Colme (Val Chiusella) jadeite-bearing rocks and will be dealt with in a subsequent paper (ANDREOLI, COMPAGNONI and LOMBARDO, in preparation).

K-feldspar remains stable until the formation of chloromelanite. Approximately when jadeite changes to white mica + albite, however, K-feldspar is replaced partly by chess-board albite and partly by characteristic intergrowths between white mica and quartz (Fig. 2, Pl. II). Some of the more intensely deformed rocks, whose high-pressure assemblage has been almost entirely replaced by albite + phengite, display a typical generation of very fine-grained, sericite-like white mica which grows on shear planes.

All the analyzed white micas turned out to be phengites (light green colour, magnetic susceptibility, X-ray data[5])). Paragonite was never observed. Some

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[4]) Aegirine-augite + albite assemblages are found also in the "eclogitic micaschists" of the Mt. Mucrone area. Optical and X-ray re-examination of the "chloromelanite" found by MARTINOTTI (1969) in equilibrium with albite, has proved the pyroxene to be aegirine-augite ($n_\beta = 1.73$; $d_{221} = 2.982$ Å).

[5]) X-ray powder diffraction data of white micas have been determined according to the method proposed by CIPRIANI et al. (1968).

rocks show small amounts of a greenish or pale-brown biotite in fine-grained aggregates, that have grown at the expense of garnet or, in some cases, of chloromelanite, and are occasionally accompanied by some green-amphibole. Late carbonate veins (with or without biotite) and albite + green-amphibole veins have also been observed.

### Na-pyroxene-bearing garnetiferous felses

These characteristic massive rocks consist of garnet-alkali pyroxene-white mica-quartz-rutile assemblages.

Euhedral garnets, often grouped in glomeroblastic aggregates, are embedded in a much finer-grained groundmass, consisting of alkali-pyroxene xenoblasts intimately associated with white mica flakes.

Physical and crystal data of the pyroxene: $n_\beta = 1.680$ (with a very low range), $d_{221} = 2.950 - 2.955$ Å, $d_{310} = 2.861 - 2.867$ Å point to an omphacitic composition.

The slight difference in d-values presented by pyroxene concentrates obtained from the same rock (due to different magnetic susceptibilities) denotes the existence of a certain range of composition. The examination of thin sections does indeed reveal, in addition to predominant larger pyroxenes the presence of another type of pyroxene occurring in narrow rims or as intergranular aggregates; its optical parameters are similar to those of previously described chloromelanites. The structural relationships point to a development of the chloromelanite later than that of omphacitic pyroxene.

In other felses with the same bulk mineralogy, garnet is present in compact aggregates and lacks the euhedral shape found in the more widespread types.

Abundant omphacite[6]) is also present together with microgranular jadeite[7]) reminiscent of the pseudomorphs after plagioclase present in the metagranites.

In these rocks jadeite is clearly older than omphacite. This can be very distinctly observed in the fels-metagranite contact zone where jadeite, which is abundant in the granite, appears as large (up to 1 mm) blasts, significantly bordered by omphacite.

Biotite is constantly absent, though its earlier presence can be deduced from the arrangement of rutile needles in both garnet and some white mica aggregates. Much of the abundant white mica seems to be a late product and to have grown at the expense of K-feldspar (now totally replaced by white mica + albite aggregates) and alkali-pyroxene.

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6) This pyroxene has been classified as omphacite on the basis of optical data ($n_\beta = 1.683$) and X-ray ($d_{221} = 2.955$ Å; $d_{310} = 2.872$ Å) data.

7) The optical and X-ray data are: $n_\beta = 1.680$; $d_{221} = 2.932$ Å). All jadeite crystals display on basal sections a very fine parting parallel to (100). Investigations of this feature are in progress.

**Xenolithic inclusions of the metagranites and related orthogneisses**

The microscopic analysis shows that these were originally foliated rocks made up of biotite, plagioclase, quartz, K-feldspar, and (locally) muscovite. Samples of these inclusions found both in metagranites and related orthogneisses reflect the metamorphic state of their country rocks.

Where transformations are only partial, the mineralogical picture repeats that of the metagranites; in particularts, plagioclase has been completely replaced by jadeite + zoisite + quartz and biotite partially recrystallized into garnet + white mica. Thin chloromelanite coronas develop around some quartz grains, especially where they are in contact with white mica. With progressing transformation jadeite is converted at first into white mica (phengite), then into albite + white mica; K-feldspar alters to white mica + quartz, than to albite (the latter in turn being partially replaced by white mica); biotite is largely replaced by a phengite-chloromelanite-titanite assemblage. Major transformation is observed only in xenoliths embedded in orthogneisses: quartz and a phengite + chloromelanite aggregate felt, together with garnet relics, are the sole components.

Besides angular xenoliths some rare, fine-grained, dark-coloured, lenticular inclusions have been found in the metagranites. A sample collected on the SE face of Mt. Mucrone (Canalino del Limbo, alt. 1950 m) shows features of a finely-foliated rock rich in biotite and plagioclase. Microscopic analysis shows well preserved garnet coronas around biotite relics and jadeite pseudomorphs after plagioclase, almost wholly replaced by white mica and minor albite.

Three features are worthy of note:

1. The presence of glaucophane.
2. The abundance of chloromelanite either in thin coronas around most of the original constituents or in granular aggregates or in large blasts.
3. The abundant growth of phengite from biotite, either contemporaneous with or following the garnet blastesis.

*Glaucophane* and white mica are closely associated with the original biotite and contain sagenite inclusions exsolved along the cleavage planes of the original biotite (Fig. 3, Pl. II). Whereas white mica usually appears as flakes variably oriented within the biotite host, glaucophane occurs in individual blasts. The arrangement of its sagenitic inclusions suggests that each blast replaces several biotite flakes[8]).

It is difficult to establish the order of blastesis. The contemporary formation of glaucophane and white mica from biotite would, however, seem unlikely. In

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[8]) Dal Piaz et al. (1971) have reported glaucophane derived from biotite in rocks of the s. c. "Seconda zona diorito-kinzigitica".

fact glaucophane is certainly subsequent to garnet (which is, together with white mica, the first product formed from biotite), and in all probability, later than chloromelanite. Its formation should, therefore, be placed between the last phases of chloromelanite blastesis and the final disappearance of jadeite. The presence of sagenite in both biotite and white mica (derived from the latter) means that glaucophane may have developed from both minerals during the initial stage of jadeite destruction.

Subsequent transformations observed in this sample include the formation of a green-amphibole rim around the glaucophane and the generation of minute biotite flakes. Carbonate veins offer further evidence of this later episode and the remarks made in this respect when dealing with the orthogneisses are equally applicable here.

### Blastomylonites

The blastomylonite bands consist of an inner part of interlocking zoisite, often flanked by two different rock types: e. g. jadeite-bearing rocks with jadeite replaced by albite on one side, and chloromelanite-bearing rocks on the other, both with two garnet generations. Apart from the abundance of zoisite, the transformation patterns repeat those of the orthogneisses.

Since zoisite is closely associated with jadeite, it is clear that these rocks are the product of high-pressure blastesis, i. e. they are blastomylonites.

## CONCLUSIONS

### Metamorphic Evolution

Field and petrographical data in the Mt. Mucrone area have shown the occurrence of original igneous rocks (ranging in composition from granites to quartz-diorites) intruded into an originally metamorphic basement. This is proved by the presence in the igneous rocks of angular inclusions with clear relict foliation[9]).

All the Mt. Mucrone rocks have a clear metamorphic imprint characterized by high-pressure jadeite-quartz-zoisite-garnet-phengite-assemblages. Both mineralogical and textural relics of the original rocks are, however, still recognizable. Among the mineralogical relics are biotite, orthoclase and quartz; textural relics include the original granitic fabric with igneous plagioclases (whose outlines are perfectly preserved: Fig. 4) wholly replaced by jadeite +

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[9]) We have only a few elements to define the metamorphic characters of the pre-granitic basement, but the occurrence of K-feldspar relics together with red-biotite and/or muscovite seem indicative of a mesozonal metamorphism, at least.

quartz + zoisite pseudomorphs. The petrographical analysis shows that the Mt. Mucrone rocks were subjected to a complex polyphasal metamorphic evolution.

The earliest phase is typified by the blastesis of jadeite + quartz + zoisite after plagioclase, and of garnet + white mica after biotite; both assemblages seem to have developed in essentially static conditions, because they are mostly found in rocks with the original texture preserved.

The second phase is marked by jadeite instability (partially replaced by phengitic mica) and by the appearance of new alkali-pyroxenes (omphacites to chloromelanites) + phengitic micas at the expense of biotite. This stage is

Table 1. *Metamorphic evolution of Mt. Mucrone metagranites and related rocks*

| | | High-pressure —— low temperature metamorphism<br>higher pressures - - - - lower pressures | | | Final (thermal?) metamorph. |
|---|---|---|---|---|---|
| | | f 1<br>Jadeite stage | f 2<br>Omphacite to chloromelanite stage | f 3<br>White mica-albite stage | f 4<br>Biotite stage |
| **Minerals of original granitic rocks (and of pre-granitic schists)** | | | | | |
| Plagioclase | —— | | | | |
| K-feldspar | —— | - - - - - - - - | - - - - - - | | |
| Muscovite | —— | - - ? | | | |
| Biotite I | —— | - - - - - - - - | - - - - - - - - | — | |
| Quartz | —— | —— | —— | —— | —— |
| **Minerals related to post-granitic metamorphism** | | | | | |
| Jadeite | | —— - - | - - - - - - - - | - - - - - - - - | |
| Omphacite | | —— | —— - - - | - - - - - - - - | |
| Chloromelanite | | | —— - - | - - - - - - - - | |
| Aegirine-augite | | | —— | - - - - - | |
| Glaucophane | | | —— | - - - - - | |
| Garnet | | —— | —— | —— - - - | |
| Zoisite | | —— | - - - - - - - - | - - - - - - - | |
| Clinozoisite | | | | —— | —— |
| White micas (phengites) | | —— | —— | —— | —— |
| Rutile | | —— | —— | - - - - - - - - | |
| Titanite | | | | —— | —— |
| Albite | | | —— | —— | —— |
| Green amphibole | | | | ?—— | —— |
| Biotite II | | | | | —— |
| Carbonates | | | | | —— |

Full lines: stable minerals
Dashed lines: unstable minerals

typical of metagranites with weak-foliation; it is lacking, however, or only barely detectable, in samples with a well preserved original fabric.

These two phases can also be recognized in the angular inclusions of metagranitic rocks and in the Na-pyroxene-bearing garnetiferous fels. In structurally more evolved rock-types (orthogneisses) alkali-pyroxenes become clearly unstable and, in most cases, completely disappear. Rocks composed of predominant phengite with minor quartz + albite ( ± relict garnet) are the end product of this evolution.

With advancing metamorphic evolution, zoisite progressively disappears being replaced by clinozoisite.

In many samples very fine biotite flakes ( ± green amphibole) occur as a late product, irrespective of the state of metamorphic evolution of the rock; moreover the same biotite is also present in late carbonate veins.

A definite interpretation of biotite blastesis is not possible: this latest phase in the Mt. Mucrone rocks may possibly be due to regional metamorphism (see the "gneiss minuti" formation in the outermost part of the Sesia-Lanzo Zone); on the other hand it may be due to the thermal effect of the Tertiary intrusion in the nearby Valle del Cervo (Biella).

## Petrological considerations

Microscopical observations on the Mt. Mucrone metagranites show that original plagioclases are completely replaced by a jadeite-quartz-zoisite-assemblage.

This transformation may be represented by the following reaction:

$$\underset{\text{plagioclase}}{16\,NaAlSi_3O_8 + 4\,CaAl_2Si_2O_8} + H_2O \rightleftarrows \underset{\text{jadeite}}{16\,NaAlSi_2O_6} + \underset{\text{zoisite}}{2\,Ca_2Al_3Si_3O_{12}(OH)} + \underset{\text{quartz}}{18\,SiO_2} + Al_2O_3 \quad (1)$$

that may, in turn, be considered as the sum of two partial decomposition reactions:

$$\underset{\text{albite}}{NaAlSi_3O_8} \rightleftarrows \underset{\text{jadeite}}{NaAlSi_2O_6} + \underset{\text{quartz}}{SiO_2} \quad (1\,a)$$

$$\underset{\text{anorthite}}{4\,CaAl_2Si_2O_8} + H_2O \rightleftarrows \underset{\text{zoisite}}{2\,Ca_2Al_3Si_3O_{12}(OH)} + \underset{\text{quartz}}{2\,SiO_2} + Al_2O_3 \quad (1\,b)$$

The other characteristic transformation observed in the Mt. Mucrone metagranites, may be written in the form:

$$\underset{\text{biotite}}{K\,(Fe,Mg)_3\,[AlSi_3O_{10}]\,(OH)_2} + \underset{\text{quartz}}{3\,SiO_2} + 2\,Al_2O_3 \rightleftarrows \underset{\text{garnet}}{(Fe,Mg)_3Al_2Si_3O_{12}} + \underset{\text{white mica}}{KAl_2\,[AlSi_3O_{10}]\,(OH)_2} \quad (2)$$

Excess alumina released from plagioclase in reaction (1b) did not combine with silica. No sign of an $Al_2SiO_5$ phase was noted in the reaction products, not even after X-ray examination of the insoluble residue obtained after rock solution with HF. Utilisation of this alumina excess in reaction (2) is suggested by the presence, along the boundary between garnet coronas (from biotite) and pseudomorphs after plagioclase, of a thin white-mica rim (Figs. 6 and 7).

Among the above mentioned reactions, only reaction (1a) is well known both theoretically and experimentally. The many relevant data available in the literature are critically summarized in a recent paper by JOHANNES et al. (1971), dealing with an interlaboratory comparison of piston-cylinder pressure calibration using the albite-breakdown reaction. The new resulting datum (average preferred value) for this reaction, of 16.3 kb at 600° C, is in good agreement with the equilibrium curve determined by HLABSE and KLEPPA (1968) for low-albite breakdown.

Accepting the HLABSE and KLEPPA equilibrium curve, the minimum pressures required for the metamorphism of the Mt. Mucrone rocks must range from 8.5 kb at 200° C to 14.5 kb at 500° C. These pressures roughly correspond to a lithostatic load between 30 and 41 km.

More difficult is to assign a thermal limit to this metamorphism. The only reference we have is the regional association of metagranites together with rocks bearing glaucophane and Na-pyroxenes (impure jadeite to omphacite). According to DE ROEVER glaucophanitic rocks "seem to have been formed at pressures higher than 4–5 kb, or also much higher, up to 8 kb; temperatures in part were rather low, 200° C and higher, but in part rather high, up to 550° C"; and "the production of the assemblage rather pure jadeite-quartz ... is confined to glaucophanitic metamorphism of very low grade" (1972, p. 69–70).

The assemblage jadeite + quartz being very common in metagranites, the temperatures in the Mt. Mucrone area should have been close to the lower limit of the glaucophanitic-schists facies.

Jadeite-bearing assemblages, in many respects similar to those found in the Sesia-Lanzo zone, have been reported from Franciscan terrains: the inferred metamorphic temperatures range from 200° C up to 300° C with pressures near or higher than 8 kb (ERNST et al., 1970). There are, however, some interesting differences between the Sesia-Lanzo and Franciscan terrains. In particular, the Mt. Mucrone rocks always carry zoisite as an essential component, whereas epidote-group members are very uncommon minerals in Franciscan terrains (ERNST et al. 1970).

Experimental data on zoisite stability, notably the equilibrium curve for the reaction: anorthite + water $\rightleftarrows$ zoisite + kyanite[10]) + quartz (NEWTON,

[10]) However, in the Mt. Mucrone metagranites kyanite has never been found in anorthite-breakdown products, the alumina excess being probably used in white mica production.

1966; BOETTCHER, 1970), show this association to be stable from 400° C up (at pressures higher than 5 kb). In reality a temperature of 400° C (or more) could explain the absence of lawsonite in this part of the Sesia-Lanzo zone; however temperatures higher than 400° C seem to be in contrast with the direct transformation of biotite into garnet, without any chlorite stage, as it is clearly proved by microscopical observations.

However, according to ESSENE and FYFE: "There is not positive evidence that epidote eclogites formed at higher temperatures than lawsonite eclogites, and distribution coefficients suggest that epidote eclogites formed at low temperatures" (1967, p. 19).

In the Mt. Mucrone rocks metamorphism evolves in such a manner that the jadeite-stage is followed by a sequence of transformations characterized by the appearance of alkali-pyroxenes progressively poorer in jadeite (i. e. from omphacites through chloromelanites to aegirine-augites). This metamorphic evolution points to a decrease in pressures (and/or an increase in temperatures) as it is shown from the equilibrium curves in the diopside-acmite-jadeite system (ESSENE and FYFE, 1967; POPP and GILBERT, 1972). A low temperature-high pressure environment during the evolution of the Mt. Mucrone rocks is also proved by the widespread occurrence of phengitic micas (VELDE, 1965).

It is interesting to note that, unlike Franciscan terrains, in the Sesia-Lanzo zone omphacite and chloromelanite have never been found in equilibrium with albite, the only Na-pyroxene stable with albite being aegirine-augite.

Throughout these transformations the garnet remains stable: this seems to denote that alkali-pyroxene development in Mt. Mucrone evolved in conditions of still prevailing high-pressures.

## Age of the high-pressure metamorphism

In agreement with NOVARESE (1929), BIANCHI and DAL PIAZ (1963) thought that the high-pressure metamorphism of the Sesia-Lanzo zone was pre-Permian. Their opinion was supported by the presence (within the unmetamorphosed porphyritic formation, between Biella and Oropa) of pebbles identical to the rocks occurring in the eclogitic micaschists.

The porphyrites were considered to be of Permian age due to lithological similarity with analogous rocks widespread in the Alps.

A pre-late-Carboniferous age of the high-pressure metamorphism has been recently proposed by F. CARRARO and G. CHARRIER (1972) on the basis of the discovery of supposed Articulates (Calamites) in the vulcano-detrital cover series of the eclogitic micaschist formation.

However HUNZIKER (1970) using radiometric data, suggested an eo-Alpine age, in accordance with geological and petrographical observations by DAL

PIAZ and NERVO (1971) on the Rafray-Klippe, and DAL PIAZ, GOSSO and MARTINOTTI (1971) on the s. c. "Seconda zona Diorito-Kinzigitica".

A new palaeobotanical revision by SCHEURING et al. (1972) with additional radiometric data seems to confirm the Tertiary age of the vulcano-detrital cover of the eclogitic micaschists formation.

According to our geological and petrographical observations in the Mt. Mucrone area, the chronological position of the high-pressure metamorphic phase depends on the age ascribed to the metagranites (intruded into originally metamorphic rocks).

Assuming the granite intrusion to be pre-Hercynian, the high-pressure metamorphism should be at least of Caledonian age, since it has features very different from those known in Hercynotype metamorphism (ZWART, 1967), at least in this part of Europe. A Caledonian age for the eclogites of the Sesia-Lanzo zone has been recently proposed by MOTTANA (1972) following BIANCHI and DAL PIAZ (1963) and on the grounds of CARRARO's work. This hypothesis, however, seems unlikely, because the possibly Caledonian eclogites of the Western Alps (e. g. the Lac Cornu eclogites in the Aiguilles Rouges Massif and the Valle della Meris eclogites in the Argentera Massif) have petrographical characters markedly different from those of the Sesia-Lanzo glaucophanitic-eclogites, the former belonging to B-Group eclogites, the latter to C-Group eclogites of COLEMAN et al. (1965).

If an Hercynian age (consistent with the abundance of Hercynian granites in the Western Alps) is assumed for the Mt. Mucrone metagranites, then the high-pressure metamorphism must necessarily be Alpine. This age is in good agreement with the present knowledge on the occurrence in the Western Alps of a high-pressure metamorphism (HUNZIKER, 1970; DAL PIAZ et al., 1971). The existence of this high-pressure eo-Alpine metamorphism, with development of glaucophanitic eclogites, is known not only in Mesozoic terrains ("calcescisti" formation) but also in the older polymetamorphic basement of the Pennidic domain (e. g. in the Monte Rosa zone, DAL PIAZ, 1971; and also in the Gran Paradiso massif[11])).

Assuming that the high-pressure metamorphism of the Sesia-Lanzo zone is eo-Alpine, a solution can be found to the apparent geological puzzle of two adjoining basement units (i. e. the Pennidic domain and the Sesia-Lanzo zone) containing rocks of similar and also unusual character, but of different age. Accepting this hypothesis the eo-Alpine high-pressure metamorphism of the Western Alps can be inserted into a more organic picture (see e. g. ERNST, 1971).

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[11]) On the eo-Alpine age of the eclogites of the Gran Paradiso massif one of us (R. C.) has a paper in preparation.

*Acknowledgments.* The authors wish to express their sincere gratitude to Prof. Ezio Callegari, whose helpful advice and constructive criticism contributed substantially to the progress of this work. The present research was completed with the financial support of the Consiglio Nazionale delle Ricerche.

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Two papers, dealing with the high-pressure metamorphism in the Sesia-Lanzo zone, have appeared after this work was drafted.

The first paper, by Velde and Kienast[12]), point out, in agreement with our study, the widespread occurrence of jadeite-rich pyroxenes in the eclogitic

12) Velde B. et Kienast J. (1973): Zonéographie du métamorphisme de la zone Sesia-Lanzo (Alpes piémontaises): étude des omphacites et grenats des micaschistes éclogitiques à la microsonde électronique. C. R. Acad. Sci. Paris, 276, 1801–1804.

micaschist formation. However, on the basis of data from the literature and from our present research, we do not share the opinion that the albite + omphacite assemblage is stable in the Sesia-Lanzo rocks. We have indeed found albite in stable coexistence only with aegirine-augite.

The second paper, by DAL PIAZ, HUNZIKER and MARTINOTTI[13]), suggests, from the point of view of plate tectonics, a new evolution scheme of the Sesia-Lanzo zone and of the inner Northwestern Alps. The rocks of the Mt. Mucrone area are also discussed: the outlined metamorphic evolution fits in well with our scheme, but it does not elucidate the complex history of the Mt. Mucrone metagranitic rocks.

Manuscript received July 11th, 1973.

[13]) DAL PIAZ G. V., HUNZIKER J. e MARTINOTTI G. (1972): La zona Sesia-Lanzo e l'evoluzione tettonico metamorfica delle Alpi nordoccidentali interne, Mem. Soc. Geol. Ital., 11, 433–460.

## PLATE I

Fig. 1. Angular block of foliated rock enclosed in the Mt. Mucrone metagranite (SL 223). A narrow chloromelanite rim develops continuously (left) along the boundary between quartz and white-mica aggregates (mainly formed at the expense of biotite). Biotite relics are evident either in white-mica aggregates or in intergrowths with garnet (upper right). Note the euhedral garnets typical of the pre-granitic foliated rocks. In the lower part of the photograph there is a jadeite-bearing pseudomorph after plagioclase, which is locally bordered by a chloromelanite rim (lower left). 175 × – Plane polarized light.

Fig. 2. Mt. Mucrone granitic orthogneiss (SL 169). Nearly continuous chloromelanite coronas developing along the boundary between quartz grains (white) and white-mica aggregates (light grey) after biotite. Remnants of biotite partially intergrown with garnet (lower left and right) are still recognizable. This texture commonly develops around original biotite flakes and seldom around jadeite + quartz + zoisite pseudomorphs. 170 × – Plane polarized light.

Fig. 3. Mt. Mucrone granitic orthogneiss (SL 162). On the left side, original biotite flakes largely replaced by a chloromelanite-white mica – titanite-assemblage. On the right side, separated from the original biotite by a thin garnet rim, a high-pressure pseudomorph after plagioclase, almost wholly replaced by white mica (light grey); only some relics of the jadeite assemblage (dark grey patches) are preserved. The chloromelanite development progresses as white-mica grows at the expense of the jadeite-quartz-zoisite assemblages. 170 × – Plane polarized light.

Fig. 4. Mt. Mucrone granitic orthogneiss (SL 172). Advanced stage of chloromelanite development: biotite flakes are completely replaced by a chloromelanite-white-mica-assemblage. 175 × – Plane polarized light.

## PLATE II

Fig. 1. Mt. Mucrone granitic orthogneiss (SL 105). Vein, filled with white-mica + chloromelanite, crossing older high-pressure pseudomorph after plagioclase: the vein assemblage is the one developing in the rock. Note the advanced transformation stage of the jadeite-bearing assemblage. 45 × – Plane polarized light.

Fig. 2. Mt. Mucrone granitic orthogneiss (SL 169). Typical vermicular intergrowths between white-micas and quartz, developing at the expense of K-feldspar. This transformation is nearly contemporaneous with the development of chloromelanite. 200 × – Crossed polars.

Fig. 3. Dark foliated inclusion in the Mt. Mucrone metagranite (SL 42). A large glaucophane blast (light grey), developed at the expense of biotite, still retains the sagenitic texture of the replaced mica flakes. A narrow rim of a green amphibole borders the glaucophane. 170 × – Plane polarized light.

Fig. 4. Mt. Mucrone metagranite (SL 53). Aegirine-augite + albite rims developing between quartz and pseudomorphs after plagioclase. Aegirine-augite needles mark the original quartz-plagioclase boundary. This aegirine-augite + albite assemblage is typical of the later stages of high-pressure metamorphism. 180 × – Plane polarized light.

Schweiz. Min. Petr. Mitt.
Volume 53/3, 1973



Fig. 1

Fig. 2

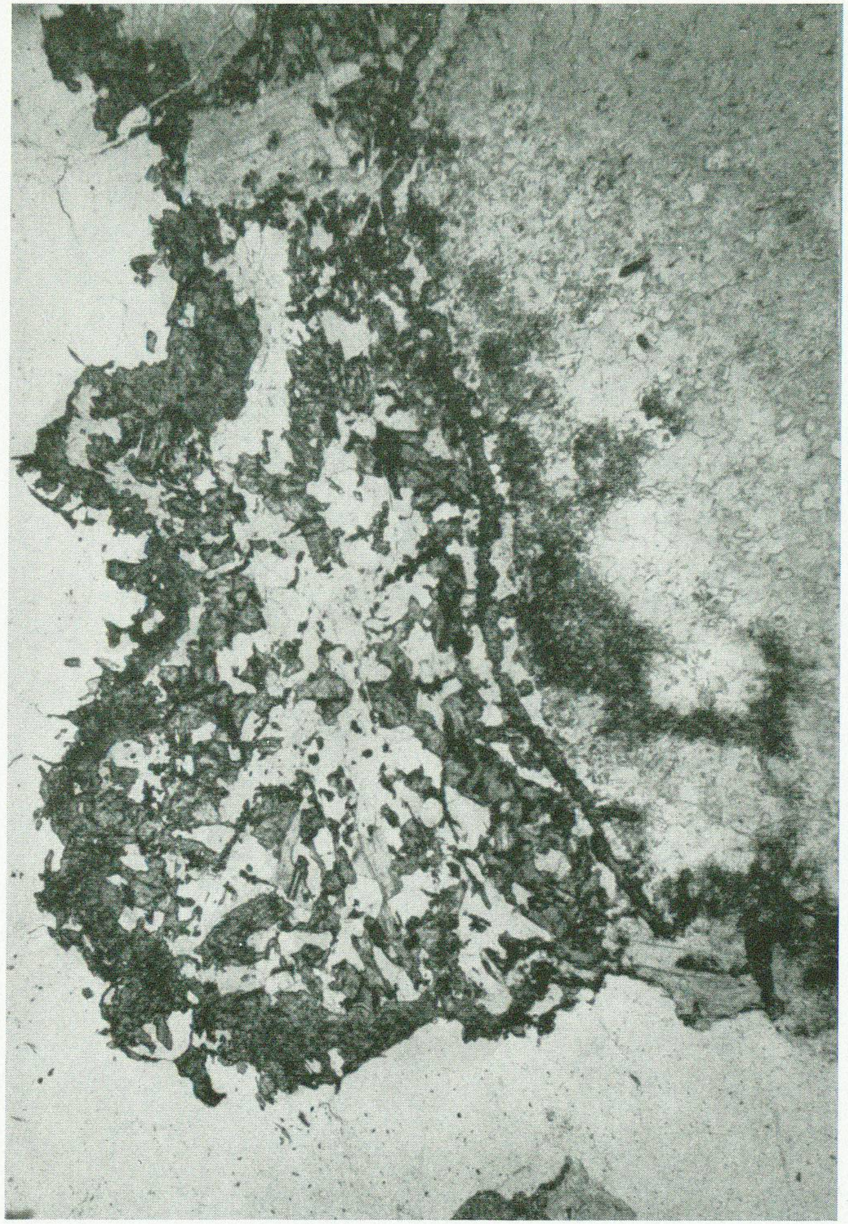

Fig. 3

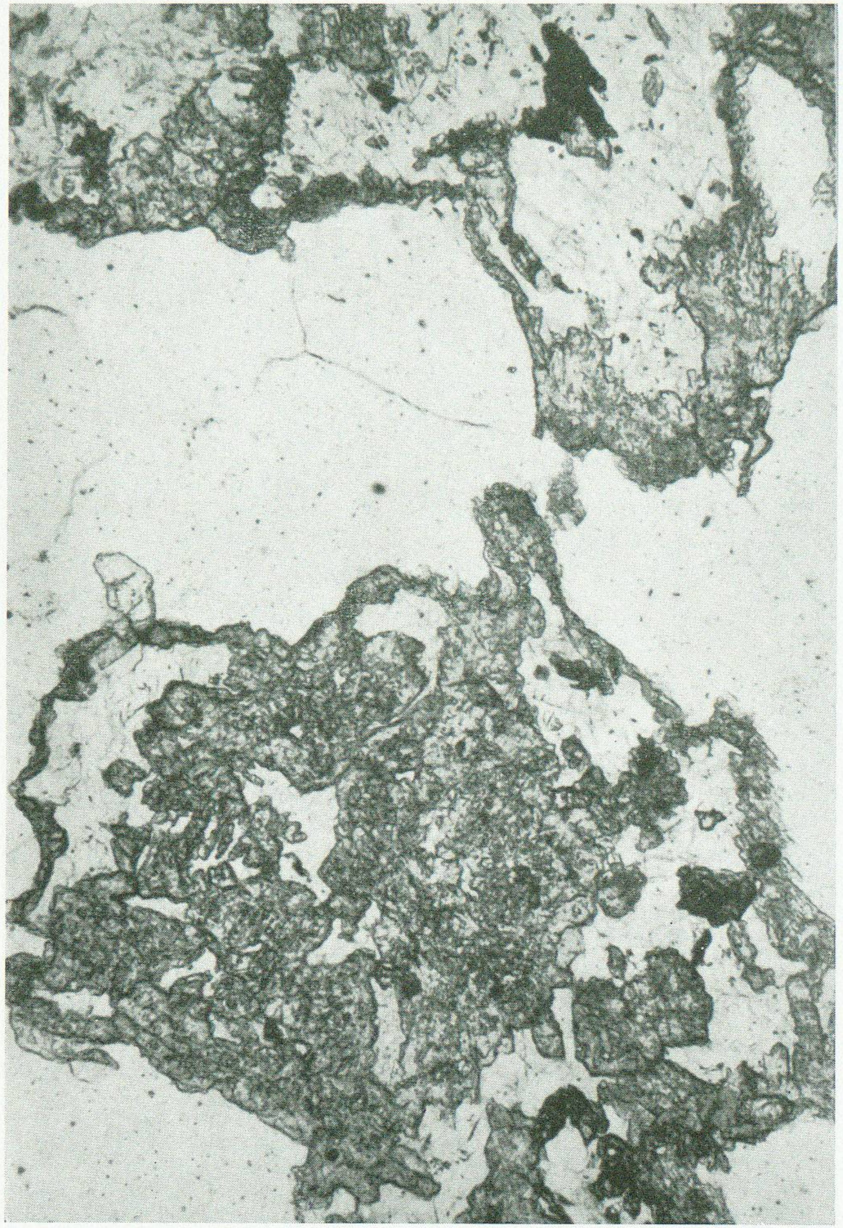

Fig. 4

PLATE II

Fig. 1

Fig. 2

Fig. 3

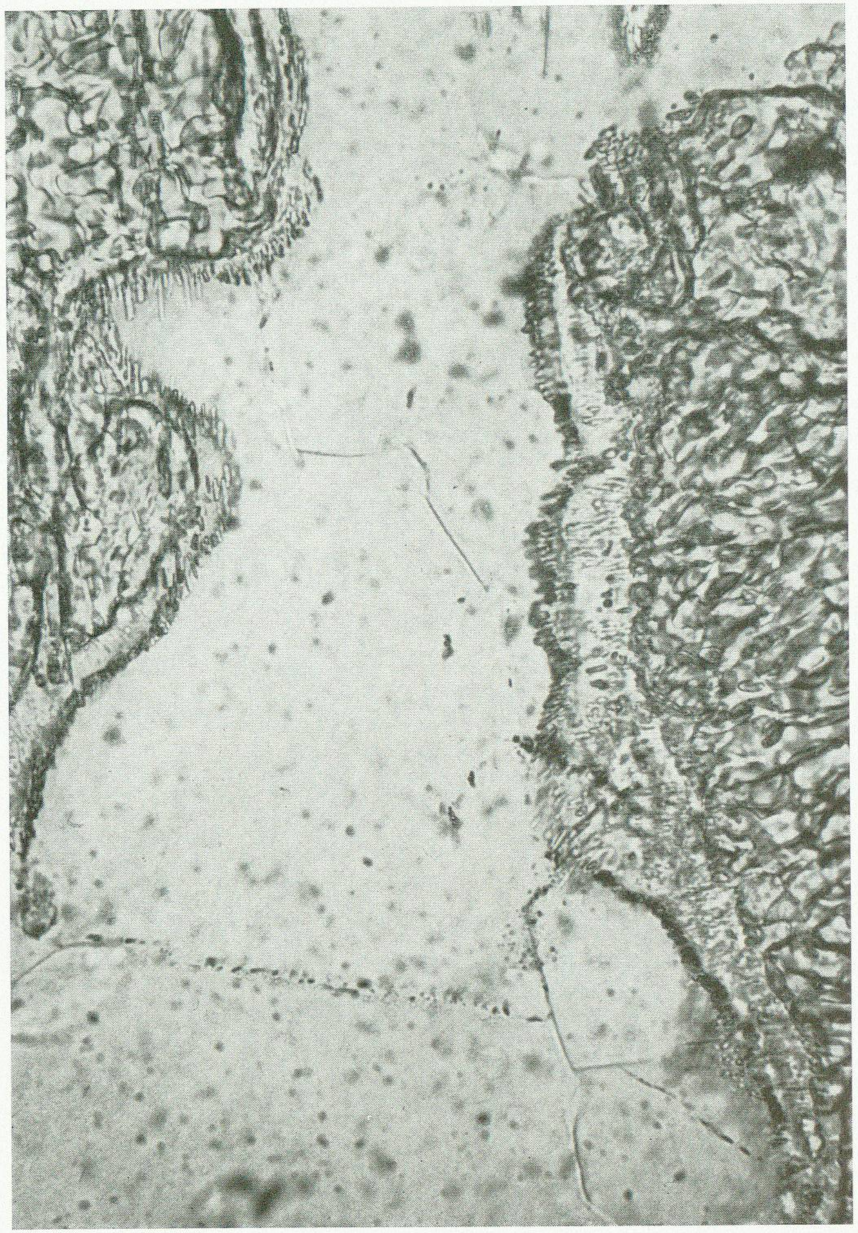

Fig. 4