High-pressure metamorphism in a ferrogabbro from Fenestrelle (Western Italian Alps)

Autor(en): **Otten, Max T. / Brouwer, Henk**

Objekttyp: **Article**

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

Band (Jahr): **59 (1979)**

Heft 3

PDF erstellt am: **22.09.2024**

Persistenter Link: https://doi.org/10.5169/seals-46066

Nutzungsbedingungen

Die ETH-Bibliothek ist Anbieterin der digitalisierten Zeitschriften. Sie besitzt keine Urheberrechte an den Inhalten der Zeitschriften. Die Rechte liegen in der Regel bei den Herausgebern.
Die auf der Plattform e-periodica veröffentlichten Dokumente stehen für nicht-kommerzielle Zwecke in Lehre und Forschung sowie für die private Nutzung frei zur Verfügung. Einzelne Dateien oder Ausdrucke aus diesem Angebot können zusammen mit diesen Nutzungsbedingungen und den korrekten Herkunftsbezeichnungen weitergegeben werden.
Das Veröffentlichen von Bildern in Print- und Online-Publikationen ist nur mit vorheriger Genehmigung der Rechteinhaber erlaubt. Die systematische Speicherung von Teilen des elektronischen Angebots auf anderen Servern bedarf ebenfalls des schriftlichen Einverständnisses der Rechteinhaber.

Haftungsausschluss

Alle Angaben erfolgen ohne Gewähr für Vollständigkeit oder Richtigkeit. Es wird keine Haftung übernommen für Schäden durch die Verwendung von Informationen aus diesem Online-Angebot oder durch das Fehlen von Informationen. Dies gilt auch für Inhalte Dritter, die über dieses Angebot zugänglich sind.

Ein Dienst der *ETH-Bibliothek*
ETH Zürich, Rämistrasse 101, 8092 Zürich, Schweiz, www.library.ethz.ch

http://www.e-periodica.ch

Schweiz. mineral. petrogr. Mitt. 59, 281–297, 1979

High-pressure metamorphism in a ferrogabbro from Fenestrelle (Western Italian Alps)

by *Max T. Otten** and *Henk Brouwer**

Abstract

The alpine metamorphism of the ferrogabbro took place in three stages, the eclogite, glaucophane-schist and greenschist stages. The two early stages developed under high-pressure conditions, the greenschist stage at lower pressures. Deformation during these stages provided channelways for the supply of fluid phases, which were necessary for the metamorphism. The eclogites are envisaged to have formed because the early supply of water was used for the oxidation of ferrous iron. When the oxidation reactions were completed, the fluid pressure could build up and glaucophane formed. It is concluded that subduction provided the high-pressure conditions for the early alpine metamorphism and that later deformation at a higher level in the crust caused the greenschist stage metamorphism.

Introduction

Ferrogabbros with their characteristic high iron and TiO_2 content are well-known from some mafic layered intrusions, where they form differentiation products of tholeiitic magmas (Wager and Brown, 1968). Only recently have these rocks been documented from strongly dismembered ophiolites in the Western Alps (Boy et al., 1976; Cortesogno et al., 1977a; Mottana and Bocchio, 1975; Piccardo, 1977; Ohnenstetter et al., 1975; Rocci et al., 1976), in the Apennines (Cortesogno et al., 1975, 1977b; Gianelli and Principi, 1974) and from a few dredge hauls in the Atlantic (Miyashiro et al., 1970) and Indian Oceans (Engel and Fisher, 1975). Rocks with comparable composition have been found in the Franciscan blueschist terrain of Oregon, but were thought to be metasomatized basalts because of their unusual chemistry (Ghent and Coleman, 1973). Ferrogabbros have never been found in the more or less complete and well-studied ophiolite complexes in Newfoundland, Cyprus, Oman and

* Vakgroep PMKGB, Instituut voor Aardwetenschappen, Budapestlaan 4, Postbus 80021, 3508 TA Utrecht, the Netherlands.

Papua New Guinea, which follow a more calc-alkaline differentiation trend (COLEMAN, 1977).

The metaferrogabbro encountered during field mapping in the Western Alps by students from Leiden University generally shows a strong imprint by high-pressure metamorphism, whereas the later greenschist metamorphism is weak. As a consequence these rocks elucidate the processes that have led to the development of the eclogites and glaucophane schists in the early stages of alpine metamorphism. The purpose of this paper is to describe the development of the alpine metamorphism with emphasis on the high-pressure stages and to present a model for the petrogenesis of the eclogites.

Geological setting

In the Western Alps several tectonic units have been recognized (DEBELMAS and LEMOINE, 1970; FREY et al., 1974) of which the Penninic domain is the most internal. The Piemonte zone is the innermost unit in the Penninic domain and consists of a basement formed by the internal crystalline massifs of Dora Maira, Gran Paradiso and Monte Rosa and the overlying Schistes lustrés unit (nappe). The area in which the metaferrogabbro occurs, lies near the northwestern margin of the Dora Maira massif (Fig. 1). This massif forms an elliptical dome of Hercynian metamorphic rocks and granites and some Late-Palaeozoic and Early-Triassic cover rocks. The overlying Schistes lustrés unit comprises the Mesozoic metasediments of the Schistes lustrés s.s. and the mafic and ultramafic ophiolitic rocks. The metasediments are marbles and calcschists with locally typical deep-sea sequences of metachert, micritic marble and shale. The ophiolitic rocks comprise serpentinites, metagabbros, metabasalts and the recently found metaferrogabbros. Except for some larger massifs, such as Rocciavrè and Monviso, the ophiolitic rocks occur as dispersed lenses in the Schistes lustrés, with which they have become intermingled in an early stage of the alpine orogeny.

In the Schistes lustrés near the Dora Maira massif three generations of mesoscopic deformation structures have been found (CARON et al., 1973; CARON, 1977). The first generation comprises isoclinal folds with an axial plane schistosity. This generation postdates the emplacement of the Schistes lustrés nappe into its present surroundings. The second generation comprises isoclinal to tight folds, also with an axial plane schistosity. The latter may be a crenulation cleavage, but more often extreme transposition has destroyed all traces of the earlier foliation. The fold axes of the second generation are approximately E-W, the schistosity has a gentle dip to the west. The strong regional schistosity is a second generation structure. The third generation comprises open folds with a coarse axial plane fracture cleavage or rarely an axial plane crenulation

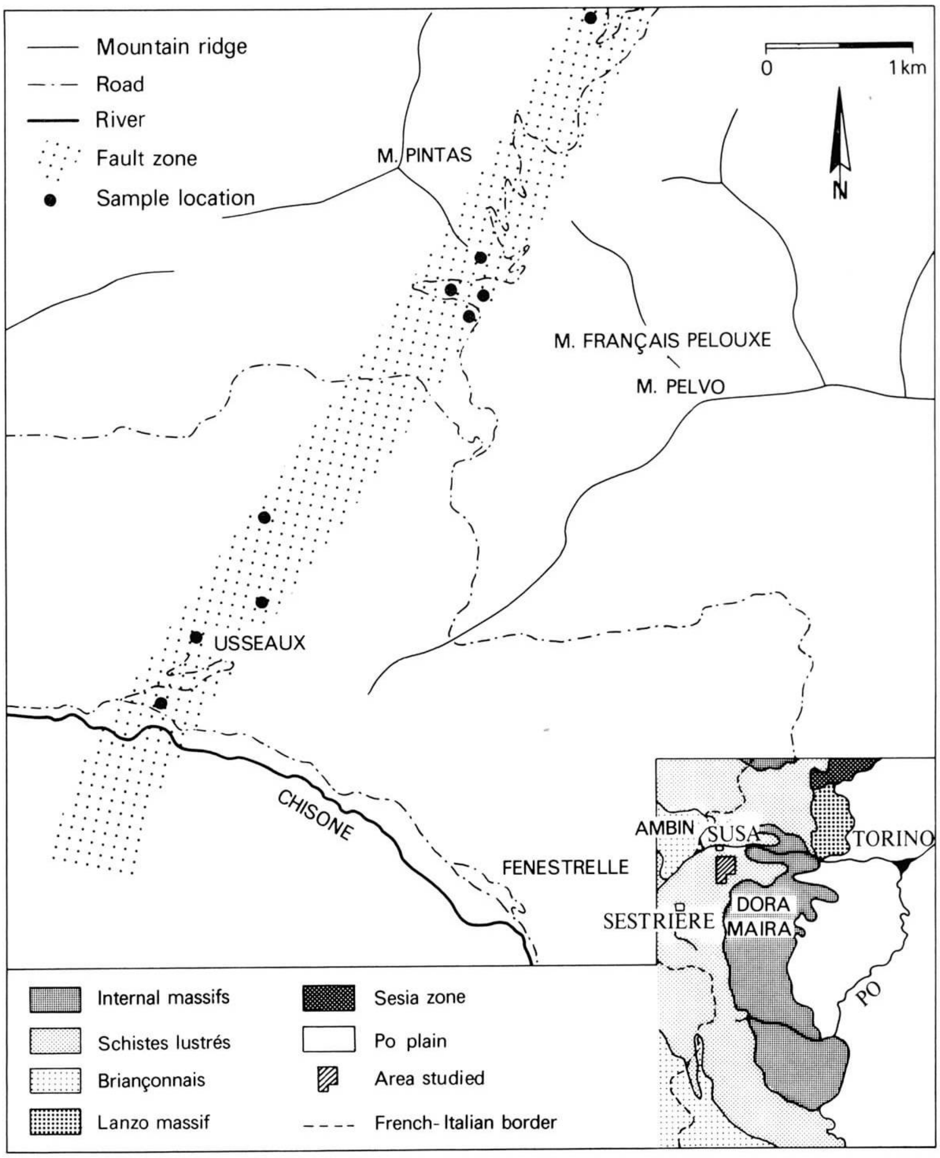

Fig. 1: Locality of the ferrogabbro in the fault zone near Fenestrelle. The inset shows the position of the area studied in the Western Alps.

cleavage. The fold axes are approximately N-S, the axial plane has a steep dip to the west. CARON (1977) has shown that peaks of metamorphism coincide with the first and second deformation generations and that metamorphism continued between these peaks. The early metamorphism is characterized by glaucophane-schist facies parageneses, the later by those of the greenschist facies. The later metamorphism is well-developed near the Dora Maira massif and decreases in intensity towards the west.

Nowhere in the Alps are ferrogabbros found in a normal stratigraphic position on top of gabbroic rocks, but they form intrusive lenses in serpentinites (CORTESOGNO et al., 1977a; MOTTANA and BOCCHIO, 1975), dykes in gabbros

(Bortolami and Dal Piaz, 1970, 142–143) or fragments in an oceanic fault breccia (Bortolotti and Gianelli, 1976; Gianelli and Principi, 1974).

In the area studied the metaferrogabbro outcrops in a NW-SE trending fault zone in the Schistes lustrés. The fault zone forms an important boundary between two lithostratigraphic series in the Schistes lustrés (Caron, 1977). Its activity must have persisted till late in the alpine history, as evidenced by shear planes truncating the regional schistosity and the brecciation of ovardites (albite-chlorite-greenschists belonging to greenschist substage C). Third generation folds are well-developed near the fault zone and may be related genetically.

The metaferrogabbro occurs together with serpentinite, metabasalt and Schistes lustrés. The relations with these other rocks are obscure, due to poor exposure and metasomatic actinolite-chlorite-calcite reaction zones at the contact with the calcareous Schistes lustrés. The overprinting of the early metamorphic stages by later ones in the metaferrogabbro increases towards contacts with other rocks. Sometimes eclogite and glaucophane-schist assemblages occur in boudins up to 1 metre, which lie in greenschist matrix. The distribution of the parageneses on a small scale is very irregular though and most rocks consist of variable amounts of these parageneses, usually in alternating thin layers or in small patches. Because of this variability the rock nomenclature is very difficult and therefore 'metaferrogabbro' is used as a collective name throughout this paper.

The imprint of deformation on the metaferrogabbro is generally weaker than in the Schistes lustrés and deformation structures could not be correlated with any of the deformation generations mentioned above.

Petrography

The division of the metamorphism into the eclogite stage, the glaucophane-schist stage and the greenschist substages A, B and C is based on the reaction series augite - chloromelanite - glaucophane - blue-green hornblende - actinolite and the subsequent alteration of Ca-silicates to chlorite and calcite (greenschist substage C). In Figure 2 the metamorphic parageneses of the stages are presented.

Five rock types may be distinguished in the field:

Massive eclogite. These are dark green rocks with coarse green pyroxenes, concentrations of small red garnets and patches of ilmenite and rutile. The pyroxenes are pseudomorphs after magmatic augite and outline the former magmatic texture. Small white patches, consisting of greenschist-stage minerals, occur locally;

Flaser eclogites. These are foliated rocks with green pyroxene augen in a matrix of irregular thin green and white layers. The pyroxenes are again pseudo-

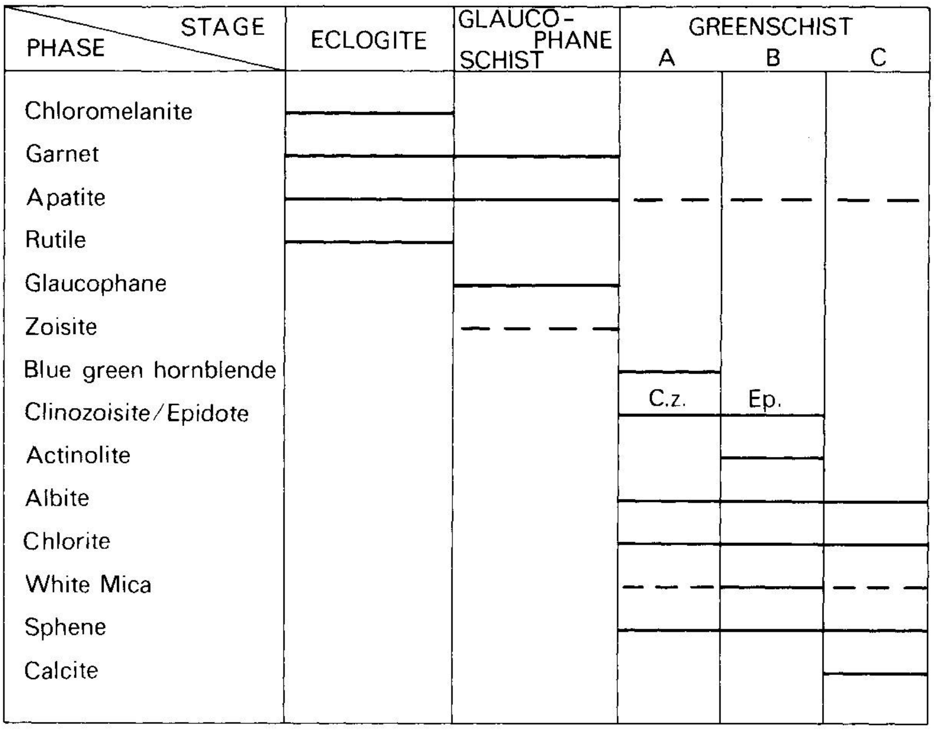

Fig. 2: Parageneses of mineral phases in the metamorphic stages in the ferrogabbro. Uncertainties are indicated by broken lines.

morphed augites and they show strongly developed cracking and boudinage. The green layers consist of eclogite-stage minerals and are mantled by thin rims of very fine-grained blue-green hornblende symplectites. The white layers are zoned and consist of greenschist-stage minerals. The centre of the layers consists of substage-A assemblages, the margins of substage B;

*Glaucophane schists.*These are blue-black foliated rocks, which contain yellowish patches. Blue-black amphiboles form a distinct lineation. In thin section coarse-grained glaucophane s.s., pseudomorphic after augite, occurs in a matrix of crenulated crossite needles. The yellowish patches consist of the greenschist-stage epidote, albite and white mica;

Greenschists. These are massive or weakly foliated fine-grained rocks consisting of albite, chlorite, epidote and blue-green hornblende and/or actinolite (prasinites) or essentially of albite and chlorite (ovardites). Locally stilpnomelane may be abundant, up to 30 vol% , replacing chlorite and amphiboles. Greenschist-stage metaferrogabbros are difficult to distinguish from metabasalt greenschists unless augite pseudomorphs are still visible;

Actinolite-chlorite-calcite rocks. These rocks are always developed at the contact with the Schistes lustrés. They contain conspicuous coarse-grained green amphiboles, which may have a preferred orientation.

MAGMATIC STAGE

The only magmatic minerals still present are augite, ilmenite and pyrite. Plagioclase is always replaced completely by assemblages of chloromelanite and garnet (eclogite stage) or of albite, white mica and epidote-group minerals (greenschist stage). *Augite* occurs as strongly corroded relics in some eclogites. In a few well-preserved grains submicroscopic lamellae have been observed parallel to (001), that are probably exsolved Ca-poor pyroxene. During the eclogite stage a set of broader lamellae formed. These are more irregular and consist of submicroscopic chloromelanite needles, which lie parallel to the c-axis of the augite (Fig. 3). Possibly they formed by topotactic replacement starting on the augite - Ca-poor pyroxene interfaces. Where these lamellae are well-developed a pronounced hatching is visible, sometimes producing herringbone patterns, where (100) twins are present (Fig. 4). Augite is deformed especially in the flaser eclogites, where it may be boudinaged and fragmented.

Ilmenite, which formed an abundant interstitial phase in the ferrogabbro, may be replaced by fine-grained aggregates of rutile, which encloses hematite along its partings, during the eclogite stage or by sphene at a later stage. *Pyrite* is always mantled by a hematite rim.

ECLOGITE STAGE

The eclogite paragenesis is made up of chloromelanite, garnet, apatite and rutile. *Chloromelanite,* a sodic clinopyroxene rich in ferric iron, is the most abundant phase, forming up to 90 vol% in some eclogites. Chloromelanite occurs in pseudomorphs after augite and in almost monomineralic layers and aggregates. In the pseudomorphs it shows several modes of occurrence:

- submicroscopic needles parallel to the c-axis of the augite. These needles are most abundant in the aforementioned lamellae, but occur also between these and in some instances the whole augite is altered to a symplectite of chloromelanite needles and very fine-grained exsolved ilmenite and hematite grains. Some of the pseudomorphs are mantled by a rim consisting of a single continuous homoaxial grain. The hatching in the pseudomorphs is usually preserved;
- homoaxial grains with the c-axis common with augite. These grains are large and have a ragged outline. They are heterogeneously clouded with inclusions, which often delineate the hatching. Among these inclusions are the submicroscopic chloromelanite needles described above. Sometimes a rim occurs, which is richer in the jadeite-component;
- small clear grains. They occur in pseudomorphs of both types mentioned

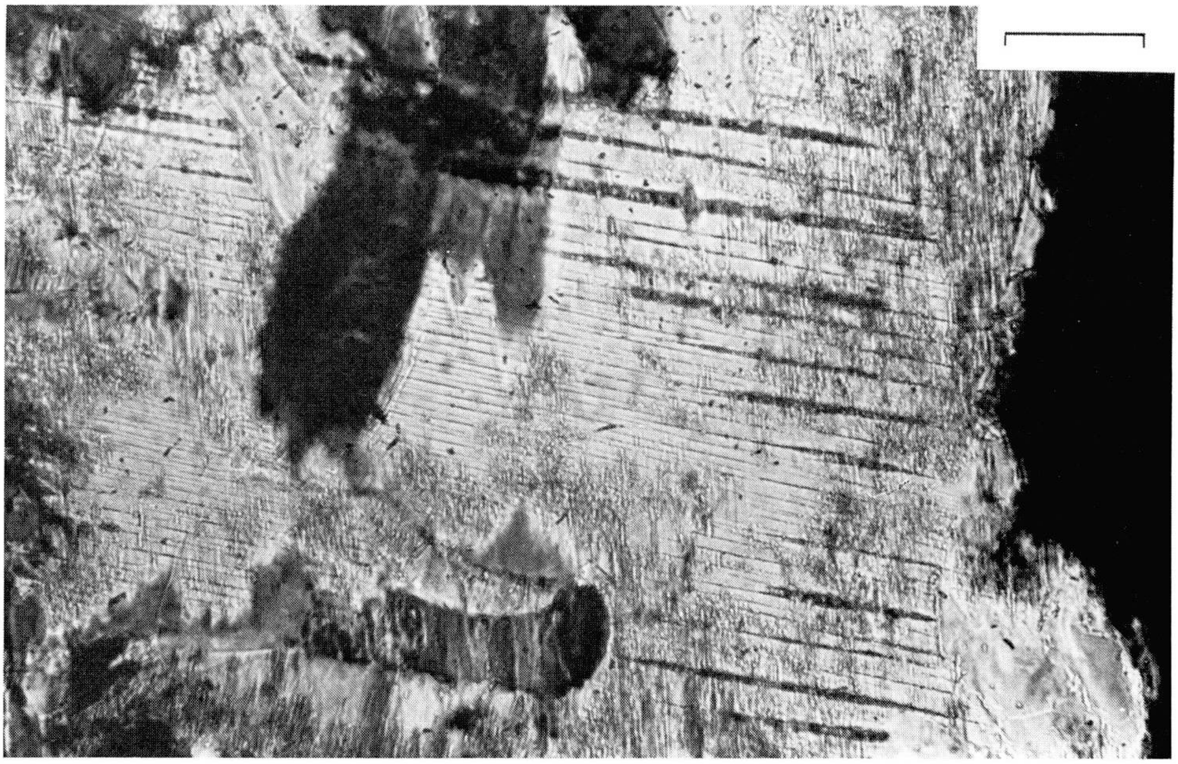

Fig. 3: Two sets of lamellae parallel with (001) in magmatic augite. The first set is fine and consists probably of exsolved Ca-poor pyroxene. The second set is broader and consists of chloromelanite needles. Note also the chloromelanite needles between the lamellae. Parallel nicols, scale mark is 0,045 mm.

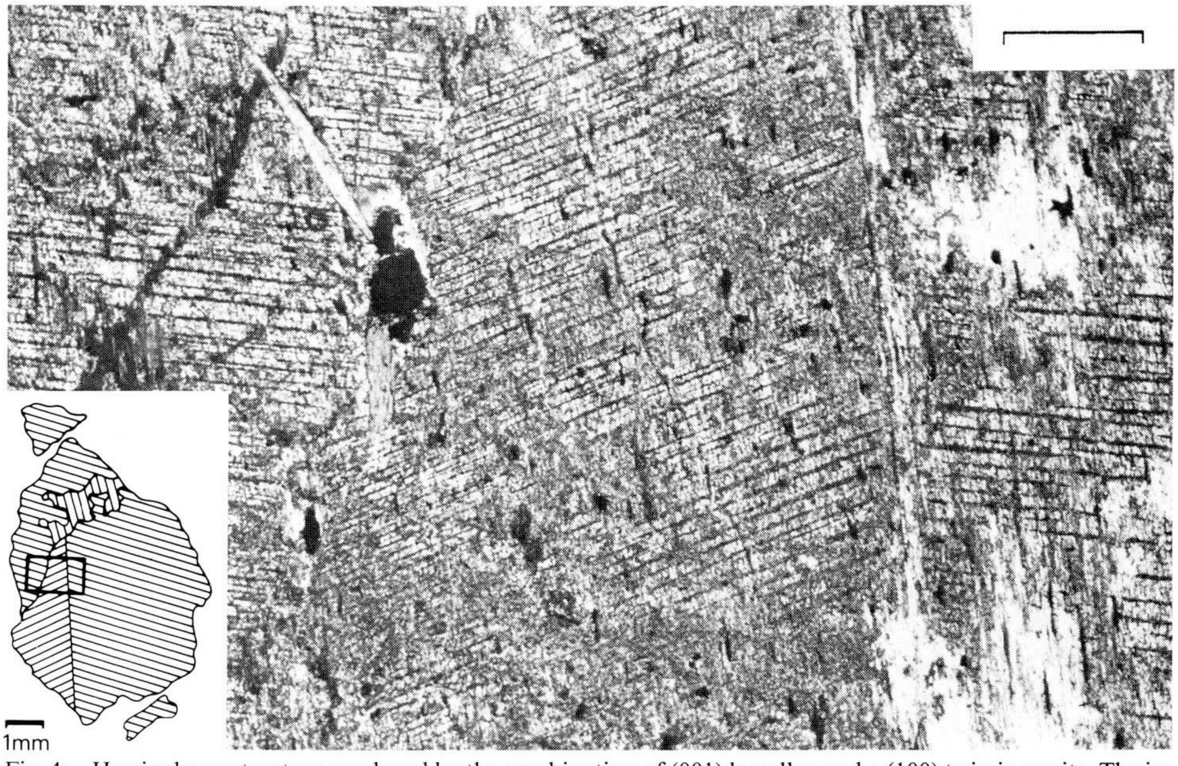

Fig. 4: Herringbone structure produced by the combination of (001) lamellae and a (100) twin in augite. The inset shows the relation between the twins, the rectangle represents the position of the micrograph. One twin is wedge-shaped and is surrounded by the other. The straight interface on the right is the (100) twinning plane, the left interface is irregular. At the point of the wedge-shaped twin another interlocking augite grain is visible. Crossed nicols, scale mark in the micrograph is 0,2 mm.

above, are hypidioblastic and lie oblique to the augite c-axis, sometimes in two sets symmetrical about the c-axis.

Where augite is fragmented elongate chloromelanite grains form comb structures (SPRY, 1969) in pressure fringes and cracks, indicating the syntectonic nature of the eclogite stage. The layers and aggregates consist of interlocking grains with irregular grain boundaries. Microstructures and grainsize vary considerably between the aggregates or layers, even in the same sample. The grains may show a preferred orientation or be unoriented, locally they lie in sheafs. Some grains have a core, consisting of a symplectite of oriented needles, suggesting they replaced augite. In larger grains zoning may be conspicuous, often it is oscillatory. The grainsize varies from submicroscopic to coarse, but it is approximately constant within the same aggregate or layer.

Garnet occurs as idioblastic grains of pink colour or the often strongly cracked and altered remains of these. It is often concentrated in patches. Usually the grains are clear, but occasionally they have a core, which is clouded with submicroscopic inclusions. The grainsize rarely exceeds 1 millimetre. Electron microprobe profiles, which show a two-stage zoning with a rather sharp break, and inclusions of chloromelanite in the core and glaucophane in the rim indicate that garnet formed during the eclogite and the glaucophane-schist stages.

GLAUCOPHANE-SCHIST STAGE

Although glaucophane occurs widespread as an accessory or minor constituent of eclogites, real glaucophane schists are rare. The paragenesis is made up of glaucophane, garnet, apatite and possibly zoisite. The latter is difficult to place in the sequence, but must predate the greenschist stage as it is altered to clinozoisite, which belongs to greenschist substage A.

Glaucophane ('glaucophane' refers to the group of sodic amphiboles, 'glaucophane s.s' to the specific member of this group) occurs as coarse homoaxial grains, pseudomorphing augite (with common c-axis), or as smaller grains both inside pseudomorphs and in the rock matrix. The homoaxial grains have irregular grain boundaries and enclose ilmenite grains, which are larger than those in pseudomorphs consisting of chloromelanite (Fig. 5). These inclusions indicate continued exsolution or segregation of material, which exsolved when chloromelanite replaced augite. The smaller glaucophane grains are either hypidioblastic with well-developed prismatic faces or are xenoblastic. They occur invariably inside chloromelanite pseudomorphic after augite or in the middle of chloromelanite aggregates. Unlike the later blue-green hornblende the glaucophane has not been observed to mantle the pyroxene.

The grain boundaries of xenoblastic grains often protrude between adjacent chloromelanite grains, indicating that the alteration of chloromelanite was

Fig. 5: Crossite, formed by alteration of chloromelanite, pseudomorphic after augite, encloses a few ilmenite grains. On the left side small crossite grains are visible in a matrix of corroded chloromelanite relics. Parallel nicols, scale mark is 0,6 mm.

easiest along its grain boundaries. Oriented inclusions, which exsolved when chloromelanite replaced augite, may continue through small idioblastic glaucophane in a pseudomorph consisting of chloromelanite. These features indicate that glaucophane formed after the eclogite stage. Glaucophane is generally clear and the hatching in augite pseudomorphs is obliterated. Zoning, which occurs frequently, is very irregular (Fig. 5). Only rarely concentric zoning is visible with increasing crossite content towards the rim. The transition between the core of glaucophane s.s. and the crossite rim is rather sharp.

The schistosity formed by crossite, which was crenulated at a later stage, provides an indication of the syntectonic nature of the glaucophane-schist stage. Although the preferred orientation may have formed either through oriented growth or through postcrystalline rotation, the latter seems improbable in the almost monomineralic crossite layers, which form the schistosity.

Zoisite occurs in a few flaser eclogites in the centre of the white layers as very fine-grained prismatic idioblasts or as rounded relics in clinozoisite.

GREENSCHIST STAGE

This stage is complex and is divided into three substages. Substage A is characterized by blue-green hornblende + clinozoisite, B by actinolite + epidote and C by the alteration of Ca-silicates to calcite and chlorite, producing ovardites. The paragenetic relationships of the greenschist stage are very difficult to decipher since members of the same mineral group, such as the amphiboles, tend to mantle each other, thereby obscuring any relationships with other mineral groups. Because of the scarcity of this stage in the metaferrogabbro some information has been extrapolated from nearby metabasalts.

Blue-green hornblende (sodic-calcic amphibole in the classification of LEAKE [1978]) occurs in several modes:

- in rims of variable thickness around glaucophane;
- as extremely fine needles in a symplectite with albite, replacing chloromelanite. In general this symplectite only rims chloromelanite grains or aggregates or occurs along cracks, but in some instances the whole rock consists of the symplectite with interspersed garnet relics, apatite and rutile;
- in aggregates of homoaxially oriented needles, that form pseudomorphs after augite. In these the hatching is still visible, formed by thin layers of needles with lighter colour and smaller extinction angle (actinolite?) (Fig. 6). Some zoning occurs with increase of pleochroism towards the rim.

Actinolite occurs predominantly in the metasomatic reaction zones at the contacts with the Schistes lustrés. Where actinolite occurs in the metaferrogabbro all traces of pre-substage B minerals have disappeared, but in many meta-

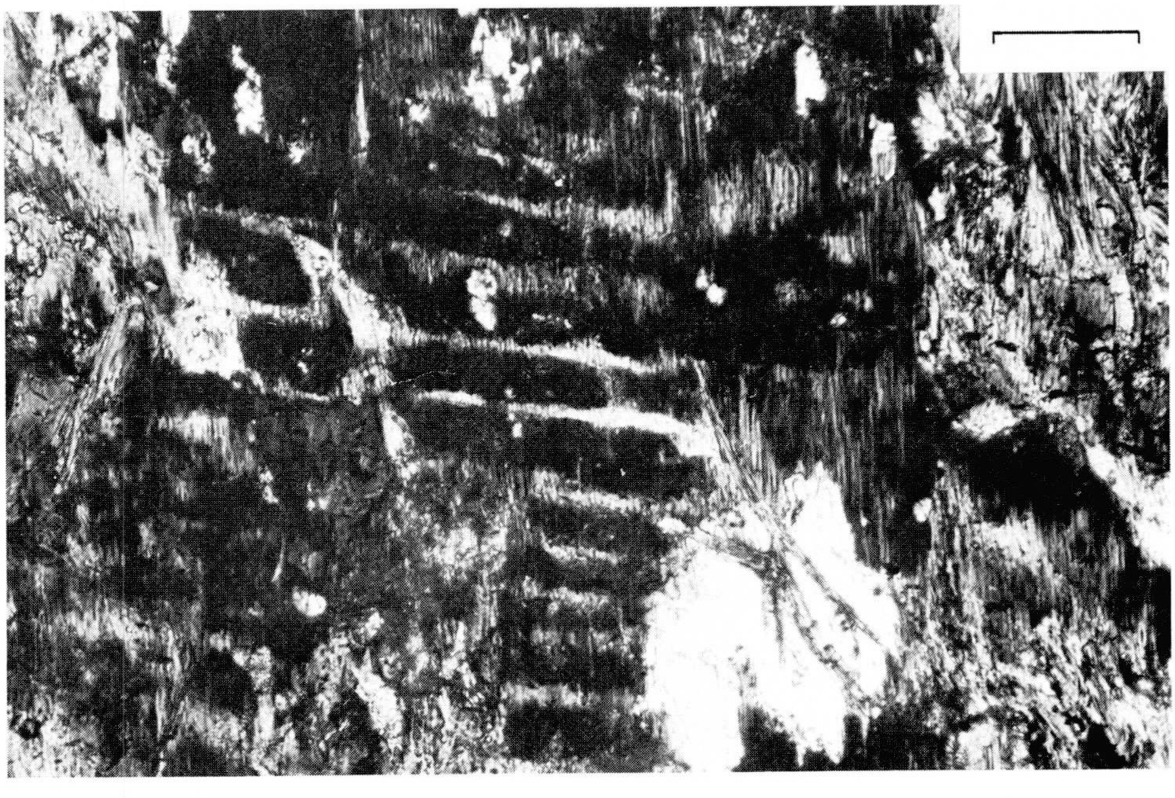

Fig. 6: Preservation of the hatching of augite as bands of amphibole needles with a smaller extinction angle (light) in blue-green hornblende (in extinction). Crossed nicols, scale mark is 0,045 mm.

basalts it is found as a rim around the blue-green hornblende and there it is associated with epidote, albite and chlorite.

Epidote-group minerals comprise clinozoisite and epidote (pistacite). The clinozoisite, which is xenoblastic and often mantled by a thin rim of epidote, occurs in the centre of the white layers in flaser eclogites. Epidote, which is distinctly coarser-grained and hypidioblastic, occurs at the margins of these layers. *Albite*,which occurs throughout the layers, also shows an increase in grainsize and becomes less poikiloblastic towards the margins of the layers. In the few real-greenschist metaferrogabbro samples epidote predominates, rarely with a small core of clinozoisite.

Stilpnomelane occurs generally as an accessory, but locally is present in larger amounts. It is found in characteristic sheaf-like aggregates and replaces chlorite, blue-green hornblende and glaucophane. The replacement of chlorite, occurring in a vein together with albite and calcite (greenschist substage C), shows that stilpnomelane formed after the greenschist stage. The reason for its formation is still enigmatic.

Actinolite in the metasomatic reaction zones often has a strong preferred orientation. As postcrystalline rotation of the long needles (up to a few centimetres) is unlikely, the orientation provides an indication of syntectonic growth. Truly paracrystalline deformation structures were observed in a sequence of strongy flattened pillow lavas, that outcrop along the road southeast of Fenestrelle. A differentiated layering consisting of alternating light green (albite + epidote) and dark green (blue-green hornblende + chlorite) layers forms a foliation parallel to the axial plane of small folds, which are visible in some thicker dark green layers. The latter often bifurcate and represent the former pillow matrix or margins. As the differentiated layering developed inside the pillows and has a constant orientation, which is not related to the form of the pillows, it must be of tectonometamorphic origin. The differentiated layering is parallel to the regional schistosity, the fold axes are statistically parallel to those of the second generation in the Schistes lustrés.

Discussion

From the distribution of the stages, especially of the glaucophane-schist and greenschist stages, along the contacts with other rocks and irregularly throughout the metaferrogabbro, e.g. along cracks or as thin layers parallel to the foliation in the flaser eclogites, it is evident that the metamorphism was to a large extent externally controlled. As temperature and solid pressure cannot vary substantially over small distances, the introduction of fluid phases, which are necessary anyway for the formation of hydrous and carbonatic minerals, must have initiated the metamorphism. The limited thickness of reaction zones along cracks demonstrates that the fluid phases could move along the cracks, but were unable to penetrate very far into the rock and as cracks and veins tend to be healed quickly by growth of new minerals, deformation was clearly necessary to provide the open channelways for the transport of the fluids. This dependence of metamorphism upon deformation also provides an explanation for the lack of metamorphism between the glaucophane-schist stage and the greenschist stage in the metaferrogabbro and for the syntectonic microstructures of the different stages.

The Schistes lustrés near the metaferrogabbro are the most likely source rocks for the fluid phases, since all other rocks (metabasalts, serpentinites) which are associated presently with the ferrogabbro have been hydrated during metamorphism. Although its calcareous composition is not suggestive of being able to produce large amounts of water, the presence of hydrous Ca-silicates, such as lawsonite (CARON, 1974), which are instable in the presence of even small amounts of CO_2, prove that the fluid phase during a large part of the alpine orogeny was water. Apparently the Schistes lustrés contained so much formational water, which could not be totally bound up in hydrous minerals, that water dominated the fluid phase until the greenschist substage C took place and CO_2 entered the fluid phase.

The dependence of the eclogite-stage metamorphism upon deformation is not so obvious as that shown by the later stages. The metaferrogabbro eclogites belong to group C (COLEMAN et al., 1965) or group O (SMULIKOWSKI, 1972) and are typical of glaucophane-schist terrains. These eclogites are generally considered to form in the glaucophane-schist facies under special conditions. The nature of the latter remains controversial. From the study of natural eclogites ESSENE and FYFE (1967) concluded that fluid pressure must have been high. ERNST (1972) has shown that the fluid phase during eclogite metamorphism consisted almost exclusively of water. Hydrothermal experiments (WIKSTRÖM, 1970) and theoretical considerations (HOLLAND, 1979) also show that omphacite can be stable in the presence of water. FRY and FYFE (1969) on the other hand concluded from experimental data that at high water pressures amphibolites form instead of eclogites. In the metaferrogabbro several features indicate that water activity was low during the eclogite stage, viz. the strong grainsize variations of chloromelanite, which indicate variable diffusion rates; the formation of chloromelanite needles inside augite instead of alteration proceeding from the grain boundaries inwards and the deposition of exsolved material in the pseudomorphs, indicating limited diffusion (it should be noted though that augite appears to be resistant to alteration, as shown by its common preservation in e.g. spilites); the absence of hydrous minerals until the glaucophane-schist stage. The oxidation reactions, which produced rutile with hematite and ferric chloromelanite from ilmenite and ferrous augite (compare e.g. the pyroxene compositions in ERNST [1976]), indicate however that water was not wholly absent for the following reason:

The strong oxidation and the presence of hematite imply that a high oxygen fugacity must have been maintained in the fluid phase during the eclogite stage. And although the fluid, which was supplied to the ferrogabbro initially may have had a high oxygen fugacity, the oxidation reactions would soon have depleted the oxygen. Thus some process is required for the production of new oxygen through the dissociation of water. This process may keep going only when the hydrogen produced by the dissociation is removed from the system. Initially this may have occurred by faster diffusion of the hydrogen, which is highly mobile and diffuses much faster than water or oxygen, into the ferrogabbro, thus leaving the more slowly moving water depleted in hydrogen and providing the stimulus for further dissociation of water and production of oxygen. Ultimately however the removal of hydrogen from the whole ferrogabbro is required to explain the oxidation. Thus it is seen that the supply of water to the ferrogabbro was a necessary requirement for the formation of eclogites.

The implications of the occurrence of chloromelanite instead of jadeite-richer omphacite, which normally occurs in eclogites, are poorly understood, as experimental evidence is available only on iron-poor jadeite-diopside solid solutions. The effect of oxygen fugacity, which must be important for the ferric chloromelanite, is completely unknown.

The formation of eclogites before glaucophane schists may be explained in several ways:

- after the eclogite stage the supply of water to the ferrogabbro increased. However, no difference in the deformation, which must open up the diffusion paths for the water supply, can be detected, the deformation during the eclogite stage if anything being strongest, as shown by the flaser gabbros and the development of the eclogite stage throughout the ferrogabbro, while the glaucophane-schist stage occurs only locally. There is also no detectable change in behaviour of the Schistes lustrés, which acted as source rocks for the water;
- during the eclogite stage the Schistes lustrés were not present near the ferrogabbro to provide the water. Although possible, this explanation requires an alternative source for the water, which was necessary for the oxidation reactions;
- high oxygen fugacities favour the formation of eclogite pyroxene instead of glaucophane as envisaged by KERRICK and COTTON (1971). Although the oxygen fugacity will influence the phase relations of chloromelanite and glaucophane, as the former is more oxidised than the latter, it is doubtful whether high oxygen fugacities alone can explain the lack of glaucophane. For there is no reason to assume that the oxygen fugacity decreased after the eclogite stage, as this must be controlled by the removal of hydrogen and as only the

accumulation of oxygen will prevent further dissociation of water;

- the supply of water to the ferrogabbro was slow and approximately constant, but the continuous dissociation into the oxygen for the oxidation reactions and the hydrogen, which was removed, prevented the building up of high water pressure. Only when the oxidation was completed and oxygen remained in the fluid phase, the water pressure could increase and glaucophane become stable. Depending on the rate of diffusion of the water, it would be possible that glaucophane already formed at the margins of the ferrogabbro, while eclogites were still forming in the middle. The development of eclogites thus would depend on the effectiveness of water supply vs. hydrogen removal. With high water supply glaucophane would form and with low supply chloromelanite would form initially and be replaced by glaucophane at a later stage. In intermediate cases both chloromelanite and glaucophane would form together.

Although experimental evidence is needed to verify the effect of oxygen fugacity upon the phase relations of chloromelanite and glaucophane, we think that the last model provides the best explanation for the formation of the eclogites.

Model for the metamorphism

The high pressures required for the formation of eclogites in glaucophane-schist terrains have puzzled geologists for many years, because estimated thicknesses of former overlying rock piles never reach realistic values for the necessary load pressures. Two mechanisms are currently adhered to, viz. subduction (Ernst, 1971) and tectonic overpressure (Coleman and Lee, 1962). In his model for the deformation and metamorphism in the Schistes lustrés of the Western Alps, Caron (1977) has elaborated upon the tectonic overpressure model. Because of the amounts of fluids that must have been present in the Schistes lustrés, an overpressure by intergranular fluids can not be ruled out as a mechanism providing the high pressures. The foregoing account on the ferrogabbro shows however that an overpressure model cannot apply to the eclogite stage, as high fluid pressures would have produced glaucophane schists directly instead of eclogites. Subduction on the other hand explains both the high-pressure and low-temperature environment and the strong deformation during the early metamorphic event. Therefore the following model is proposed for the metamorphism and deformation in the ferrogabbro:

Subduction of oceanic lithosphere, which consisted a.o. of ferrogabbro, and the sediments of the Schistes lustrés caused high-pressure conditions and strong deformation. As water was supplied slowly to the ferrogabbro, high-pressure metamorphism took place. Initially eclogites formed, because enough water was used in the oxidation of ferrous iron to prevent water pressure building up. After the oxidation was completed, the water pressure increased and glaucophane formed locally. Before the alteration of chloromelanite to glaucophane had proceeded far, the subduction stopped, e.g. through plate-flip (DEWEY, 1976) or shifting of the subduction zone (MIYASHIRO, 1973, 402), and deformation came to a halt. Because of this, water was no longer supplied and the metamorphism in the ferrogabbro stopped. In the Schistes lustrés on the other hand metamorphism continued with conditions changing from the glaucophane-schist to the greenschist facies, showing that the rocks rose slowly to the surface.

Vigorous underthrusting of the Schistes lustrés nappe under the Briançonnais zone (CABY et al., 1978) caused a second phase of deformation and metamorphism under greenschist-facies conditions. As shown by the changes in conditions between the greenschist substages, this deformation took place over a prolonged period.

Epeirogenetic movements caused a weak third deformation, which produced open folds and renewed movements along fault zones.

Acknowledgements

The authors would like to thank Prof. dr. E. den Tex and Drs. A. Senior and P. F. Williams for discussions and criticism of the manuscript. We are also indebted to Messrs. W. C. Laurijssen and J. J. J. Bergenhenegouwen for microphotographs and drawings.

References

BORTOLAMI, G.C. and G.V. DAL PIAZ (1970): Il substrato cristallino dell'anfiteatro morenico di Rivoli-Avigliana (Prov. Torino) e alcune considerazioni sull'evoluzione paleogeografica e strutturale della eugeosinclinale piemontese. Mem. Soc. Ital. Sc. Nat., *18*, 125–169.

BORTOLOTTI, V. and G. GIANELLI (1976): Le rocce gabbriche dell'Apennino settentrionale: 1. Dati recenti su rapporti primari, posizione stratigrafica ed evoluzione tettonica. Ofioliti, *1*,99–105.

BOY, M., B. MESSIGA and G.B. PICCARDO (1976): Caratteristiche petrografiche e chimiche di Fe-gabbri e Fe-metagabbri delle ofioliti liguri. Ofioliti, *1*, 135-162.

CABY, R., J.R. KIENAST and P. SALIOT (1978): Structure, métamorphisme et modèle d'évolution tectonique des Alpes Occidentales. Rev. Géogr. Phys. Géol. Dynam., *XX*, 307–322.

CARON, J.M. (1974): Rapports entre diverses 'générations' de lawsonite et les déformations dans les Schistes lustrés des Alpes cottiennes septentrionales (France et Italie). Bull. Soc. géol. France, *XVI*, 255–263.

CARON, J.M. (1977): Lithostratigraphie et tectonique des Schistes lustrés dans les Alpes cottiennes septentrionales et en Corse orientale. Sc. géol. Mém., *48*.

CARON, J.M., F. SCHUMACHER and P. TRICART (1973): Chronologie et évolution longitudinale des structures dans les Schistes lustrés piémontais des Alpes cottiennes (France et Italie). Sc. géol. Bull., *26*, 245–258.

COLEMAN, R.G. (1977): Ophiolites, ancient oceanic lithosphere? Springer Verlag, Berlin.

COLEMAN, R.G. and D.E. LEE (1962): Metamorphic aragonite in the glaucophane schists of Cazadero, California. Amer. J. Sc., *260*, 577–595.
COLEMAN, R.G., D.E. LEE, L.B. BEATTY and W.W. BRANNOCK (1965): Eclogites and eclogites: their differences and similarities. Geol. Soc. Amer. Bull., *76*, 483–508.
CORTESOGNO, L., W.G. ERNST, M. GALLI, B. MESSIGA, G.M. PEDEMONTE and G.B. PICCARDO (1977a): Chemical petrology of eclogitic lenses in serpentinite, Gruppo di Voltri, Ligurian Alps. J. Geol., *85*, 255–277.
CORTESOGNO, L., G. GIANELLI and B. MESSIGA (1977b): Le rocce gabbriche dell'Apennino settentrionale. III. Caratteristiche petrografiche: Evoluzione metamorfica in ambiente oceanico e orogenico, confronti con metagabbri a metamorfismo alpino-tipo. Ofioliti, *2*, 75–113.
CORTESOGNO, L., G. GIANELLI and G.B. PICCARDO (1975): Preorogenic metamorphic and tectonic evolution of the Ophiolite mafic rocks (Northern Apennine and Tuscany). Boll. Soc. Geol. Ital., *94*, 291–327.
DEBELMAS, J. and M. LEMOINE (1970): The Western Alps: palaeogeography and structure. Earth-Sc. Rev., *6*,221–256.
DEWEY, J.F. (1976): Ophiolite obduction. Tectonophysics, *31*,93–120.
ENGEL, G.C. and R.L. FISHER (1975): Granitic to ultramafic rock complexes of the Indian Ocean Ridge System, western Indian Ocean. Geol. Soc. Amer. Bull., *86*, 1553–1578.
ERNST, W.G. (1971): Do mineral parageneses reflect unusually high-pressure conditions of Franciscan metamorphism? Amer. J. Sc., *270*, 81–108.
ERNST, W.G. (1972): CO_2-poor composition of the fluid attending Franciscan and Sanbagawa low-grade metamorphism. Geochim. Cosmochim. Acta, *36*, 497–504.
ERNST, W.G. (1976): Mineral chemistry of eclogites and related rocks from the Voltri Group, western Liguria, Italy. Schweiz. mineral. petrogr. Mitt., *56*, 293–343.
ESSENE, E.J. and W.S. FYFE (1967): Omphacite in Californian metamorphic rocks. Contrib. Mineral. Petrol., *15*,1–23.
FREY, M., J.C. HUNZIKER, W. FRANK, J. BOCQUET, G.V. DAL PIAZ, E. JÄGER and E. NIGGLI (1974): Alpine metamorphism of the Alps, a review. Schweiz. mineral. petrogr. Mitt., *54*, 247–290.
FRY, N., and W.S. FYFE (1969): Eclogites and water pressure. Contrib. Mineral. Petrol., *24*, 1–6.
GHENT, E.D. and R.G. COLEMAN (1973): Eclogites from southwestern Oregon. Geol. Soc. Amer. Bull., *84*, 2471–2488.
GIANELLI, G. and G. PRINCIPI (1974): Studies on mafic and ultramafic rocks. 4. Breccias of the ophiolitic suite in the Monte Bocco area (Ligurian Apennine). Boll. Soc. Geol. Ital., *93*, 277–308.
HOLLAND, T.J.B. (1979): High water activities in the generation of high pressure kyanite eclogites of the Tauern Window, Austria. J. Geol., *87*, 1–27.
KERRICK, D.M. and W.R. COTTON (1971): Stability relations of jadeite pyroxene in Franciscan metagraywackes near San Jose, California. Amer. J. Sc., *271*, 350–369.
LEAKE, B.E. (1978): Nomenclature of amphiboles. Can. Mineral., *16*, 501–520.
MIYASHIRO, A. (1973): Metamorphism and metamorphic belts. George Allen & Unwin, London.
MIYASHIRO, A., F. SHIDO and M. EWING (1970): Crystallization and differentiation in abyssal tholeiites and gabbros from mid-oceanic ridges. Earth Planet. Sc. Lett., *7*, 361–365.
MOTTANA, A. and R. BOCCHIO (1975): Superferric eclogites of the Voltri Group (Pennidic Belt, Apennines):. Contrib. Mineral. Petrol., *49*, 201–210.
OHNENSTETTER, M., D. OHNENSTETTER and G. ROCCI (1975): Essai de réconstitution du puzzle ophiolitique corse. C. R. Acad. Sc. Paris, *280*, sér. D, 395–398.
PICCARDO, G.B. (1977): Le ofioliti dell'areale ligure: petrologia e ambiente geodinamico di formazione. Rend. Soc. Ital. Mineral. Petrol., *33*,221–252.
ROCCI, G., D. OHNENSTETTER and M. OHNENSTETTER (1976): Le log ophiolitique corse. Bull. Soc. géol. France, *XVIII*, 1229–1230.
SMULIKOWSKI, K. (1972): Classification of eclogites and allied rocks. Krystalinikum, *9*, 107–130.

SPRY, A. (1969): Metamorphic textures. Pergamon Press, Oxford.
WAGER, L. R. and G. M. BROWN (1968): Layered igneous rocks. Oliver & Boyd, Edinburgh.
WIKSTRÖM, A. (1970): Hydrothermal experiments in the system Jadeite-Diopside. Norsk Geol. Tidsskrift, *50*, 1–14.

Manuscript received January 31, 1980