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THE SESIA-LANZO ZONE:  
HIGH PRESSURE-LOW TEMPERATURE METAMORPHISM  
IN THE AUSTROALPINE CONTINENTAL MARGIN

ABSTRACT. — The Sesia-Lanzo Zone is composed of three units: the « II zona dioritokinzigitica », the « Eclogitic Micaschist Complex » and the « Gneiss Minuti Complex », characterized by prevailing pre-Alpine amphibolite-facies, early-Alpine « eclogite »-facies and late-Alpine greenschist-facies mineral assemblages respectively. In the present paper the Eclogitic Micaschist Complex (EMC) is extensively considered for its peculiar high pressure-low temperature metamorphic imprint. It consists of polymetamorphic rocks intruded by pre-Alpine (most likely late-Hercynian) igneous rocks (mainly granitoids), re-equilibrated under eclogitic conditions during the early-Alpine metamorphic event.

On the ground of pre-Alpine textural and mineralogical relics, so far recognizable all over the EMC, the following lithologies have been distinguished: metagranitoids, metamorphic leucocratic dykes, paraschists (pre-Alpine « kinzigites »), pre-Alpine amphibolites, and intermediate to basic metaintrusives. Their microscopical examination has provided the unique opportunity to follow the metamorphic reactions occurring in a wide spectrum of lithologies of a continental crust submitted to eclogitic conditions. Of particular interest result the metagranitoids and the metamorphic leucocratic dykes, which contain jadeite-rich (up to 95 % Jd) alkali-pyroxenes, in equilibrium with quartz and an almandine-rich garnet, and the pre-Alpine amphibolites, which show all the transformation stages into eclogites.

The rocks pervasively reworked and completely re-equilibrated during the early-Alpine eclogitic event are then considered: eclogitic micaschists and glaucophane eclogites are largely prevailing, the former consisting of quartz, white-micas (mainly phengites), omphacite, the former consisting of quartz, white-micas (mainly phengites), omphacite, garnet and minor glaucophane, zoisite, rutile, and the latter consisting of omphacite, garnet and rutile with widely variable amounts of glaucophane, zoisite and white-micas.

The high-pressure minerals occurring in the EMC are then considered in detail, emphasizing the primary parageneses and later metamorphic transformations. They are: Na-pyroxenes, Na-amphiboles, garnets, epidotes, white-micas, kyanite, chloritoid, lawsonite, pumpellyite, carbonates, chlorites and stilpnomelane. Petrographical observations point to a polyphase metamorphic evolution, in which two main metamorphic events have been distinguished. The first one (early-Alpine event) is characterized by initial high-pressure (eclogitic) conditions, followed by a significant pressure decrease and moderate temperature decrease leading to blueschist-facies conditions. The second one (late-Alpine or « Lepontine » event) is characterized by mineral assemblages evolving under low-pressure conditions from low- to high-grade greenschist-facies. The areal extent of the late-Alpine metamorphic overprinting, mainly active towards the external EMC, has been shown by tracing two « isograds » indicative of the disappearance of jadeite and glaucophane respectively, replaced by greenschist-facies mineral assemblages.

On the ground of experimental phase equilibria of diagnostic minerals, the EMC appears to have recrystallized, during the peak of the early-Alpine metamorphic event, at temperatures between 500 and 600° C, under pressures in excess of 15-17 Kb, with fluid pressure significantly lower than total pressure. Since fluid phase mainly consisted of water the crystallization of hydrous minerals should have been of great significance for the development of the eclogitic assemblages.

The paper ends with a short discussion relevant the existence and possible extent of the eclogite facies, considered in the light of the latest informations gained from the detailed study of the EMC.

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## Introduction

The Sesia-Lanzo Zone comprises the most internal tectonic unit involved in the Alpine orogeny and metamorphism in the Western Alps. Its internal boundary is marked by a major tectonic line, known as the Canavase line, whereas its external limit is with the « calcescisti » with metaophiolites of the Piemonte Zone.

In the Sesia-Lanzo Zone 3 major units have been distinguished, on the grounds of lithology, age and character of the metamorphic assemblages, and structural position. They are:

- 1) the « Eclogitic Micaschist » Complex;
- 2) the « Gneiss Minuti » Complex;
- 3) the « II Zona diorito-kinzigitica ».

The first two complexes together comprise the *lower tectonic element*, which is covered by an *upper element*, mainly composed of the « II Zona diorito-kinzigitica ». The original contacts between the juxtaposed complexes have been strongly modified by later deformations and recrystallizations.

In the Sesia-Lanzo Zone, as in most of the Western Alps, two different Alpine metamorphic events have been recognized both petrographically and geochronologically. The first one, known as *early-Alpine* (or *Eo-Alpine*) *event*, is characterized by high pressure-low temperature mineral assemblages with glaucophane eclogites very common. Minerals of this event have given radiometric ages ranging from 90 to 60 m.y. (DAL PIAZ et al., 1972; HUNZIKER, 1974). The early-Alpine event has been locally overprinted by a later greenschist facies metamorphic event, whose climax has been dated around 40-35 m.y..

In the literature the second event is known as the *late-Alpine* or *Lepontine event* from the « Lepontine area » in the Central Alps, where this metamorphism reached the amphibolite facies.

Though everywhere present in the Sesia-Lanzo Zone, the two metamorphic events show very different characters and intensities in the three complexes. The Eclogitic Micaschist Complex is characterized by the occurrence of well preserved early-Alpine mineral assemblages, only locally destroyed by overprinting by late-Alpine parageneses.

On the contrary in the Gneiss Minuti Complex the late-Alpine greenschist facies event has almost completely transformed the early-Alpine mineral assemblages.

In the « II Zona diorito-kinzigitica » the pre-Alpine amphibolite-facies mineralogy is still extensively preserved; really the two Alpine metamorphic events only locally have completely recrystallized the older assemblages.

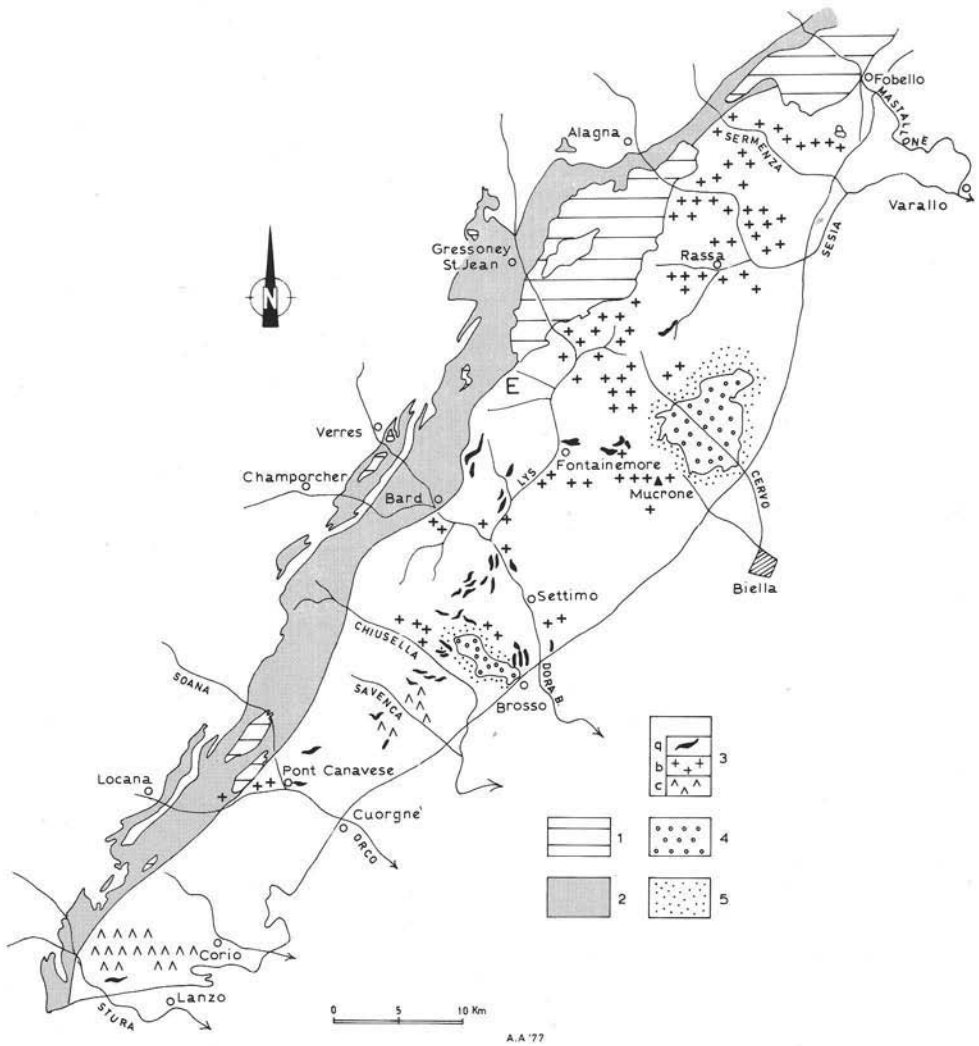


Fig. 1. — Tectonic sketch map of the Sesia-Lanzo Zone. 1 - «II zona diorito-kinzigitica». 2 - Gneiss Minuti Complex. 3 - Eclogitic Micaschist Complex. 4 - Postmetamorphic stocks of Brosso-Traversella and of the Cervo Valley. 5 - Contact-metamorphic aureole. In the Eclogitic Micaschist Complex marbles (3a), metagranitoids (3b) and intermediate to basic metaintrusives (3c) have been distinguished.

The main purpose of present paper is to describe the high pressure-low temperature mineral transformations, which occurred in the Sesia-Lanzo Zone during the early-Alpine metamorphic event. For this reason the Eclogitic Micaschist Complex will be extensively considered because it offers the unique opportunity of following the development of a low temperature «eclogitic» metamorphism at the expense of a continental crust consisting of high-grade (amphibolite-facies) metamorphics and intrusives.

## The Eclogitic Micaschist Complex <sup>(1)</sup>

The Eclogitic Micaschist Complex mainly consists of early-Alpine metamorphics, characterized by the widespread occurrence of high pressure (and comparatively low temperature) mineral assemblages such as jadeite + quartz (in felsic rocks) or garnet + omphacite + glaucophane (in metabasics).

The subsequent « Lepontine » metamorphic event produced a minor retrogression in the internal portion of the Eclogitic Micaschist Complex, whereas, towards the boundary with the Gneiss Minuti Complex, it deeply transformed the early-Alpine mineral assemblages. Such a transformation is associated with a progressive grain-size decrease, from the coarse-grained parageneses of the typical eclogitic micaschists to fine-grained mineral assemblages quite comparable with that of the adjoining « Gneiss Minuti Complex » <sup>(2)</sup>.

A reconstruction of the extent of the Lepontine overprinting is reported in Fig. 22).

In addition to the Lepontine retrogression, the internal Eclogitic Micaschists have been locally transformed by the thermal metamorphism induced by the intrusion of the two monzonitic stocks of Traversella (lower Val Chiusella) and of the Valle del Cervo (near Biella) (Fig. 1).

Due to local preservation of pre-Alpine textures and minerals it has been possible to reconstruct in outline the pre-Alpine lithology of the Eclogitic Micaschist Complex. It consisted of high-grade metamorphics, with interlayered metabasics and marbles, intruded by large masses of igneous rocks, mainly granitoids and minor gabbros (Fig. 1).

The pre-Alpine metamorphics are represented by K-feldspar - sillimanite - garnet - biotite schists, with veins and layers of quartz - feldspar pegmatoids, quite similar to the « Kinzigites » widely occurring in the Ivrea Zone or in the « II Zona diorito-kinzigitica ». The interbedded metabasics correspond to hornblende amphibolites, with widely variable amounts of the original plagioclase.

In the following sections, petrography and metamorphic evolution of the Eclogitic Micaschist Complex is described treating the rocks with pre-Alpine minerals and fabric separate from the rocks completely reworked by the Alpine polyphase metamorphism and deformations.

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<sup>(1)</sup> The name of « Eclogitic Micaschists » (Italian: micascisti eclogitici) has long been used in the literature (STELLA, 1894), to stress the unusual petrography of the most peculiar rocks, widely occurring within the internal Sesia-Lanzo Zone. They consist of phengitic micaschists usually including either eclogitic minerals such as omphacite and garnet, or layers and lenses of eclogites.

<sup>(2)</sup> In Italian « Gneiss Minuti » means « fine-grained gneisses ».

## Pre-Alpine rocks partially re-equilibrated under « eclogitic conditions »

Small bodies (from tens to hundreds meters in length) of pre-Alpine rocks seemingly unaffected or only slightly affected by usually pervasive early-Alpine deformation outcrop within the « Eclogitic Micaschists » showing gradual transitions with the surrounding rocks.

On the ground of origin, occurrence, mineralogy and bulk chemical composition the following pre-Alpine rocks have been distinguished:

- 1) Metagranitoid;
- 2) Metamorphic leucocratic dykes;
- 3) Pre-Alpine paraschists (« kinzigites »);
- 4) Amphibolites;
- 5) Intermediate to basic meta-intrusives.

### 1) METAGRANITOIDS <sup>(3)</sup>

The structurally best preserved metagranitoids have been discovered in the Mt. Mucrone area (upper Valle d'Oropa, Biella).

Original granodiorites to tonalites, that have largely escaped pervasive Alpine deformation, exhibit an extraordinarily well preserved igneous fabric, and a magmatic mineralogy (only partially re-equilibrated under eclogitic conditions) which consisted of quartz, plagioclase, K-feldspar, biotite, allanite.

Since these rocks have been described elsewhere (DAL PIAZ et al., 1972; COMPAGNONI & MAFFEO, 1973; COMPAGNONI et al., 1976) only the most significant metamorphic transformations of the original igneous mineralogy, will be mentioned here.

Magmatic quartz grains have recrystallized to finer-grained polygonal aggregates. Biotite has been partly transformed into coronitic garnets ( $\pm$  rutile) and minor phengitic white micas.

Original plagioclases have been completely replaced by pseudomorphs consisting of practically pure jadeite + quartz + zoisite. On the contrary potassium feldspar appears unaffected by the eclogitic metamorphism, and still maintains its original orthoclase state: a detailed examination, however, shows that the orthoclase only along the boundaries is usually replaced by a narrow rim of white-mica + quartz. Finally the crystals of accessory allanite are locally overgrown by a narrow rim of clinozoisite.

### 2) METAMORPHIC LEUCOCRATIC DYKES

Of particular interest in understanding the mineral transformations occurring

<sup>(3)</sup> Recently REINSCH (1976) has proposed the name « Mucronite » for such rocks (from the Mt. Mucrone, the type locality). However we think that it is unnecessary to coin a new word for rocks better defined by common terms such as jadeite-bearing metagranite, or garnet-omphacite micaschist, or glaucophane eclogite. Furthermore the rocks defined as « Mucronite » by Reinsch have long been (STELLA, 1894) known in the geological literature by the name of « eclogitic micaschists » (see footnote pag. 338).

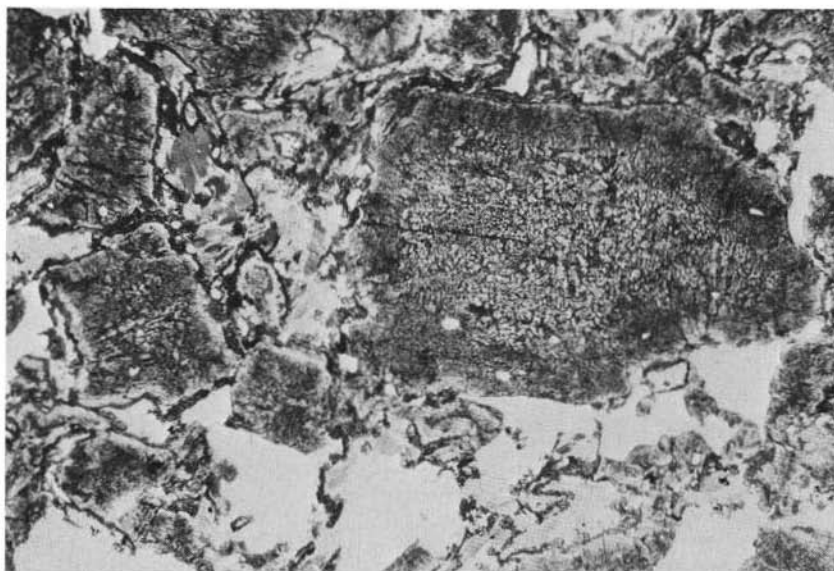


Fig. 2. — Metatonalite (SL 548). Monte Mucrone, upper Oropa valley, Biella. Subhedral crystals of magmatic plagioclases appear pseudomorphically replaced by a fine-grained aggregate of jadeite + quartz + zoisite. Plane polarized light - 30 x.

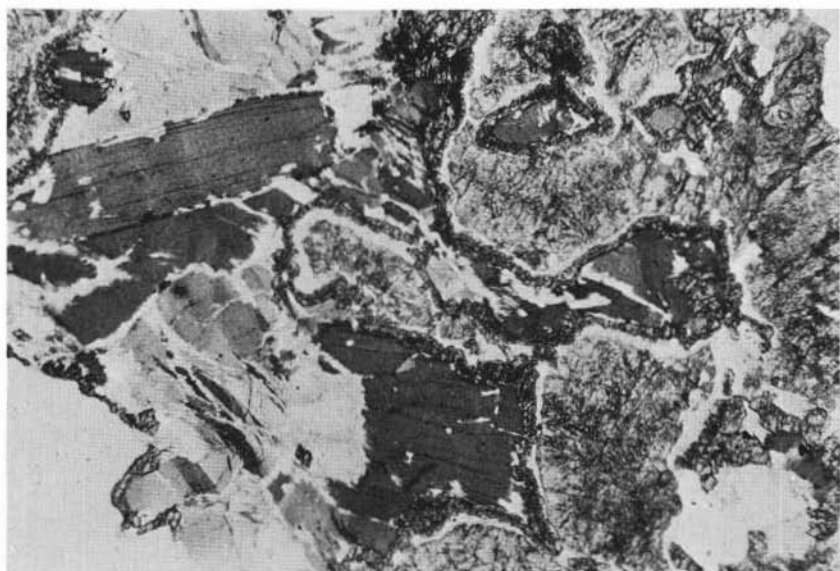


Fig. 3. — Metatonalite (SL 550). Monte Mucrone, upper Oropa valley, Biella. Relict magmatic biotites are surrounded by a continuous corona of early-Alpine garnet. A narrow rim of white-mica + quartz develops beside the garnet coronas towards the pseudomorphosed plagioclases. Plane polarized light - 25 x.

in the Eclogitic Micaschist Complex are the leucocratic dykes, recognized within the paraschists. The original magmatic fabric is preserved only in very few places (e.g. Bric Vert, lower Aosta Valley: see COMPAGNONI et al., 1976) where the mineralogy is still represented by quartz, jadeite pseudomorphs after acid plagioclase, potassium feldspar, and accessory biotite.

Usually, due to the transposition produced by the polyphase Alpine deformation, the metamorphic dykes appear as concordant layers interbedded in the paraschists. In such occurrences the dykes consist of quartz, phengite, practically pure jadeite, and accessory zoisite and rutile: potassium feldspar, often with porphyroclastic appearance, is commonly the only relic of the magmatic assemblage. The usual lack of garnet confirms that primary biotite was very poor.

In several metamorphic dykes of the area jadeites have developed rounded porphyroblasts of unusual dimensions (up to 10-15 cm in length) producing a peculiar pseudo-conglomeratic appearance. (See ANDREOLI et al., 1976).

Finally it is noteworthy that the jadeites of the leucocratic dykes are (together with the pseudomorphs after plagioclases) even purer than in other rocks of the Sesia-Lanzo containing up to about 95% of the jadeite end-member.

### 3) PRE-ALPINE PARAGNEISSES (« KINZIGITES »)

Large relics of pre-Alpine paraschists, representing the original country rocks in which granitoids intruded, have been recognized and carefully described in the Mt. Mucrone area (DAL PIAZ et al., 1973; COMPAGNONI et al., 1976). The occurrence within the paraschists of centimeter-sized veins or lenses (generally concordant) and of quartz-feldspar ( $\pm$  biotite) pegmatoids, strikingly recalls the « Kinzigites » of the Ivrea Zone or of the « II Zona diorito-kinzigitica ».

Microscopic examination reveals that the relict paraschists of Lago Mucrone consisted of quartz, plagioclase, biotite, garnet, sillimanite, orthoclase and rare muscovite. Quartz, plagioclase, biotite and K-feldspar show the same transformations as observed in the metagranitoids.

The large pre-Alpine garnets are generally mantled by a small rim of a newly formed (early-Alpine) garnet, similar to the coronitic garnets developed around biotites, and clearly recognizable by its dusty appearance, due to very fine-grained inclusions of rutile. Fibrolitic sillimanite is always pseudomorphically replaced by aggregates of kyanite often surrounded by a rim of very fine-grained white-micas.

The rare large muscovite flakes appear strongly deformed and seem to recrystallize, mainly along the kink-bands, into finer-aggregates of a new white-mica.

In paraschists other than the kinzigites primary textures and minerals are usually completely transformed due to development of pervasive deformations. The only garnet appears to survive also in most sheared rocks. Relics of the original foliation are locally preserved as helicitic inclusion patterns in porphyroblasts, such as chloritoid or omphacite. Where primary mineralogy is completely obliterated by early-Alpine recrystallization, the pre-Alpine paraschists have been transformed into

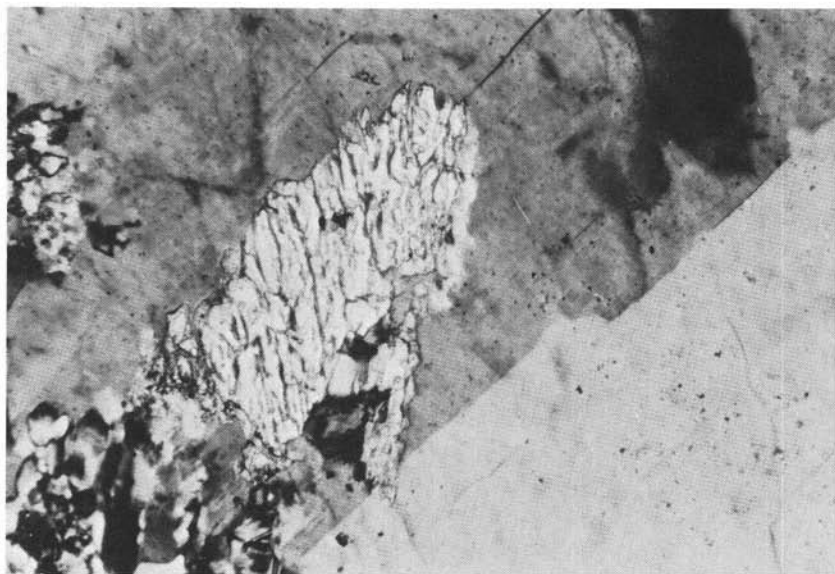


Fig. 4. — Meta-aplite (6537). Monte Mucrone, upper Oropa valley, Biella. An original sodic plagioclase, transformed into jadeite + worm-like quartz, is enclosed in a monoclinic K-feldspar twinned according to the Carlsbad law. Fine-grained albite (lower left) derives from the alteration of jadeite. Crossed polars - 160 x.

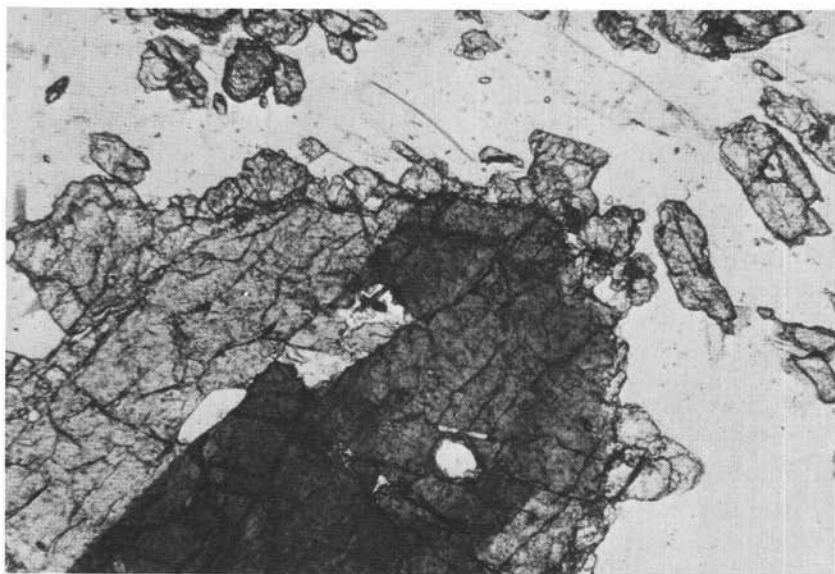


Fig. 5. — Retrograded eclogitic micaschist (MEC 323). Bard, Aosta valley. Relic of twinned magmatic allanite is surrounded by a narrow rim of colourless clinozoisite. Occurrence of this type is common in the « eclogitic micaschists » derived from primary igneous rocks of tonalitic composition. Crossed polars - 180 x.



typical « eclogitic micaschists », consisting of quartz, phengite, garnet, omphacite  $\pm$  glaucophane  $\pm$  zoisite + rutile.

#### 4) AMPHIBOLITES

In the Eclogitic Micaschist Complex metabasics are generally represented by glaucophane-eclogites. However, a systematic investigation revealed, within many eclogite masses interbedded in the paraschists, relics of pre-Alpine amphibolites. The best found so far is a large mass of amphibolite, only partially eclogitized, on the Croix Corma ridge, on the North-Est side of the Val d'Aosta, above Donnaz (see COMPAGNONI et al., 1976, stop 5). The amphibolites, deep-green in colour, are usually characterized by a centimeter-sized layering, depending on the variation in grain-size and in relative amount of mineral constituents. The rocks mainly consist of strongly lineated hornblendes and minor epidote aggregates, most likely replacing primary Ca-plagioclases. The formerly brown hornblendes usually appear almost completely decoloured, retaining only irregular patches of the original colour. The resulting pale-green amphibole is nevertheless very distinctive for it maintains the original shape of the hornblende and is crowded with fine-grained rutile needles. A new, early-Alpine eclogitic assemblage is locally observed clearly superimposed on the relict structure and mineralogy. It consists of garnet and omphacite with minor phengite, glaucophane, rutile and Mg-chlorite. Omphacite randomly develops as prismatic crystals often crosscutting the lineation defined by preferred orientation of the hornblende (Fig. 8). Garnet typically grows as skeletal, intergranular blasts, mainly at the expense of the epidote aggregates and of pre-Alpine hornblende. Corroded remnants of both the minerals (together with omphacite and rutile) can usually be observed within the largest (up to 2 or 3 cm) poikiloblastic garnets (Fig. 9).

#### 5) INTERMEDIATE TO BASIC INTRUSIVES

Meta-igneous rocks of intermediate to basic composition extensively outcrop in the southwestern sector of the Eclogitic Micaschist Complex, between Lanzo and the Valley of Torrente Malone. The main masses of Corio and Monastero di Lanzo, described by NOVARESE (1894, 1931) and carefully studied by BIANCHI et al. (1965), consist of meta-igneous rocks ranging from prevailing hornblende-bearing gabbros and diorites to minor quartz-bearing diorites, tonalites and leucocratic dykes.

Recently a minor body, consisting of meta-hornblendites to meta-diorites and meta-tonalites, has been found at Cima della Bossola, lower Valchiusella (COMPAGNONI & FIORA, 1976).

Due to the widespread occurrence of glaucophane most of these rocks have been distinguished on the Italian Geological Maps (sheets Ivrea, Susa and Torino) as « glaucophanites » or « gastaldites ».

In such rocks very often the granular igneous fabric is still recognizable, in spite of the pervasive deformation. Magmatic assemblage is represented by relics of brown-hornblende and, in very few cases, of a clinopyroxene preserved in the core

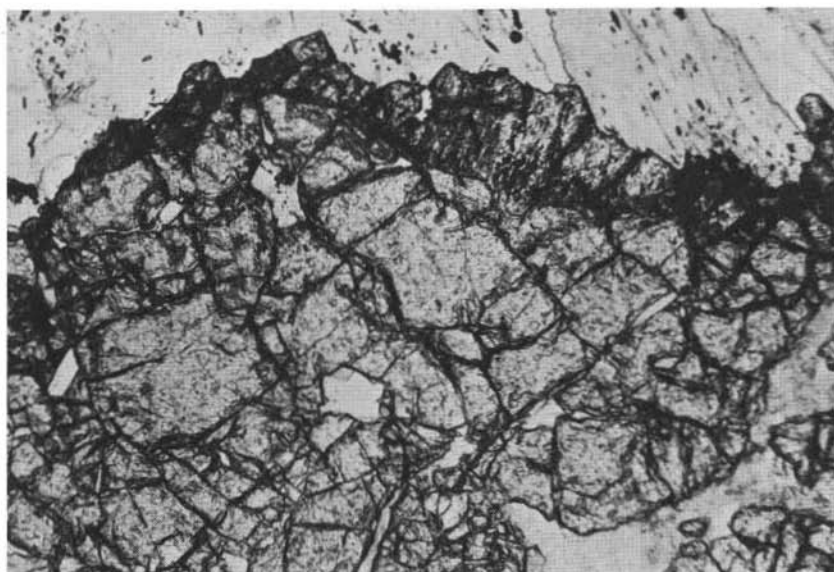


Fig. 6. — Garnet-chloritoid micaschist (SL 734). Est ridge of Cima di Bossola, lower Valchiusella. Pre-Alpine garnet is overgrown by a narrow rim of early-Alpine garnet: the latter is clouded with very fine-grained inclusions of rutile, suggesting its development from original pre-Alpine biotite. Plane polarized light - 200 x.

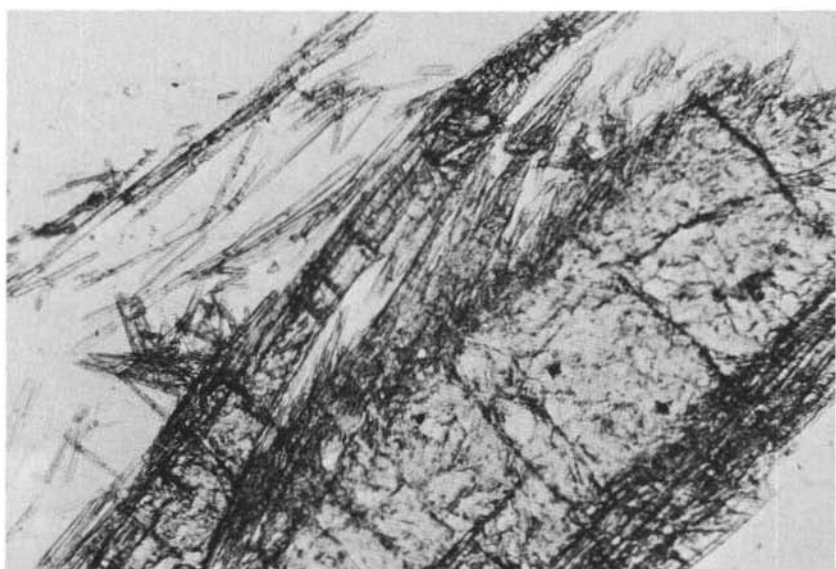


Fig. 7. — Relict pre-Alpine « kinzigite » (MEC 19). Lago Mucrone, upper Oropa valley, Biella. Pre-Alpine fibrolitic sillimanite, enclosed in a quartz-rich layer, is pseudomorphically replaced by an aggregate of kyanite. Crossed polars - 180 x.

of the hornblende; plagioclase and biotite, on the other hand, appear completely transformed. Usually, however, the brown-hornblende itself is pseudomorphically replaced by a single crystal of pale-coloured glaucophane  $\pm$  very fine-grained rutile needles. Locally the pseudomorphs consist of a polycrystalline aggregate of glaucophane, most likely deriving from recrystallization of a previous single-crystal of glaucophane. The magmatic plagioclase is always replaced by a zoisite ( $\pm$  clinozoisite/epidote) aggregate, plus garnet usually developed at the original plagioclase-hornblende boundary. The primary occurrence of biotite is inferred from the sagenitic arrangement of rutile needles either within the garnet or within Mg-chlorite, the commonest metamorphic products of transformation of the biotite.

Finally, the occurrence, in metatonalites, of cm-sized pseudomorphs of vermicular quartz and partially retrograded jadeite, which most likely correspond to original phenocrysts of albitized potassium-feldspar, is noteworthy.

### **Pre-Alpine rocks completely reworked and recrystallized under eclogitic conditions**

Most rock types of the Eclogitic Micaschist Complex appear to have been pervasively reworked and completely recrystallized under eclogitic conditions during the early-Alpine metamorphic event. The most representative metamorphics produced by the intensive early-Alpine reworking are the typical « eclogitic micaschists » and the associated glaucophanic eclogites (Fig. 10).

The *eclogitic micaschists* are schists mainly consisting of quartz, phengite and garnet,  $\pm$  omphacite,  $\pm$  glaucophane,  $\pm$  zoisite (less commonly clinozoisite/epidote)  $\pm$  chloritoid,  $\pm$  paragonite,  $\pm$  rutile,  $\pm$  opaque ore minerals (commonly pyrrhotite and/or pyrite)  $\pm$  carbonates. Many different types of schists result from local variation in abundance of the constituent minerals.

Genetically two main groups of *eclogitic micaschists* can be often distinguished: the paraschists and the orthoschists.

The *paraschists* are characterized by: banded appearance due to lithologic heterogeneity; reddish-brown colour related to the widespread occurrence of iron sulphides; distinctive occurrence of phengite- and/or quartz-rich differentiated layers; occurrence of chloritoid-bearing schists, or eclogite intercalations.

In the other hand, the *orthoschists* (namely the schists derived from intrusives, mainly of tonalitic compositions) are characterized by: lithologic homogeneity with poorly developed (mm or cm-sized) metamorphic layering; local occurrence of primary magmatic features (still recognizable in spite of the pervasive deformation) such as igneous quartz-grains recrystallized into flattened lenticular quartz aggregates, or the dark microgranular enclaves (see DIDIER, 1973) now transformed into strongly deformed eclogitized lenses. Furthermore microscopic observations

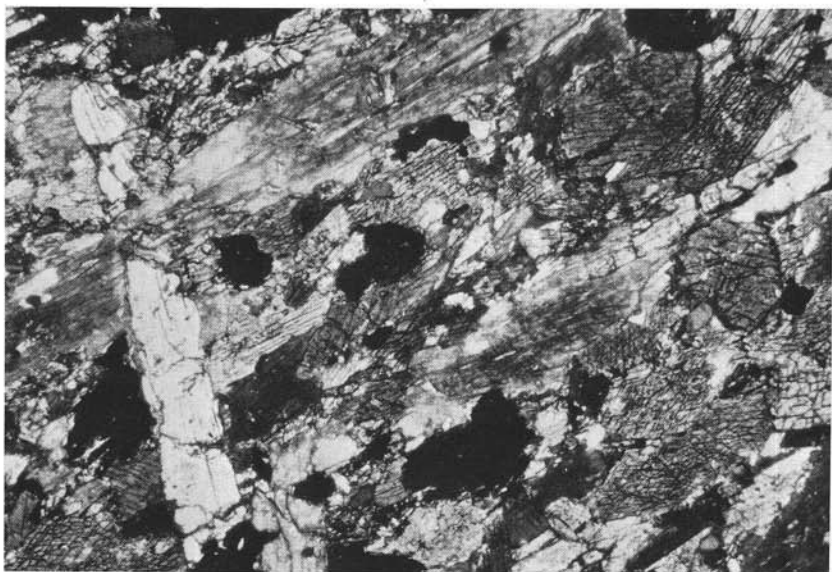


Fig. 8. — Relict pre-Alpine amphibolite (SL 624). Croix Corma ridge above Donnaz, Aosta valley. Early-Alpine omphacite (elongated crystal, on the left side, crossing the foliation of the amphibolite) grows in an aggregate of original brown-hornblende mostly decoloured. Crossed polars - 45 x.

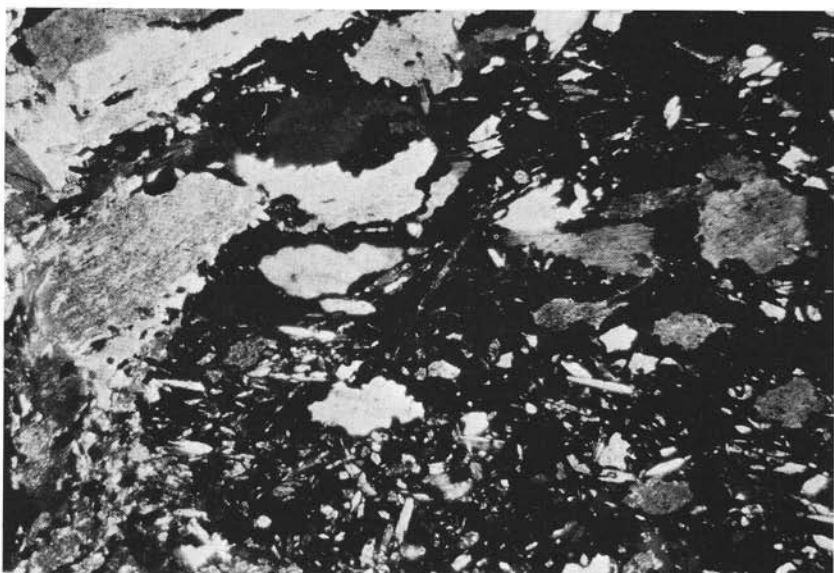


Fig. 9. — Relict pre-Alpine amphibolite (SL 630). Croix Corma ridge above Donnaz, Aosta valley. An early-Alpine garnet is growing in a relict pre-Alpine amphibolite. Corroded crystals inside the garnet are relict pre-Alpine hornblende; unoriented needles are early-Alpine omphacites. Note the skeletal shape of marginal garnet clearly developing along intergranular boundaries at the expense of decoloured brown-hornblende. Plane polarized light - 20 x.

reveal that the orthoschists include broken and corroded relics of allanite, a distinctive accessory minerals of tonalitic rocks (see Fig. 5).

*Eclogites*, in addition to the distinctive assemblage omphacite  $\pm$  garnet  $\pm$  rutile, generally contain in largely variable amounts glaucophane, phengite, zoisite (less frequently clinozoisite/epidote) quartz and sulphides (Fig. 11). Locally a light-green amphibole, derived from brown-hornblende (as testified by the occurrence of patches crowded with very fine-grained rutile needles) has also been formed. These eclogites derived from pre-Alpine amphibolites and most probably represent the polymetamorphic product of original basaltic flows interbedded in a sedimentary sequence, which is now the paraschists. (See DAL PIAZ et al., 1972; MOTTANA, this volume). On the basis of mineral assemblages and composition of the main phases the eclogites of the EMC belong to the ophiolitic type of SMULIKOWSKI (1964), or to the Alpine-type of BEARTH (1965) or to the Group C eclogites of COLEMAN et al. (1965).

Besides these «*ortho-eclogites*» another carbonate-bearing variety of eclogite has been recognised in the Eclogitic Micaschist Complex, characterized by the occurrence of a significant amount (up to about 20%), of a primary *Fe-dolomite* in equilibrium with *omphacite*, *garnet*, *glaucophane* and *rutile*. Due to the peculiar mineralogy and the close association with carbonate-bearing rocks such eclogites could be considered as «*para-eclogites*», that is the metamorphic equivalent of original marly rocks.

*Lawsonite bearing-glaucophanites* — A peculiar variety of glaucophanite, characterized by the occurrence of lawsonite porphyroblasts (up to 2 cm), has been found in the southern internal part of the Sesia Zone between Corio (to the south-west) and the Aosta Valley (CARON & SALIOT, 1969; KIENAST & VELDE, 1970; LIEBEAUX, 1975; COMPAGNONI et al., 1976). (See Fig. 22).

Lawsonite-bearing glaucophanites are associated with chloritoid-bearing paraschists (e.g. Alpette, lower Orco Valley), with jadeite-bearing orthoschists (e.g. Courgné, lower Orco Valley) or with igneous metabasics (e.g. Corio region).

Though primary relationships between such lithologies have been completely obliterated by later Alpine polyphase deformation, a primary granular texture is still recognizable locally in metabasics, suggesting their derivation from intrusive basic rocks. This interpretation is furthermore supported by occasional relics of pink-coloured variety of a clinopyroxene (Courgné), together with epidote aggregates derived from primary Ca-plagioclase.

In addition to lawsonite porphyroblasts the glaucophanites are composed of fine-grained glaucophane, clinozoisite/epidote, minor garnet and white-mica (phengite and/or paragonite) + quartz and accessory sphene, Fe-sulphides and apatite.

Microscopic examination indicates that glaucophane mainly develops after pre-Alpine amphibole (or clino-pyroxene) and lawsonite grows at the expense of

fine-grained epidote aggregates, derived from primary saussuritized Ca-plagioclases (Fig. 12).

Lawsonite is partly to completely replaced by very fine-grained pseudomorphic aggregates of zoisite  $\pm$  white-micas (mainly paragonite)  $\pm$  sphene  $\pm$  quartz (?).

However, even in the most altered rocks, the former occurrence of lawsonite can be easily inferred, even in the field, from the perfect preservation of the pseudomorphs, whose considerable dimensions, rhombic shape, and mineralogy are diagnostic.

*Marbles and carbonate-rich rocks* — Marbles occur in the paraschists as intercalations of a few centimeters to more than a hundred meters thickness. Dolomite-rich and calcite-rich layers commonly alternate in the same outcrop. Calc-silicate felsels are locally associated with marbles.

Pure marbles consist of one or two carbonate (calcite, dolomite, ankerite) with accessory phengitic white-mica, graphite and Fe-sulphides. Impure marbles, in addition to the carbonate minerals, contain one or more of the following minerals: quartz, phengitic white-mica, omphacite, zoisite (mainly  $\beta$ -zoisite), Mg-chlorite, and a tremolitic amphibole; garnet is not ubiquitous and glaucophane is rare. Typical accessories are sphene, Fe-sulphides and graphite.

The quartz-carbonate schists, generally associated with marbles (e.g. Bric Vert, lower Aosta Valley; square of Pont Canavese, Orco Valley) are very similar both in appearance and in composition to the mesozoic « calcescisti » of the Piemonte Zone. Their mineralogy composition to the mesozoic « calcescisti » of the Piemonte Zone. Their mineralogy comprises quartz and carbonates (calcite and/or Fe-dolomite) in approximately equal amounts, minor phengitic white-mica, zoisite, Mg-chlorite, glaucophane, Fe-sulphides, sphene, graphite, and accessory tourmaline (pale-green to colourless), apatite and zircon.

### **The minerals of Eclogitic Micaschist Complex as a record of the Sesia-Lanzo metamorphic evolution**

#### **PYROXENES**

The most distinctive minerals of Sesia-Lanzo Zone, occurring in all the lithologies of the Eclogitic Micaschist Complex, are the alkali-pyroxenes. According to the diagram by ESSENE & FYFE (1967) their composition ranges from jadeites (Jd = 80 to 95 %) to omphacites (Jd = 40 to 60 %), the acmite-content usually never exceeding 10 %. (See COMPAGNONI et al., 1977).

Acmite-rich pyroxenes (chloromelanite to aegirine-augite or aegirine) also occur in the more advanced stages of the early-Alpine metamorphic evolution, as secondary products related to the destabilization of older Jd-richer alkali-pyroxenes. (See COMPAGNONI & MAFFEO, 1973; ANDREOLI et al., 1976).

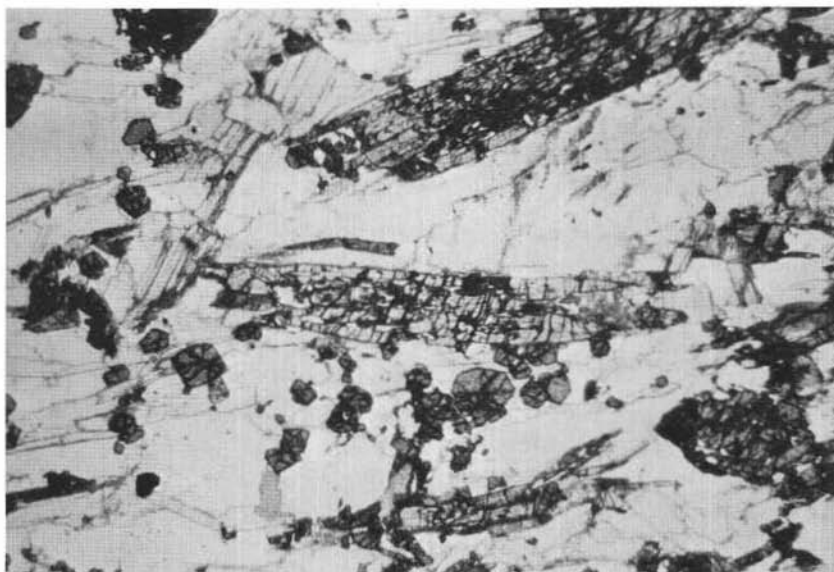


Fig. 10. — Eclogitic micaschist (SL 529). Monte le Colme, lower Valchiusella-lower Val d'Aosta divide. Typical mineral assemblage of an eclogitic micaschist: large prismatic crystals of omphacite (and minor glaucophane), granoblasts of almandine-rich garnets and white-mica flakes are enclosed in a quartz  $\pm$  rutile matrix. Plane polarized light - 20 x.

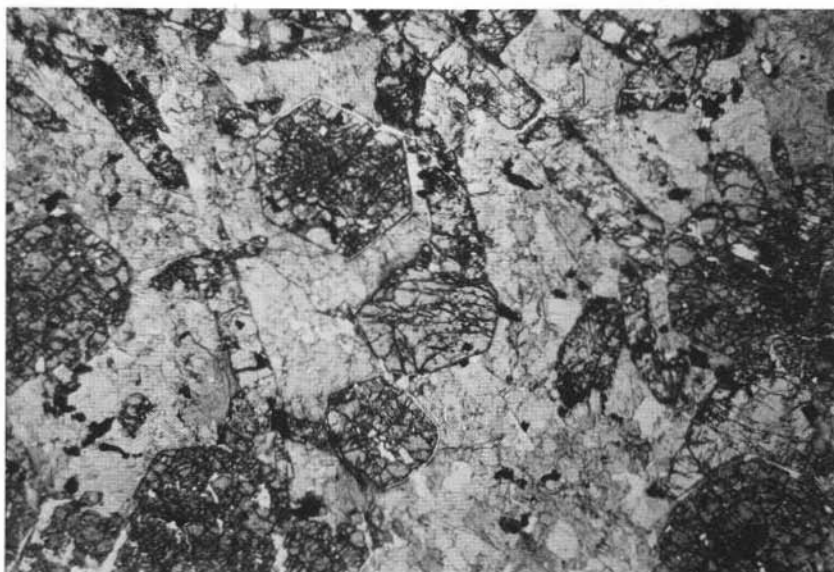


Fig. 11. — Glaucophanitic eclogite (SL 101). Lago Mucrone, upper Oropa valley, Biella. Idioblastic garnets and randomly oriented omphacites are enclosed in a fine-grained matrix of pale-coloured glaucophane. Plane polarized light - 20 x.

Chemical composition of the primary Na-pyroxenes is related to the bulk chemistry (mainly Ca/Na ratio) of the host rock. (See LOMBARDO et al., 1976).

Practically *pure jadeite* (Jd = 90-95 %) has been found as pseudomorphs after plagioclase in metagranitoids and paraschists exhibiting well-preserved pre-Alpine structure, and as independent blasts often of unusual dimensions (up to 10-15 cm) in phengitic-micaschists derived from reworking of original leucocratic-dykes high in almina and soda and low in lime, magnesia and FeO.

The *omphacite* develops in ortho- and para-schists of suitable composition, in metabasics (eclogites and related rocks) in marbles and in early-Alpine metamorphic veins, crosscutting the eclogitic micaschists. (LOMBARDO et al., 1976; LIEBEAUX, 1975).

Jadeites and omphacites occur in stable association with quartz, zoisite, garnet, white-micas (phengite and possibly paragonite), glaucophane, rutile, carbonates (mainly Fe-dolomites) and Fe-sulphides.

*Pyroxene alteration* — Owing to later metamorphic evolution and particularly to the «Leontine» event, Na-pyroxenes are partially or completely transformed into pseudomorphs consisting mainly of albite.

Jadeites, more sensitive than omphacites to changing P-T conditions, are commonly replaced by aggregates of albite + white-mica (phengite and/or paragonite) + magnetite, along with accessory acmite-rich pyroxenes (aegirine and aegirine-augite), crossitic blue-amphibole, barroisitic blue-green amphibole, actinolite, Fe-epidote, usually arranged in coronitic textures around quartz inclusions, green-biotite and chlorite. On the contrary, as a general rule, omphacites alter into albite + green amphibole (mainly actinolite), commonly intergrown in very fine-grained aggregates.

#### AMPHIBOLES

*Blue-amphiboles* — Blue-amphiboles are also common and widespread in the Eclogitic Micaschist Complex. However, whereas in metabasics they are generally abundant or even the commonest mineral, in many micaschists they are only accessories, and in the best preserved metagranitoids they are completely absent. Such uneven occurrence of blue-amphiboles is most probably a consequence of the bulk chemistry of the host rocks and mobility of sodium and water during metamorphism.

The few chemical analyses so far available (DAL PIAZ et al., 1973; LIEBEAUX, 1975; DESMONS & GHENT, 1976) plot in the glaucophane field of MIYASHIRO (1957). (See: COMPAGNONI et al., 1976, this volume). Optically they are pale-coloured glaucophanes, sometimes zoned with rims which are slightly deeper-coloured than the cores. This corresponds to a weak increase in Fe and decrease in Mg content (DESMONS & GHENT, 1976).

Very occasionally more deeply coloured rims (with very small 2V and the optical orientation of crossites) also occur: most probably they represent the extreme



Fe-enrichment of zoned blue-amphiboles, which formed at the end of the early-Alpine metamorphic evolution.

Several generations of glaucophanes can be recognized on microtextural grounds. They have no doubt crystallized over a long period of time, since they occur both in stable association with Jd-rich pyroxenes, and as product of the jadeite-breakdown in equilibrium with albite and acmite. In metabasics many large glaucophanes have replaced pre-Alpine hornblende, the pseudomorphs being revealed by the presence of darker patches crowded with very fine-grained unoriented rutile needles.

In consequence of later deformations the large glaucophane crystals commonly recrystallize into polycrystalline aggregates (See e.g. Gosso, 1976, this volume), modifying the original relations with coexisting minerals.

In my opinion the microstructural relationship between glaucophanes and omphacite has been changed in many of the eclogites by recrystallization of the glaucophane under deformation conditions, that only produced subgrains in the omphacite.

Furthermore, in contrast to the ophiolitic eclogites of the adjoining Piemonte Zone, in the Sesia-Lanzo Zone there is no general evidence that glaucophane developed at the expense of omphacite. It follows that, at least in many metabasics, the first generation of glaucophane should have grown at the same time as omphacite, both minerals utilizing the Na released from the plagioclase breakdown.

The oldest generation of glaucophane is usually coexisting with omphacite, jadeite, garnet, white-micas (phengite and possibly paragonite), zoisite (in places clinozoisite and epidote as well), chloritoid, lawsonite, rutile (and locally sphene), carbonate minerals (calcite, ankerite, dolomite), graphite and Fe-sulphides. On the other hand the youngest Fe-richer glaucophane generation (only locally occurring among the breakdown products of jadeite) is in equilibrium with albite, acmite-rich pyroxene (aegirine and/or aegirine-augite), Fe-epidote (clinozoisite and/or epidote), quartz and magnetite.

*Other amphiboles* — In addition to glaucophanes other amphiboles can be commonly recognized in the Eclogitic Micaschist Complex. They can represent relics of pre-Alpine parageneses, varieties of early-Alpine amphiboles, or late-Alpine («Lepontine») products of destabilized early-Alpine minerals. In the absence of chemical analyses, at present they can be only characterized on the ground of their optical data, particularly the colour. Thus for example there is a pale-green amphibole, pseudomorphically derived, through decolourization, from pre-Alpine brown-hornblende; a colourless amphibole occurring in marbles devoid of glaucophane; and the blue-green to green amphibole (barroisitic actinolites to actinolites) commonly developed from destabilization of older minerals during late-Alpine metamorphic events (LATTARD, 1974).

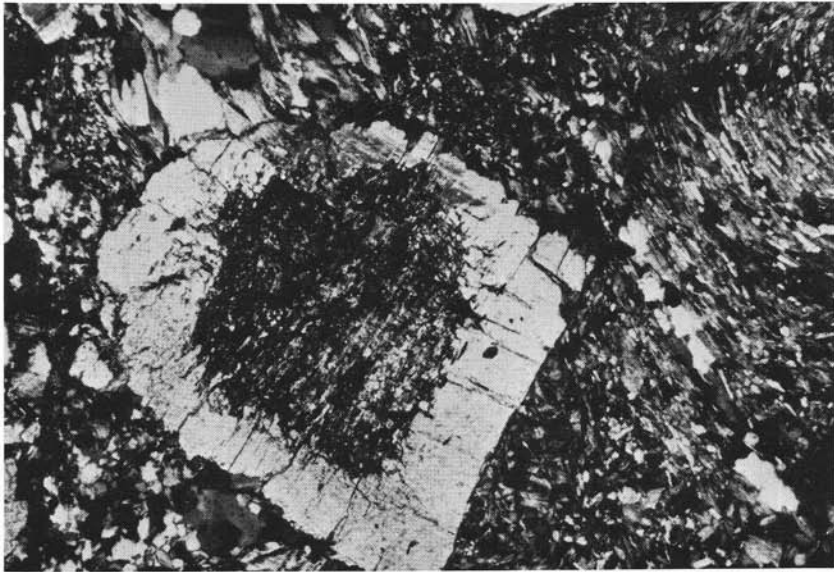


Fig. 12. — Lawsonite-bearing glaucophanite ( $33^{x11}$ ). Road Cuorné-Alpette, lower Orco valley. A lawsonite porphyroblast, enclosed in a glaucophane-chlorite-quartz matrix, retains in its core a fine-grained zoisite-aggregate most probably derived from primary plagioclase. Crossed polars - 30 x.

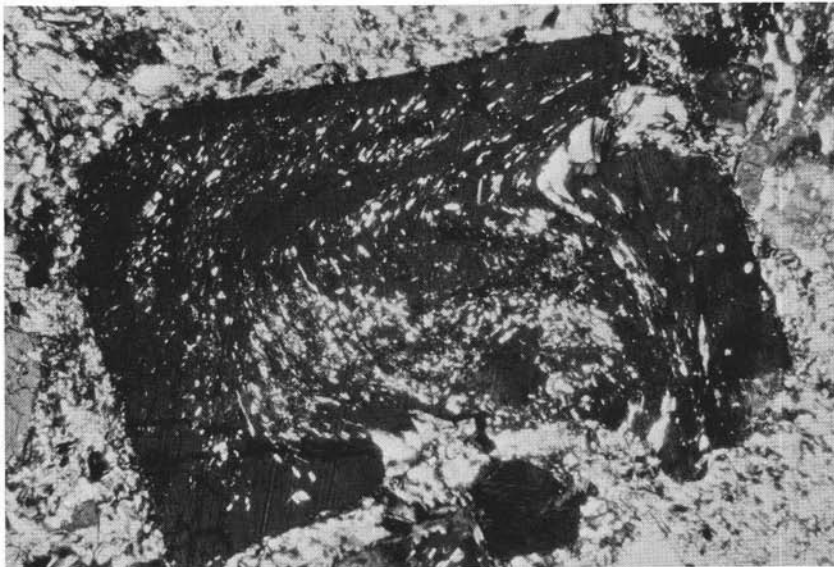


Fig. 13. — Lawsonite-bearing glaucophanite ( $33^{x1}$ ). Road Cuorné-Alpette, lower Orco valley. Porphyroblastic lawsonite contains a foliation defined by fine-grained glaucophane needles and quartz alignments. Note secondary polysynthetic twinning produced by deformations. Crossed polars - 25 x.

## GARNETS

Garnets are widespread in all lithologies of the Eclogitic Micaschist Complex. They occur as red-brown crystals usually idioblastic, up to 2 cm in diameter.

In micaschists and metagranitoids garnet typically develops at the expense of primary biotite, and its abundance is thus roughly indicative of the original pre-Alpine biotite content of the rock.

In metabasics garnet appears to develop mainly at the expense of pre-Alpine hornblende and epidotes from primary plagioclase.

In some micaschists two generations of garnets can be recognized, the first one consisting of large clear porphyroblasts, the second one characterized by finer-grained dusty crystals aligned along the rock foliation or developed as coronitic rims around older garnets.

Microscopical examination of structurally well preserved pre-Alpine paraschists (e.g. the « kinzigites » of the Lago Mucrone, see DAL PIAZ et al., 1973), reveals that the large garnets are relics of a pre-Alpine mineral assemblage, whereas the coronitic garnets are early-Alpine ones, produced at the expense of pre-Alpine biotite; the original titanium content of biotite has been exsolved as very fine-grained rutile needles with sagenitic arrangement.

The garnets of the Eclogitic Micaschist Complex are almandines (50-60 % Alm) rich in grossularite (25-40 % Gro), with pyrope component usually not exceeding 10 %, and spessartine very low (0.5 % Spes).

Garnets exceptionally rich in pyrope component (up to 40 % Pyr) found in some metabasics can be interpreted either as relics of pre-Alpine garnets or as early-Alpine garnets grown in rocks of peculiar bulk chemistry.

Almandines anomalously rich in spessartine component (about 40 % Spes) have been reported from distinctive quartz-phengite-jadeite micaschist layers (meta-plites) interbedded in the paraschists of M.te Colme (ANDREOLI et al., 1976). The unusual garnet composition has been interpreted as due the occurrence in leucocratic dykes, from which the micaschists originated, of primary igneous garnets rich in Mn and Fe.

Recently DESMONS & GHENT (1976) have identified in some schists two generations of garnets, the second-one forming small grains or rims around big older grains: garnets of first generation are Mg-poorer and Ca-richer than second ones. Most probably the two generations correspond respectively to pre-Alpine and early-Alpine garnets recognized in the paraschists of Lago Mucrone (see above).

Alpine garnets appear to have developed during the oldest early-Alpine metamorphic event, together with jadeite-omphacite pyroxenes, zoisite, phengite, glaucophane, rutile, Mg-chlorite and carbonates. During later metamorphic evolution garnet became unstable and transformed either into chlorites or, less commonly, into white-mica: the former reaction is undoubtedly related to the « Lepontine » event, while the latter most probably occurred during the early-Alpine event.

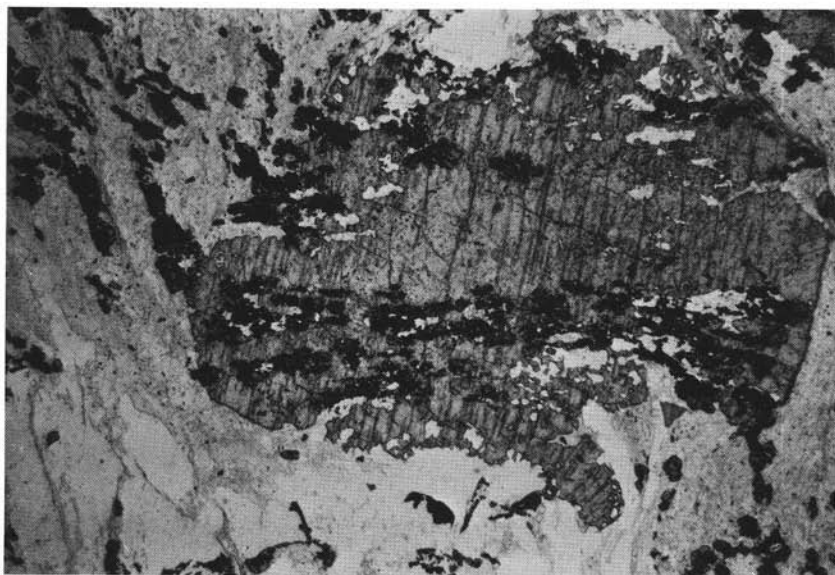


Fig. 14. — Chloritoid-bearing paraschist (SL 570). Trail Lago Mucrone-Monte Camino, upper Oropa valley, Biella. A chloritoid porphyroblast overgrows an earlier foliation defined by alignments of fine-grained garnets developed from pre-Alpine biotite. Plane polarized light - 20 x.

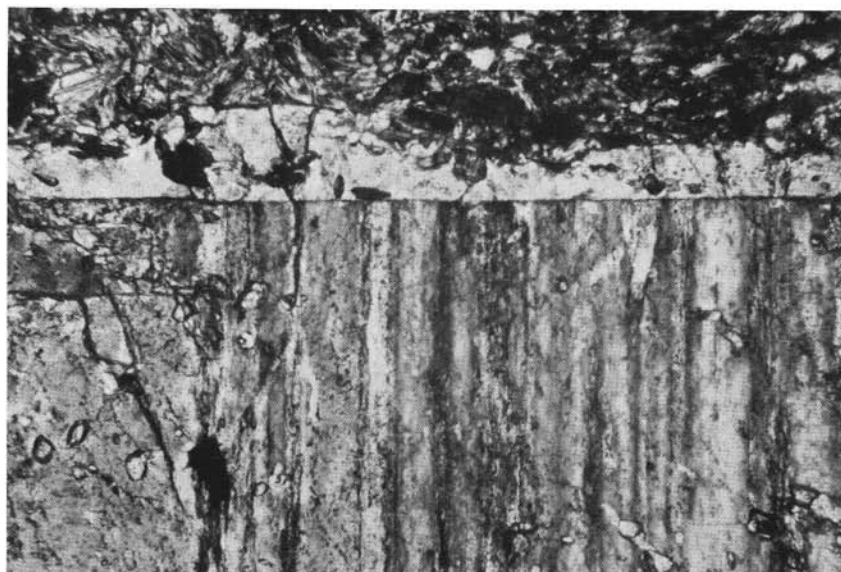


Fig. 15. — Lawsonite-bearing glaucophanite (SL 540). Road Courgné-Alpette, lower Orco-Valley. A narrow rim of pumpellyite (white) homoaxially overgrows a lawsonite porphyroblast. Crossed polars - 180 x.

## EPIDOTES

In the Eclogitic Micaschist Complex the most widespread members of the epidote group are the zoisites represented by alpha and beta varieties. Zoisite developed during the first phase of the early-Alpine metamorphic event, in equilibrium with garnet, jadeites/omphacites, glaucophanes and white-micas. Monoclinic epidotes however have been formed in only a very few places and usually appear included in garnets and or omphacites.

In metabasics, parashists, marbles and metagranitoids zoisites appear to have developed at the expense of the anorthite-component of pre-Alpine plagioclases.

Zoisites are the main constituents of many metabasics (eclogites included), in which they can locally form almost monomineralic layers consisting of white prismatic crystals as much as 1 cm long. In a few of these rocks zoisites appear to have crystallized in several generations: they can occur either lineated and enclosed in garnets, or randomly oriented and including remnants of lineated glaucophanes. However polyphase growth of zoisite is not a general feature, but seems localized to strongly foliated rocks, presumably favoured by a rock shearing, which occurred in earliest phase of the early-Alpine metamorphic event.

In following metamorphic phases monoclinic epidotes begin to develop, but Fe-rich members widely crystallize only during the greenschist-facies «Lepontine» metamorphic event. The Alpine metamorphic evolution of the Eclogitic Micaschist Complex is therefore characterized by a gradual iron-enrichment in the epidote minerals successively developed. This general trend is frequently recorded within a single epidote grain: a core of zoisite is surrounded by a rim of clinozoisite outwards grading into a Fe-richer epidote.

Besides ordinary epidotes, entire or fragmented allanite crystals are frequently observed in rocks of the Eclogitic Micaschist Complex. Allanites however are not metamorphic but are relics of magmatic crystals which commonly occur as accessories in many pre-Alpine granitoids. Due to its extraordinary resistance to structural and metamorphic reworking allanite is often, in schists originated from pre-Alpine intrusives, the only relic of the magmatic mineral assemblage (Fig. 5).

## KYANITE

Of the  $Al_2SiO_5$  polymorphs only kyanite has been identified in the Eclogitic Micaschist Complex. The kyanite indeed occurs only in structurally well preserved pre-Alpine parashists of suitable composition, as fine-grained aggregates of interwoven crystals, pseudomorphic after pre-existing sillimanite (DAL PIAZ et al., 1972) (Fig. 7).

Individual grains of kyanite have been found in only one rock where they are seemingly protected by a chloritoid porphyroblast in which they are included. Most kyanite pseudomorphs after sillimanite are slightly to largely replaced by very fine-grained white-mica aggregates.

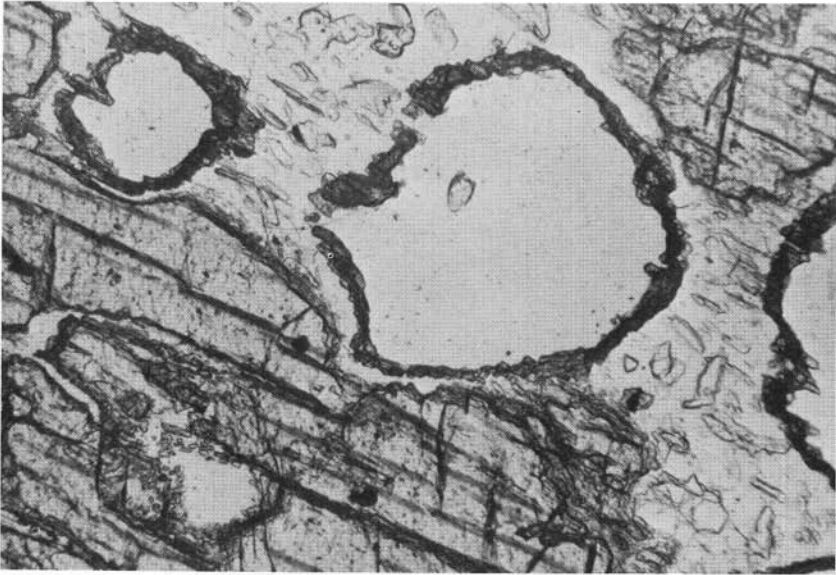


Fig. 16. — Quartz-phengite-jadeite pegmatoid (SL 504). Settimo Vittone, Aosta valley. Aegirine-augite coronas are developed around quartz inclusions in a large jadeite crystal (high relief with cleavage) altering into albite + white-mica. Aegirine-augite is the only Na-pyroxene observed in equilibrium with albite all over the Eclogitic Micaschist Complex. Plane polarized light - 200 x.

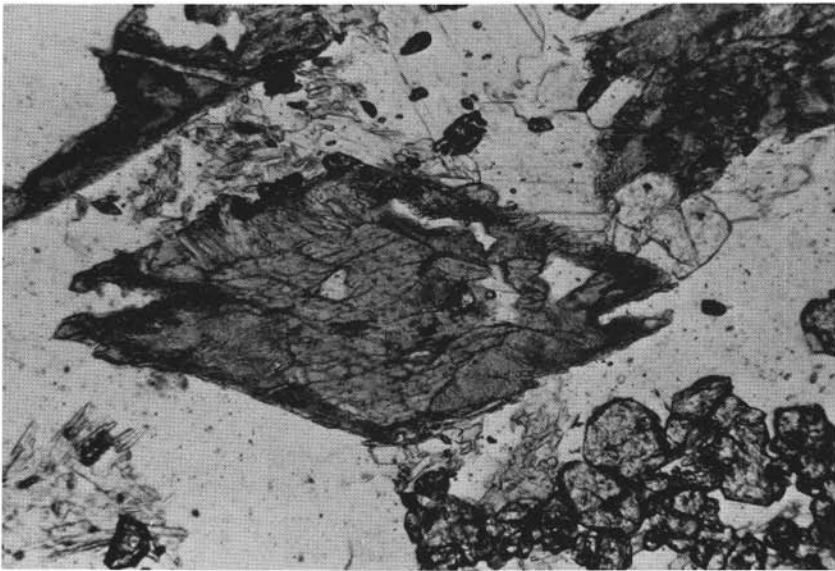


Fig. 17. — Foliated metagranitoid (SL 779). Clapey near Donnaz, Aosta valley. Glaucophane is partly replaced along borders by a very fine-grained biotite-albite symplectite. A narrow rim of green-amphibole follows the original boundary of the glaucophane crystal. Such glaucophane alteration is activated by the temperature rise (in a low-pressure environment) produced by the late-Alpine metamorphic event. Plane polarized light - 180 x.

As inferred from microscopical observations carried out on the structurally best preserved « kinzigites », kyanite has no doubt developed during the earliest phase of the Alpine metamorphic evolution in equilibrium with garnet, jadeite, zoisite, quartz and possibly glaucophane.

#### WHITE MICAS

Both phengites and paragonites have been identified in the Eclogitic Micaschist Complex. They can occur either separately or together in the same specimen or even as interlayered crystals (LIEBEAUX, 1975). Muscovite has also been reported (see e.g. FIORENTINI POTENZA & MORELLI, 1968), but it possibly represents a relic of a pre-Alpine mineral assemblage. Large flakes of relict muscovites have been described by DAL PIAZ et al. (1972) in the pre-Alpine « kinzigites » of lago Muchrone.

Phengites are undoubtedly the most widespread white-micas in the Sesia-Lanzo Zone, occurring in micaschists, in eclogites and in marbles.

Typical phengites occur as large flakes (up to 1 cm, or exceptionally up to several cm in diameter) usually light-green to light-brown coloured.

In thin section phengites show a very pale pleochroism, and can be both either uniaxial and biaxial in a single specimen. The very widespread uniaxial varieties correspond to polytype 3T, while biaxial correspond to polytype 2M<sub>1</sub> (FIORENTINI POTENZA & MORELLI, 1968).

Several generations of phengites (and paragonites) have been recognized. The older ones are usually coarser-grained than the later ones; finer-grained phengites appear to have formed either at the expense of older destabilized minerals (such as chloritoid or jadeites; see e.g. ANDREOLI et al., 1976) or by microstructural evolution of pre-existing coarser grains of micas involved in the development of new cleavages (similarly to what observed in the eclogitic micaschists of P.ta Plaida by Gosso, 1976).

Chemical analyses have shown that primary phengites contain high amounts of celadonite in solid solution (mainly the MgAl-component), whose values (expressed as tetrahedral silicon content on the basis of 12 O, OH) range from Si = 3.2 to more than Si = 3.5 (MICHEL, 1953; FIORENTINI POTENZA & MORELLI, 1968; FIORENTINI POTENZA, 1969; VELDE & KIENAST, 1973; LIEBEAUX, 1975).

From microstructural relationships most phengites and paragonites appear to have developed during the early-Alpine metamorphic event. They have possibly « recrystallized » during earliest times of the « Lepontine » event, but certainly they become unstable towards the end of the same event, since they appear to have been largely replaced by albite. (See e.g. DAL PIAZ et al., 1971; Gosso, 1976) (Fig. 21).

#### LAWSONITE

The presence of lawsonite appears to be limited to the southern portion of the Eclogitic Micaschist Complex, between Monastero di Lanzo and the lower Aosta Valley (Fig. 22). The best outcrops are in the Orco Valley between Alpette (Pont Canavese) and Cuorné, where lawsonite occurs in glaucophanites as large (up to

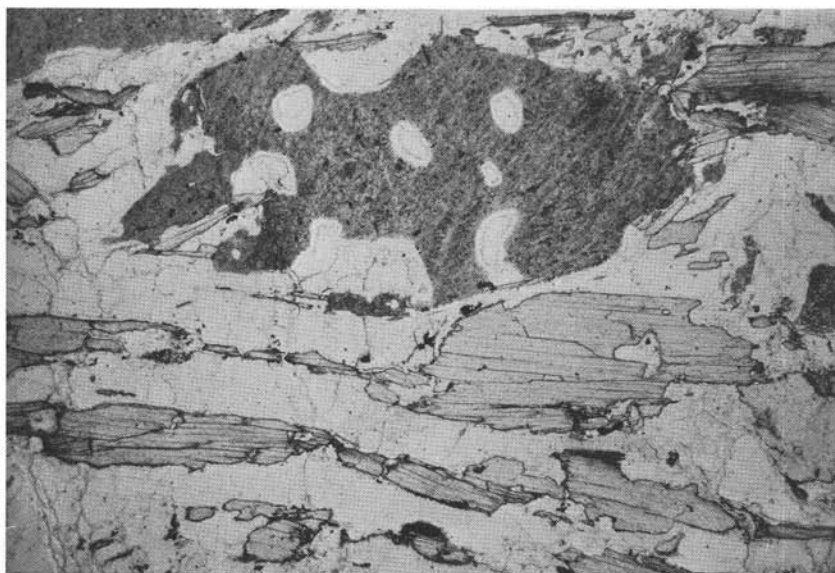


Fig. 18. — Meta-aplite from the contact aureole of the Brosso-Traversella stock (SL 522). Monte le Colme, Valchiusella-Val d'Aosta divide. A very fine-grained aggregate of white-mica + albite replaces an early-Alpine poikilitic jadeite. In the external Eclogitic Micaschist Complex similar pseudomorphs are the only evidence of primary occurrence of jadeite, completely altered by the late-Alpine metamorphic event. Plane polarized light - 10 x.

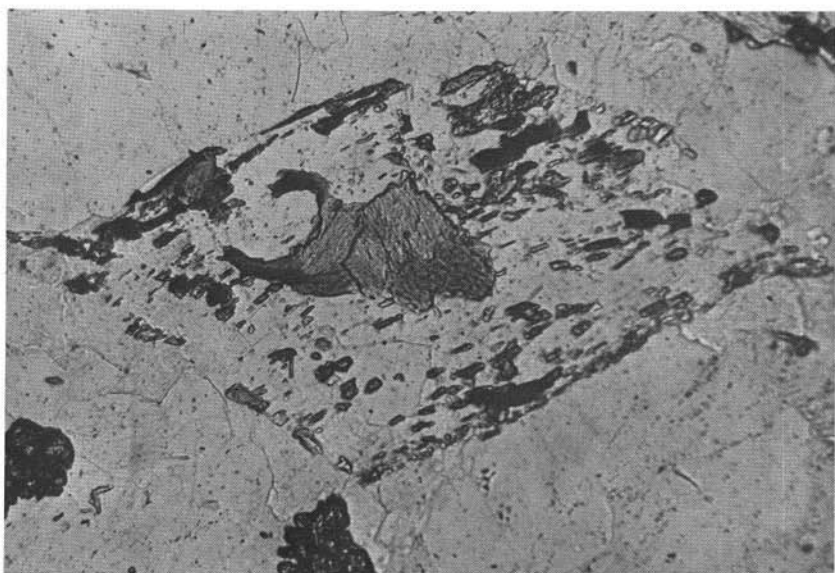


Fig. 19. — Retrograded eclogitic micaschist (MEC 328). Bard, Aosta valley. In the most external part of the eclogitic micaschists, where strongest is the late-Alpine metamorphic overprint, early-Alpine glaucophane is completely replaced by pseudomorphs of albite  $\pm$  chlorite  $\pm$  biotite  $\pm$  actinolite. Plane polarized light - 180 x.



1-2 cm long) porphyroblasts with typical rhombic sections (CARON & SALIOT, 1968; LIEBEAUX, 1975). It develops from fine-grained zoisite aggregates (locally preserved in the lawsonite cores) most probably derived from primary magmatic Ca-plagioclase (Fig. 12).

Usually lawsonite porphyroblasts contain helicitic patterns indicating the crystals have grown in rocks having a folded foliation defined by alignments of fine-grained glaucophane needles, quartz grains and minor garnet (Fig. 13). Most lawsonites exhibit a conjugate system of polysynthetic twinning or appear dismembered into cleavage prismatic fragments. Locally lawsonite porphyroblasts appear overgrown by a continuous homoaxial rim of pale-coloured pumpellyite (Fig. 15). Usually, however, lawsonite appears completely replaced by a very fine-grained pseudomorphic aggregate consisting of clinozoisite, minor white-mica (phengite and/or paragonite), accessory rutile or sphene, and quartz. Such pseudomorphs usually retain the original crystal shape and are very useful to recognize the primary occurrence of lawsonite in retrograded rocks. For example, in a garnet-omphacite-amphibole metabasic of the Aosta Valley the presence of lawsonite has been revealed by the occurrence of pale-green pseudomorphs, consisting of paragonite flakes and minor zoisite (COMPAGNONI et al., 1977).

In addition to porphyroblastic lawsonite, another variety of lawsonite has been found in «glaucophanites» of the Corio region. It occurs as fine-grained tabular platelets, oriented parallel to the schistosity, in association with deep-coloured blue-amphibole (optically crossite), white-mica and iron-rich epidote.

The mineral association strongly recalls metabasites of the external Pennine domain (i.e. of the Briançonnais Zone) rather than the typical glaucophanites occurring in the Sesia-Lanzo or in the Piemonte Zone. Therefore it is possible that tabular lawsonite, which occurs in metabasites devoid of garnet, could represent a second generation of lawsonite locally developed at the end of the early-Alpine metamorphic event. It is noteworthy that DOBRETSOV et al. (1974) observed that lawsonites from different metamorphic conditions exhibit different diagnostic features: in low-temperature schists it is characterized by compressed, lath-like shapes; in higher-temperature rocks it occurs as coarser-grained crystals with square and rhombic sections, usually showing two intersecting systems of fine polysynthetic twinning.

#### CHLORITOID

Chloritoid is distributed all over the EMC as a main constituent of micaschists of suitable bulk chemical composition. Furthermore in the southern most Sesia-Lanzo Zone (Corio and Monastero), chloritoid has been found in metabasites, developing as minor constituent either in zoisite pseudomorphs after pre-Alpine Ca-plagioclase or inside relict brown-hornblende (BIANCHI et al., 1965).

No chemical analyses are available, but its very pale pleochroism suggests a Mg-rich composition. Usually it develops as nematoblasts oriented parallel to the



Fig. 20. — Retrograded eclogitic micaschist (SL 938). Colle Dondeuil, Gressoney Valley. Flakes of stilpnomelane (dark) partially replaced by fine-grained green-biotite (grey) are enclosed in a matrix of white-mica, quartz and epidote (high relief). The biotite development is related to the second stage of the late-Alpine metamorphic event. Plane polarize light - 180 x.



Fig. 21. — Retrograded eclogitic micaschist (SL 1002). Cresta Rossa, upper Gressoney valley. In the most external Eclogitic Micaschists a narrow rim of oligoclase locally develops around the large helicitic albites grown coeval with the biotite. Crossed polars - 30 x.

schistosity in stable association with white-micas (mainly phengites), glaucophane, garnet, quartz, rutile and zoisite. In parascists of the Mt. Mucrone area, cm-sized crystals of isodiametric chloritoids retain alignments of fine-grained garnets developed from pre-Alpine biotite, suggesting their development later than garnets (Fig. 14). This is further supported by the occurrence in a schist of the same area of kyanite included in a chloritoid porphyroblast. However, due to the widespread occurrence of chloritoids in foliated rocks, where all the minerals appear to be coeval, it cannot be excluded that the chloritoid development could have occurred still during the first stage of the early-Alpine metamorphic event. (See also Gosso, 1977).

#### PUMPELLYITE

This mineral has been reported only from a few localities where also fresh lawsonite has been found, i.e. from the lower Valle dell'Orco (CARON & SALIOT, 1969) and from the Corio area (BIANCHI *et al.*, 1965).

Pale-green coloured pumpellyite develops either from zoisite aggregates after pre-Alpine Ca-plagioclase or from lawsonite. In the glaucophanites of Cuorné pumpellyite homoaxially overgrows lawsonite, before it alters to clinozoisite.

It is therefore later than lawsonite, but older than clinozoisite produced from lawsonite during the late-Alpine metamorphic event.

#### CARBONATES

In marbles and carbonate-bearing rocks both calcite and dolomite have been detected by X-rays. In eclogites only dolomite occurs as a primary mineral in equilibrium with omphacite, garnet, white-mica, rutile, epidote, glaucophane and pyrrhotite. In marbles carbonates are in coexistence with omphacite, zoisite, Mg-clorite, white-micas, graphite, quartz, Fe-sulphides and sphene.

No chemical analyses of carbonates are so far available; however it is probable that most dolomites contain in solid solution variable amounts of iron as inferred from their yellowish to red-brown colour on weathered surfaces.

Aragonite has never been found in the EMC; however, on the basis of data of the experimental petrology (see later on) it is very likely that it formed during the peak of the early-Alpine metamorphic event, but it completely inverted to calcite during later metamorphic evolution.

#### CHLORITES

Primary chlorites, developed during the peak of the early-Alpine metamorphic event, are Mg-rich end-members plotting in the clinocllore field (LIEBEAUX, 1975). They occur, as minor constituents, in marbles and metabasics, where they can be easily recognized for the low birefringence, positive optic sign and a characteristic repeated (001) twinning. In metamorphic gabbros from lower Valchiusella (COM-

PAGNONI & FIORA, 1976) they appear to develop mainly at the expense of magmatic biotite. In metabasics Mg-chlorite is in equilibrium with garnet, glaucophane, white-micas, quartz, zoisite and rutile; in marbles with carbonate minerals, phengite zoisite and possibly omphacite. Most chlorites occurring in the EMC, however, are

TABLE 1  
*Metamorphic evolution in the Sesia-Lanzo Zone*

MINERALS	PRE-ALPINE		ALPINE METAMORPHISM				VEIN MINERALS
	Schists and metabasics	Intrusives	Early - alpine event		Late-alpine event (Lepontine phase)		
K-feldspars							adularia
plagioclases	plagioclase	plagioclase			albite	albite	albite
biotite	reddish-brown	reddish-brown				green	yellowish-brown
muscovite							
garnet						Mn	
sillimanite							
clinopyroxene							
brown-hornbl.							
Kyanite							
chloritoid							
phengites							
paragonite							
jadeite							
omphacite							
chloromelan.							
aegirine - augite							
Na-amphiboles							
Ca-amphiboles							
epidotes	allanite		zoisite	clinozoisite		Fe-epidote	Fe-epidote
lawsonite							
pumpellyite							
stilpnomelane			Mg	Mg	Mg-Fe	Fe-Mg	Fe-Mg
chlorites							Fe
rutile							
sphene							
carbonates							
Fe-sulphides			pyrrhotite			pyrite	
zeolites							

Fe-richer end-members (LIEBEAUX, 1975) developed, during later metamorphic evolution, from destabilization of eclogitic minerals, particularly of garnets.

Secondary chlorites are characterized by distinct green pleochroism, anomalous interference colours and negative optic sign. They are in equilibrium with clinozoisite/epidote, albite, quartz, actinolite, sphene and possibly white-micas.

#### STILPNOMELANE

Though stilpnomelane has been found all over the Sesia-Lanzo Zone it is not very frequent in the EMC. Probably more than one generation of stilpnomelane

exists as previously suggested by DAL PIAZ *et al.* (1972). For peculiar textural features of its development, seemingly unrelated to destabilization of other minerals, its chronological position in the EMC metamorphic evolution is difficult to understand. However, on the basis of the observation that it develops during or immediately after the glaucophane destabilization, but before the biotite (see Fig. 20), the stilpnomelane occurring in the EMC can be placed at the end of the early-Alpine metamorphic evolution.

### Metamorphic evolution

Table 1 summarizes the Alpine metamorphic evolution of the EMC as inferred from microscopical observations of more than 3000 thin sections. Minerals of pre-Alpine assemblages are distinguished from Alpine parageneses. Five Alpine metamorphic stages have been recognized: three related to the early-Alpine and two to the late-Alpine metamorphic event; a stage of vein-filling minerals follows, later than the main folding phases which occurred in the EMC.

Mineral assemblages of the first early-Alpine and first late-Alpine stage are widely prevailing in the internal and external EMC respectively. On the contrary assemblages of the other metamorphic stages occur only locally, overprinting or overprinted by minerals of the other two stages.

The first stage of the early-Alpine metamorphic event is characterized by the development of jadeite + quartz (in felsic rocks of suitable bulk chemical composition) and omphacite (in all the other lithologies). Almandine-rich garnet, white-micas (mostly phengites), zoisite, glaucophane, Mg-chlorite, carbonates (Ca-carbonate and dolomite), rutile and Fe-sulphides. Kyanite developed as well but its occurrence appears to be limited to the pseudomorphs after sillimanite. Sphene grew only in marbles.

The later metamorphic stage is characterized by the development in metabasics of lawsonite in equilibrium with glaucophane and in micaschists of suitable bulk chemical composition of chloritoid + white mica  $\pm$  glaucophane. Most probably during this stage both glaucophane and white-micas largely recrystallized. Lawsonite however is not occurring all over the EMC but appears to be limited to its southern portion. At present however it has not been clarified if its limited distribution is due to the occurrence in the EMC of the isograd lawsonite-zoisite/clinozoisite or to the effect of different physical conditions (e.g. the water partial pressure).

The third stage is characterized by the complete destabilization of jadeites producing albite + aegirine-augite + blue-amphibole + clinozoisite/epidote; by the irregularly distributed development of stilpnomelane; by the local growth of pumpellyite in lawsonite-bearing metabasites. Crystallization of the platy variety of lawsonite from the Corio region can be tentatively assigned to this stage.

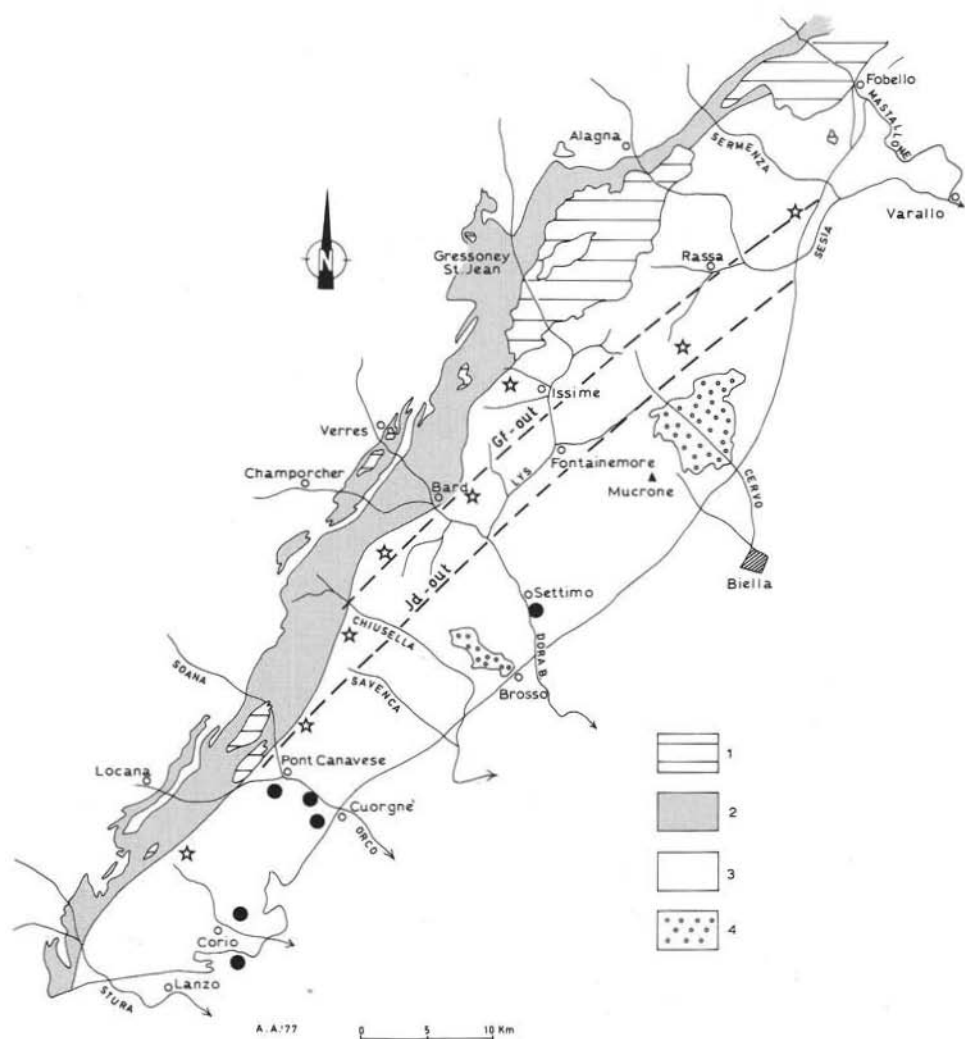


Fig. 22. — Metamorphic zonation in the Eclogitic Micaschist Complex. Stars: external limit of eclogite occurrences; dots: lawsonite occurrences. Dashed lines show the areal extent of the late-Alpine metamorphic overprinting as inferred from the jadeite-breakdown (Jd-out) and glaucophane-breakdown (Gf-out). Symbols 1 to 4 as in Fig. 1.

In conclusion the early-Alpine metamorphic evolution is characterized by mineral assemblages, which suggest a significant pressure decrease and a low to moderate temperature decrease. This evolution from initial « eclogitic » conditions (stage I) to metamorphic conditions of lower-pressure blueschists facies (stage III) is suggested: by progressive jadeite-content decrease of Na-pyroxenes following the trend jadeite/omphacite → omphacite → chloromelanite → aegirine/aegirine-augite; by the subsequent recrystallization of the amphiboles: glaucophane → glaucophane/

crossite → barroisite → actinolite; by the progressive iron-enrichment of epidotes from zoisites to pistacites through clinozoisites.

A temperature decrease is suggested by the development in internal EMC of lawsonite later than zoisite and of pumpellyite later than lawsonite, and by final growth of stilpnomelane. A similar temperature trend is further supported by the development of blueschists later than eclogites.

The early-Alpine metamorphic event is overprinted by the late-Alpine event in which two different stages have been recognized: a first one characterized by chlorite in equilibrium with quartz, albite, actinolite, clinozoisite/epidote, sphene, calcite and possibly white-mica; a second one characterized, in addition to the minerals just considered (chlorite excepted), by the widespread occurrence of yellow-brown biotite and locally by the incipient development of oligoclase rims around albites (Fig. 21).

Such a sequence of minerals suggest a moderate temperature increase from lower- to higher-grade greenschist-facies, under low pressure conditions, as inferred from the absence of an Alm-rich garnet (see WINKLER, 1976, p. 215).

The areal distribution and intensity of the late-Alpine metamorphic overprinting is visualized in Fig. 22. Two « isogrades » have been drawn and labelled *jadeite-out* and *glaucophane-out* respectively. On the internal side of each isograd, the quoted mineral can still be found in relics, whereas on the external side it is completely transformed and its primary occurrence can be inferred only owing to the presence of the typical albite-rich pseudomorphs (Fig. 18-19). From the relative position of the two isograds it is evident that jadeite is more sensitive than glaucophane to the temperature rise produced by Lepontine overprinting. The eclogites still occur within the most external EMC. They are usually surrounded by a retrograde shell of fine-grained albite-actinolite intergrowth, whose development armoures against further transformations the innermost eclogite core.

In conclusion, the early-Alpine metamorphic evolution of the EMC can be regarded as a continuous process characterized by initial high-pressure eclogitic conditions, followed by a significant pressure decrease and a moderate temperature decrease, leading to blueschist-facies conditions. The early-Alpine event is followed by a lower pressure event (late-Alpine or Lepontine) evolving from lower-temperature to higher-temperature greenschist-facies. This event occurred only in the external part of the EMC.

### **Inferred P-T conditions and petrological considerations**

Combining the previously described mineral assemblages with the phase equilibria known from the experimental petrology it is possible to define the physical conditions prevailing during the early-Alpine metamorphic recrystallization of the EMC.

*Lower limit of pressure* — During the climax of the early-Alpine metamorphic event jadeite + quartz instead of albite was the stable phase within the Eclogitic Micaschists of suitable bulk chemical composition. This conclusion, drawn on the ground of textural relationships, is in agreement with the results of the experimental petrology; in fact, since jadeite occurs in the EMC together with quartz, the equilibrium curve for the reaction albite  $\rightleftharpoons$  jadeite + quartz has been overstepped and therefore albite cannot survive.

The presence all over the EMC of jadeite + quartz instead of pre-Alpine albite can provide a minimal pressure for the climax of the early-Alpine metamorphic event. Adopting for the albite-breakdown reaction the equilibrium curve determined experimentally by BOETTCHER & WYLLIE (1968) pressures higher than 15-17 Kb result for temperatures between 500° and 600° C (Fig. 23).

*The upper temperature limit* can be inferred from the stability field of chloritoid.

In Fig. 23 we have reported the equilibrium curve for the reaction: chloritoid + quartz  $\rightleftharpoons$  staurolite + almandine + water (RICHARDSON, 1968), which can be reasonably considered as representing the upper stability limit of chloritoid in silica-oversaturated rocks. From such equilibrium curve temperatures lower than about 600° C can be inferred for pressures higher than the albite-breakdown.

Similar temperatures can also be inferred from VELDE's work (1965) on the limits of the solubility of celadonite in muscovites (= Phengites). From this study it appears that at high-pressures (greater than about 15 Kb) the solubility of celadonite in muscovite rapidly decreases as a function of increased T. Though the data of VELDE apply specifically only to the assemblages muscovite + biotite + K-feldspar + quartz + water, it seems reasonable that the celadonite content of phengites within the equivalent assemblages of the Eclogitic Micaschist Complex will also decrease as a function of temperature increase in a similar fashion. (See also GUIDOTTI & SASSI, 1976).

Therefore considering the maximum celadonite content (Ce = 50) observed in phengites of the EMC (VELDE & KIENAST, 1973), from the curves reported in Fig. 23, metamorphic temperatures lower than 550-600° C are expected.

*Lower temperature limit* — Because zoisite, instead of lawsonite, occurs widely all over the EMC, the upper stability limit of lawsonite can be used to infer a lower temperature limit. In Fig. 23 the equilibrium curve (extrapolated towards higher pressure) of the reaction: lawsonite  $\rightleftharpoons$  zoisite + margarite + quartz + water (NITSCH, 1974) is reported. Such reaction, although not relevant when dealing with metamorphism of basic rocks, is considered the maximum stability limit of lawsonite (WINKLER, 1976, p. 187). From this curve a lower temperature limit of about 500°-550° C can be inferred.

In conclusion, from the foregoing it appears that the climax of the early-Alpine metamorphic event in the EMC should have occurred at pressures higher than 15-17 Kb and temperatures between 500° and 600° C.



Such temperatures are in good agreement with the average value of 540° C obtained both from oxygen isotope measurements on quartz-rutile and quartz-muscovite pairs (DESMONS & O'NEIL, 1976) and from partitioning coefficients of  $Fe^{2+}$  to Mg in coexistent garnet and clinopyroxene of EMC eclogites (DESMONS & GHENT, 1976).

*Composition of the fluid phase* — During the eclogitic metamorphism of the Eclogitic Micaschist Complex the fluid phase predominantly consisted of water. This is proved by the widespread occurrence in all lithologies (but particularly in carbonate-bearing rocks) of Ca-Al minerals, such as zoisite or lawsonite (NITSCH, 1972; GHENT & DE VRIES, 1972; STORRE & NITSCH, 1972), whose stability field is severely limited by the presence of  $CO_2$  in the fluid phase. A very low  $CO_2$  pressure is further corroborated by the stable coexistence of quartz +  $CaCO_3$  instead of wollastonite and of sphene rather than rutile + quartz +  $CaCO_3$  (GREENWOOD, 1967; SCHUILING & VINK, 1967; ERNST, 1972). Moreover the presence of sulfur in the fluid phase is suggested by the occurrence in the mineral assemblages of iron sulphides rather than iron oxides.

*Fluid pressure versus load pressure* — Different considerations suggest that during the eclogitic metamorphism fluid pressure must have been lower than load pressure. Both experimental and thermodynamic data in fact indicate that eclogitic assemblage (garnet + omphacite + water) can be stable relative to amphibole only at very high water pressure i.e. above the breakdown curve of the amphibole (GREEN & RINGWOOD, 1967; ESSENE & FYFE, 1967). On the other hand FRY & FYFE (1969) and BRYNI et al. (1970) have shown that formation of eclogites at lower pressures (i.e. below the maximum stability limit of the amphibole for  $P_s = P_{H_2O}$ ) is possible only at water pressure significantly lower than load pressure. In Fig. 23 two curves of BRYNI et al. (1970) for the stability limit of amphibole for  $P_{H_2O} = P_s$  and  $P_{H_2O} = 2$  Kb respectively are reported. In both cases amphibolites are stable below, eclogites above the curve. From the curves it appears that to obtain eclogites from amphibolites at P-T conditions such as those inferred for the Eclogitic Micaschist Complex, water pressure should have been significantly lower than load pressure and in any case less than 2 Kb. This value however must be considered an average indicative value. Furthermore it is most probable that, due to the great difference between fluid pressure and load pressure, fluid pressure could have been very different in various environments, according to mechanical features of the rock and the occurrence of crystallizing hydrous minerals. As elsewhere suggested by FRY & FYFE (1969) it seems feasible that the conditions necessary for eclogite formation within the EMC could have been generated by suitable water buffering in environments, produced by coeval crystallization of hydrous minerals such as white-micas, epidotes and glaucophanes. Low water pressure is further suggested by the widespread occurrence of garnet rather than a compositionally equivalent hydrous assemblage (HSU, 1968; BURNHAM et al., 1969; GHENT & COLEMAN, 1973).

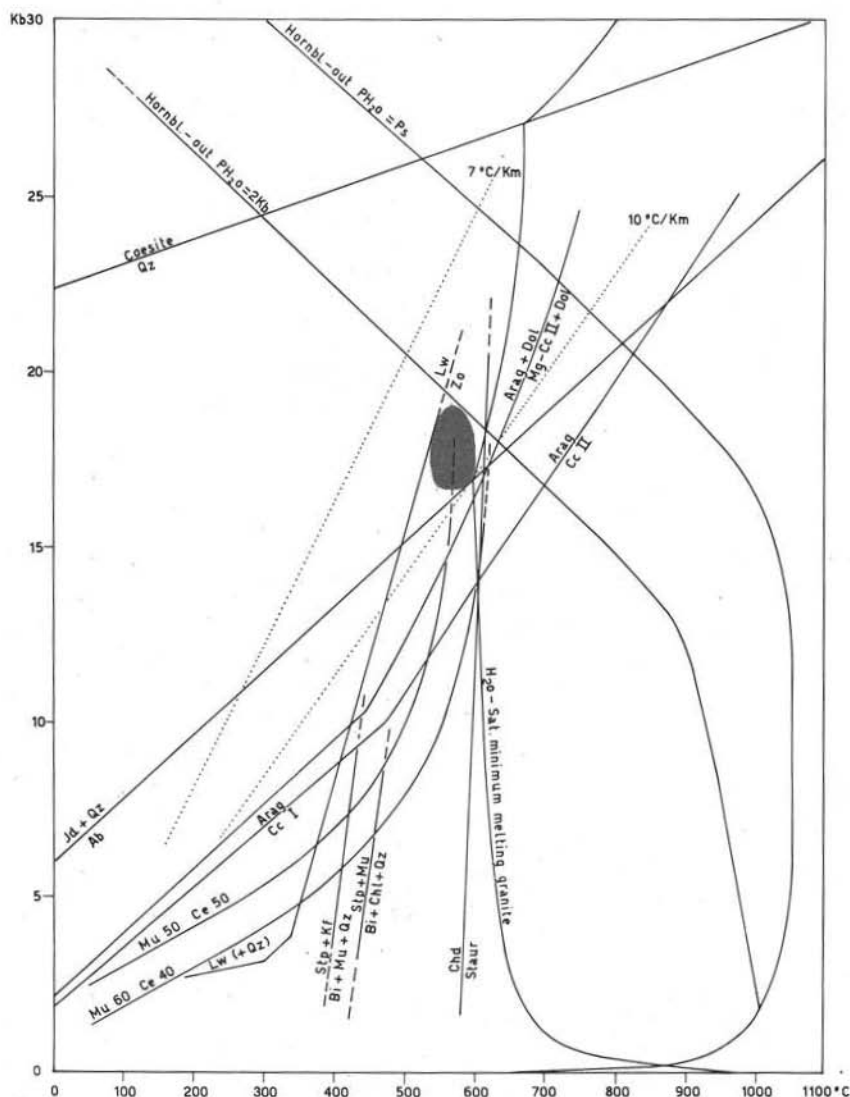


Fig. 23. — Stability fields for various minerals relevant to the metamorphism of the Eclogitic Micaschist Complex: the equilibrium curves for the reactions jadeite + quartz = albite, and coesite = quartz, and the minimum melting of water-saturated granite are from BOETTCHER & WYLLIE (1968); the position of calcite (I and II) = aragonite and Mg-calcite (I and II) + dolomite = aragonite + dolomite are taken from GOLDSMITH & NEWTON (1969); the upper stability limit of lawsonite, referred to the reaction: lawsonite = zoisite + margarite + quartz +  $H_2O$ , extrapolated towards high-pressures, is from NIRSCH (1974); the reaction: chloritoid + quartz = staurolite + almandine +  $H_2O$ , considered as representing the upper stability limit of chloritoid, is from RICHARDSON (1968); the two curves representing the thermal stability of phengites with compositions  $Mu_{50}Ce_{50}$  and  $Mu_{60}Ce_{40}$  are from VELDE (1965), extrapolated towards high-pressures; the upper stability limit of the stilpnomelane, according to the reactions: stilpnomelane + K-feldspar = biotite + quartz +  $H_2O$ , and stilpnomelane + muscovite = biotite + chlorite + quartz +  $H_2O$ , are taken from NIRSCH (1970). The P-T conditions inferred for the « eclogitic » metamorphism of the Eclogitic Micaschist Complex is shown by a shaded area

*The scarcity of kyanite and of potassium feldspar* — From the foregoing it is evident that the Eclogitic Micaschists recrystallized under P-T conditions well within the stability field of kyanite. Kyanite however is very rare, since it has been found only in structurally well preserved « kinzigites » as pseudomorphs after pre-Alpine sillimanite. Furthermore in such occurrences kyanite usually appears surrounded by a rim of a very fine-grained white-mica aggregate suggesting that kyanite has been replaced by phengite according the following ionic reaction (see EUGSTER, 1970):  $3 \text{ kyanite} + 3 \text{ quartz} + 2 \text{ K}^+ + \text{H}_2\text{O} = 2 \text{ muscovite} + 2 \text{ H}^+$ . In the same rocks potassium feldspar as well appears partially replaced by white-mica + worm-like quartz according a reaction which can be written (see HEMLEY, 1959; HELGESON, 1967, 1969):  $3 \text{ orthoclase} + 2 \text{ H}^+ = \text{muscovite} + 6 \text{ quartz} + 2 \text{ K}^+$ .

Therefore because in pervasively reworked « kinzigites » both kyanite and potassium feldspar are usually lacking the following general reaction can be proposed:  $3 \text{ sillimanite (or kyanite)} + 3 \text{ orthoclase} + \text{H}_2\text{O} = 3 \text{ muscovite} + 3 \text{ quartz}$ , to account both for the inhibited development of kyanite and the disappearance of potassium feldspar.

From experimental petrology in fact potassium feldspar does not transform until about 100 Kb in the absence of water (RINGWOOD et al., 1967) and up to 20-25 Kb under high water pressure for temperatures around 500-600° C (SEKI & KENNEDY, 1964).

*The absence of aragonite* — On the basis of experimental and thermodynamic data, the Ca-carbonate stable under the P-T conditions inferred for the metamorphism of the Eclogitic Micaschist Complex should have been aragonite (see e.g. BOETTCHER & WYLLIE, 1967, 1968; KUNZLER & GOODELL, 1970; CRAWFORD & HOERSCH, 1972). This is true even though the stability field of the calcite is enlarged due to the presence of  $\text{MgCO}_3$  in solid solution (GOLDSMITH & NEWTON, 1969). From the first finding of COLEMAN & LEE (1961) in Californian Franciscan Formation, metamorphic aragonite has been reported from many blueschist belts all over the world. However, in spite of careful investigations only calcite has been found in the EMC.

BROWN et al. (1962) studying the kinetics of the aragonite-calcite transformation have noticed that the reaction rate rises exponentially with temperature for pressures close to the inversion curve: thus, whereas at low temperatures (200 to 300° C) aragonite can metastably survive unloading for times of the order of the geological periods, at temperatures of about 400° C aragonite completely inverts to calcite in a time of about 100 years.

From the foregoing it can be concluded therefore that aragonite most probably formed during the early-Alpine metamorphic event, but completely inverted to calcite during later unloading.

*The coexistence of chloritoid and glaucophane* — The assemblage chloritoid + glaucophane ( $\pm$  garnet) very rarely occurs in other blueschists belts (see ERNST,

1963); this mineral association, on the contrary, is rather common in Western Alps both in the Sesia-Lanzo Zone and in the Penninic domain (see BOCQUET, 1971; NIGGLI & NIGGLI, 1965; BEARTH, 1967; BOCQUET, 1974). The problem has been recently clarified by KIENAST & TRIBOULET (1972), who considered the stability field of chloritoid and glaucophane in the simplified system  $\text{Na}_2\text{O}-\text{Al}_2\text{O}_3-\text{MgO}$ , also taking into consideration their natural occurrences. The calculated univariant curves indicate that the assemblage chloritoid + glaucophane is stable in a large range of high P-T conditions in the stability fields of both lawsonite and zoisite. Negative slope of the curves, furthermore, shows that lower is the temperature the higher is the pressure necessary to stabilize the association. Therefore this assemblage is unlikely to occur in lower-temperature blueschist belts, owing to the extremely high pressures required, but it can widely develop in higher-temperature blueschists such as the Sesia-Lanzo Zone.

### Conclusions

Phase compatibilities, oxygen isotope ratios and partitioning coefficients of Mg and Fe indicate that the EMC recrystallized at temperatures between 500° and 600° C and pressures in excess of 15-17 Kb, corresponding to a lithostatic load of approximately 50-60 Km.

Such physical conditions, rather uncommon for the earth's crust, require a low geothermal gradient of less than 10° C/Km. Similar gradients have been inferred for the metamorphism of other blueschists belts, such as the Franciscan Formation of California (COLEMAN & LEE, 1963; ERNST et al., 1970).

The temperatures inferred for recrystallization of the EMC correspond to the highest temperatures so far obtained for glaucophane-bearing metamorphic rocks; temperatures of the order of 500° C have been defined by oxygen isotope analysis only for the highest-grade blueschists of New Caledonia and Type IV tectonic blocks from California (COLEMAN & LEE, 1963; COLEMAN et al., 1965; TAYLOR & COLEMAN, 1968). However, the New Caledonia blueschist belt is characterized by lower metamorphic pressures; this is suggested by regional development of albite, which indicates that the rocks have recrystallized below the albite-breakdown equilibrium curve (BROTHERS & BLAKE, 1973; BLACK, 1974). Likewise, for Type IV Californian eclogites only a pressure limit « most probably in excess of 7 Kb » could be inferred (TAYLOR & COLEMAN, 1968). In conclusion both pressure and temperature under which the EMC recrystallized result the highest so far recorded for blueschist metamorphic belts.

Structurally the EMC represents a polymetamorphic basement re-equilibrated under eclogitic conditions during the early-Alpine metamorphic event, which preserved its identity (structural integrity) during the whole Alpine tectono-metamorphic evolution. For this reason eclogites from the Sesia-Lanzo Zone are

found in their primary position as layers or lens-like bodies interbedded in a continuous sequence, where lithologies ranging from metapelites to amphibolites and from acid to basic intrusives still preserve a cofacial, eclogitic imprint. This occurrence of a complete spectrum of crustal lithologies with eclogitic assemblages raises again the problem of the existence of the « eclogite facies » (ESKOLA, 1921, 1939) removing one of the main objections relative to the occurrence in this facies of only basic rocks, acid and intermediate types being essentially absent.

In the EMC there is clear textural evidence that hydrous minerals (such as white-micas, glaucophanes, Mg-chlorites and zoisite) or carbonates did not develop during « the latest phases of retrogressive metamorphism of eclogites » as, for example, suggested by DOBRETsov et al. (1974, p. 159) but they have grown at the same time of the eclogitic assemblage. Similar conclusions were also drawn by SMULIKOWSKI (1960, 1964, 1967) for the eclogites of the Snieznick Mountains migmatites and by COLEMAN et al. (1965) and COLEMAN & GHENT (1973) for the eclogites associated to blueschists of California and Oregon respectively.

Furthermore, unlike most eclogites (which appear to have formed at the expense of dry materials) the eclogitic rocks of the EMC formed from rocks containing hydrous minerals (biotite, hornblende, muscovite). In particular there is field and textural evidence that eclogites can form at the expense of amphibolites within the amphibole (hornblende) stability field, provided  $P_{H_2O}$  is significantly lower than  $P_n$ .

In this respect primary growth of hydrous phases in eclogites appears of great importance for the development of the eclogitic minerals by buffering  $F_{H_2O}$  at low values.

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