

Early Alpine eclogitisation in talc/chloritoid - bearing Mg-metagabbros and in jadeite - Fe-omphacite - bearing metatrandhjemites from the ophiolites of the Western Alps

UGO POGNANTE

Dipartimento di Scienze della Terra, via Valperga Caluso 37, 10125 Torino, Italy

ABSTRACT. — Ophiolitic Mg-metagabbros from the Rocciavré massif and metatrandhjemites from Val Susa (Western Alps, Italy) are studied in this paper. The Mg-metagabbros are characterized by omphacite - garnet - zoisite - talc or by omphacite - garnet - zoisite - Mg-chloritoid - Mg-chlorite - amphibole eclogite assemblages of early Alpine age, while the metatrandhjemites display jadeite - quartz - garnet - ferro-glaucophane - sphene \pm ferro-omphacite assemblages of comparable age.

Eclogitisation of the little-deformed Mg-metagabbros was governed by local equilibrium and slow reaction kinetics which split the rock in partly independent subsystems corresponding to the domains of the magmatic minerals. In such rocks zoning of metamorphic minerals record either the incomplete re-equilibration of pre-metamorphic phases, or the relative sequence of sub-reactions which proceeded, at different rates, in the bulk-rock system. In metatrandhjemites the stability of jadeite with ferro-omphacite supports the existence of a miscibility gap at low-temperature along the omphacite-jadeite join.

P-T estimates based on garnet-pyroxene thermometry, phase compatibilities in the system Al_2O_3 - $(FeO + MgO)$ - SiO_2 (+ H_2O) and other equilibria, point to temperatures around 500°C at pressures of 13-18 kb for the eclogitic peak. Metatrandhjemites of the northern western Alps were eclogitised at more severe P-T conditions characterized by temperatures of 500-600°C and pressures in excess of 18-20 kb.

In ophiolitic intrusive suites, hydration reactions characterized the Mg-metagabbros, while prevalent reactions not involving significant amounts of H_2O , or possible dehydration reactions, occurred in some Fe-Ti metagabbros during eclogitisation. The different behaviour of the protoliths favored fluid diffusion and caused a heterogeneous distribution of H_2O during metamorphism with the temporary instauration of fluid-deficient conditions in a few rock-volumes.

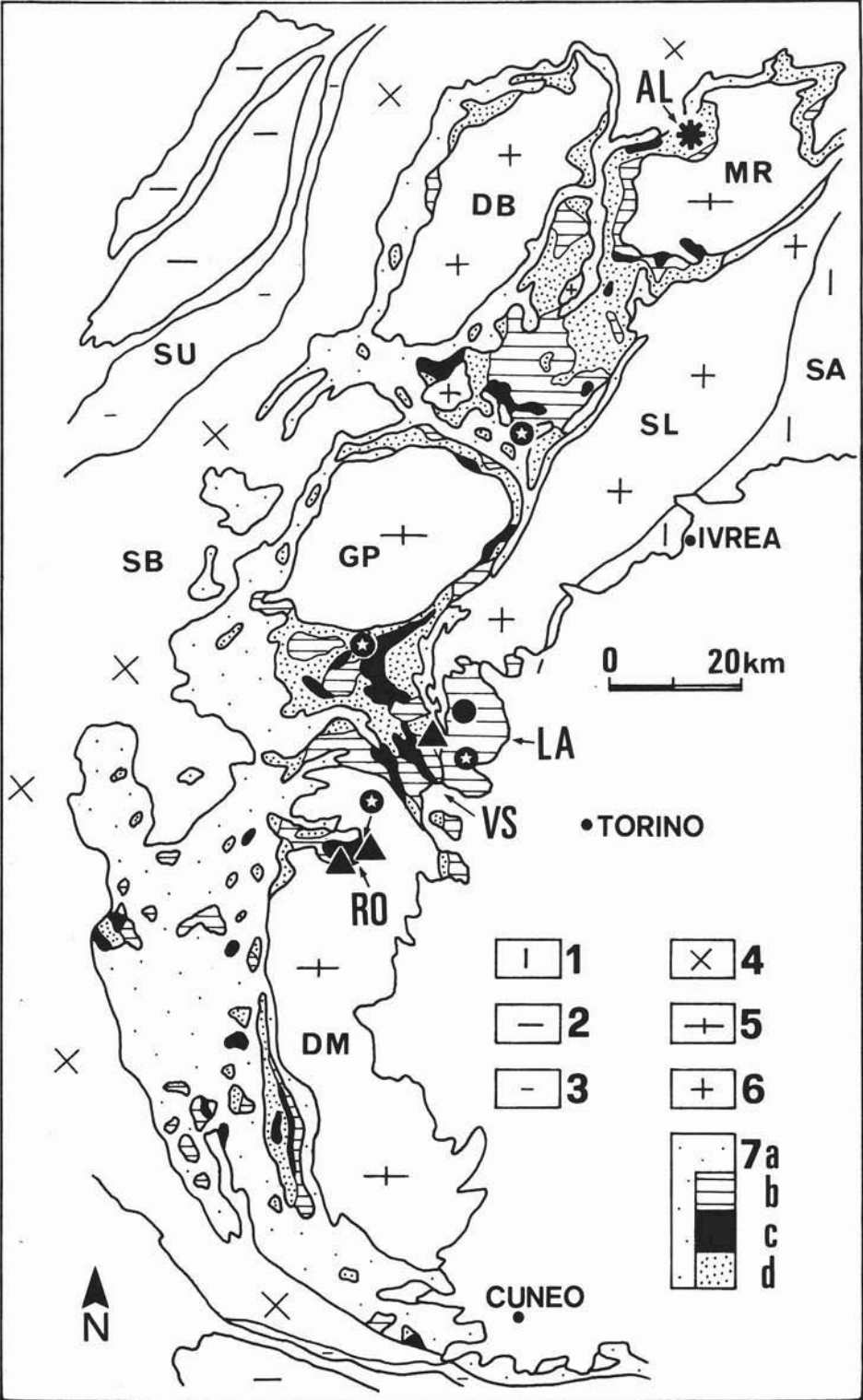
Key words: eclogite metamorphism, reaction mechanism, phase relationships, thermobarometry, western Alps.

RIASSUNTO. — In questo lavoro viene studiata la ricristallizzazione eclogitica coalpina in alcuni Mg-gabbri ofiolitici del massiccio Rocciavré ed in alcuni differenziati trondhjemitici della Val Susa (Alpi Occidentali).

I meta Mg-gabbri comprendono paragenesi a onfacite - granato - zoisite - talco oppure a onfacite - granato - zoisite - Mg-cloritoide - Mg-clorite - Ca/Na anfiboli. Le metatrandhjemiti sono costituite da giadeite - quarzo - granato - ferro-glaucofane - titanite \pm ferro-onfacite. I dati petrografici, di chimismo dei minerali e termobarometrici di queste rocce sono paragonabili con quelli di protoliti analoghi affioranti in altri settori dell'arco alpino occidentale.

Il metamorfismo eclogitico nei meta Mg-gabbri poco deformati è controllato da equilibri locali e della lenta cinetica di reazione che suddividono la roccia in micro-sistemi chimici corrispondenti ai domini delle fasi magmatiche; tra i vari micro-sistemi presenti nella roccia la diffusione intercristallina è lenta ed è differenziata per i diversi componenti. Per determinazioni termobarometriche in rocce non completamente equilibrate la zonatura delle fasi metamorfiche deve essere valutata attentamente; essa può infatti registrare l'incompleta riequilibrio di fasi pre-metamorfiche oppure l'incompleta eliminazione dei gradienti chimici durante la crescita dei minerali (crescita condizionata da cinetiche di reazione differenti nei vari micro-sistemi). Nelle metatrandhjemiti la stretta associazione di giadeite e ferro-onfacite testimonia la lacuna di miscibilità esistente nei pirosseni sodici lungo la congiungente giadeite-onfacite.

Le stime dei parametri intensivi basate sulla classica geotermometria granato-pirosseno e su altri equilibri, indicano temperature di circa 500°C a pressioni di 13-18 kb per il picco del metamorfismo eclogitico nelle ofioliti studiate. In protoliti Mg-gabbri ricchi in MgO e Al_2O_3 che non hanno subito deformazioni pervasive durante il metamorfismo, lo studio delle topologie nel sistema Al_2O_3 - $(FeO + MgO)$ - SiO_2 (+ H_2O) può rappresentare un valido complemento ai classici metodi termobarometrici usati per le eclogiti e permette di valutare le relazioni di fase nel micro-sistema dell'originaria olivina forsteritica. L'applicazione di tale metodo



alternativo anche ad altri meta Mg-gabbri affioranti nell'arco alpino occidentale, conferma che durante l'eclogizzazione coalpina le metafoliti più settentrionali (Vallese, Svizzera) sono state sottoposte a temperature di 50-100°C superiori e a pressioni di alcuni kb più elevate rispetto agli altri settori.

Viene infine proposto un modello che spiega la ricristallizzazione eclogitica nelle sequenze ofiolitiche stratificate di Mg-gabbri e di Fe-Ti gabbri. Secondo tale modello reazioni di idratazione hanno caratterizzato i meta Mg-gabbri, mentre prevalenti reazioni che non coinvolgono significative quantità di H₂O (o eventualmente reazioni di disidratazione) si sono verificate in alcuni meta Fe-Ti gabbri. Tutto ciò favorisce una distribuzione eterogenea della fase fluida (nello spazio e nel tempo) durante il metamorfismo ed è forse pure la causa indiretta della localizzazione della deformazione sin eclogitica in corrispondenza di zone di shear.

Parole chiave: metamorfismo eclogitico, meccanismi di reazione, relazioni di fase, termobarometria, Alpi occidentali.

Introduction

The metaophiolites of the Western Alps formed in the small Piemonte-Ligurian ocean of Jurassic-lower Cretaceous age (e.g. ELTER, 1971; DAL PIAZ, 1974; POGNANTE and PICCARDO, 1984). During the Cretaceous the internal (eastern) metaophiolites were subducted and sustained an early Alpine eclogitic metamorphism followed by a low pressure greenschist metamorphism which is of late Alpine (middle Tertiary) age in the north-western Alps and may be older more to the south (DAL PIAZ, 1974; POGNANTE, 1984; CARPENA et al., 1986).

Study of the high pressure metamorphism is of particular interest in the metagabbros because they allow an estimate not only of the P-T conditions of metamorphism, but also of possible reaction mechanisms and the role played by syn-metamorphic deformation and fluid phase. Among the metagabbros of the

Western Alps, recent works focus mainly on Fe-Ti gabbro protoliths. The Fe-Ti gabbros were transformed to eclogites during the early Alpine event and are characterized by well developed and typical assemblages rich in omphacite, almandine garnet and rutile (LOMBARDO et al., 1978; ERNST and DAL PIAZ, 1978; OTTEN and BROWER, 1979; POGNANTE, 1981, 1985; KIENAST, 1983; BALDELLI et al., 1985; NISIO, 1985; LARDEAUX et al., 1986; SANDRONE et al., 1986; POGNANTE and KIENAST, 1987). Detailed works on eclogitisation in the other gabbro compositions are less common. For Mg-metagabbros they concern rocks from the Allalin massif (BEARTH, 1967; CHINNER and DIXON, 1973; MEYER, 1983), the Lanzo peridotite body (KIENAST and POGNANTE, 1988) and the Monviso massif (KIENAST, 1983; KIENAST and MESSIGA, 1987). As for the rare trondhjemitic veinlets associated with Fe-Ti metagabbros, general descriptions of the high pressure assemblages or of their products of transformation are restricted to the Rocciavré massif (POGNANTE, 1981) and to Val d'Ala di Lanzo (SANDRONE et al., 1986).

This work provides new data on mineral chemistry, thermobarometry, phase relations in Mg-metagabbros from the Rocciavré massif (POGNANTE, 1979) and in metatondhjemitic from Val Susa (POGNANTE, 1980), west of Torino, NW Italy (Fig. 1). The petrography of the above rocks is compared to that of similar protoliths described elsewhere in Alpine metaophiolites, and petrologic implications are discussed with particular attention to possible mechanisms of eclogitisation, thermobarometry and phase relationships and, lastly, the complex interplay among metamorphic recrystallization, granular scale deformation and fluid-rock interaction.

Fig. 1. — Geologic-tectonic sketch-map of western Alps. Legend. 1: Southern Alps (SA); 2: external crystalline massifs; 3: Subbriançonnais (SU); 4: Gran San Bernardo unit (SB); 5: internal crystalline massifs (MR = Monte Rosa, GP = Gran Paradiso, DM = Dora-Maira); 6: Sesia-Lanzo unit (SL) and Dent Blanche nappe (DB); Piemonte metaophiolites; 7a: undifferentiated calcschists; 7b: ultramafics (including Lanzo peridotites); 7c: main bodies of metagabbros; 7d: metabasalts and other metabasics. Triangles: two samples of Mg-metagabbro from Rocciavré (RO) and the metatondhjemitic from Val Susa (VS) studied here. Circle and asterisk: Mg-metagabbros from Lanzo (LA) and Allalin (AL). Stars: jadeite-quartz assemblages in other eclogitised trondhjemitic from the Piemonte metaophiolites (see text).

TABLE 1

Major- (wt %) and trace- (ppm) element abundances of Rocciavré Mg-metagabbros (average of 4 analyses; POGNANTE *et al.*, 1982; POGNANTE and TOSCANI, 1985) and of one metatrodhjemite from Val Susa (POGNANTE and TOSCANI, 1985)

	SiO ₂	TiO ₂	Al ₂ O ₃	Fe ₂ O ₃ tot	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	LOI	Cr	Ni	Zr
A	51.01	0.31	15.42	14.34	0.09	11.03	12.80	2.70	0.06	0.04	1.79	1580	269	12
B	67.67	0.54	14.03	7.17	0.12	0.53	1.59	7.77	0.09	0.17	0.31	8	4	1016

Analyses have been recalculated to 100. Abbreviations: A=Mg metagabbros; B=trondhjemites; LOI=loss on ignition.

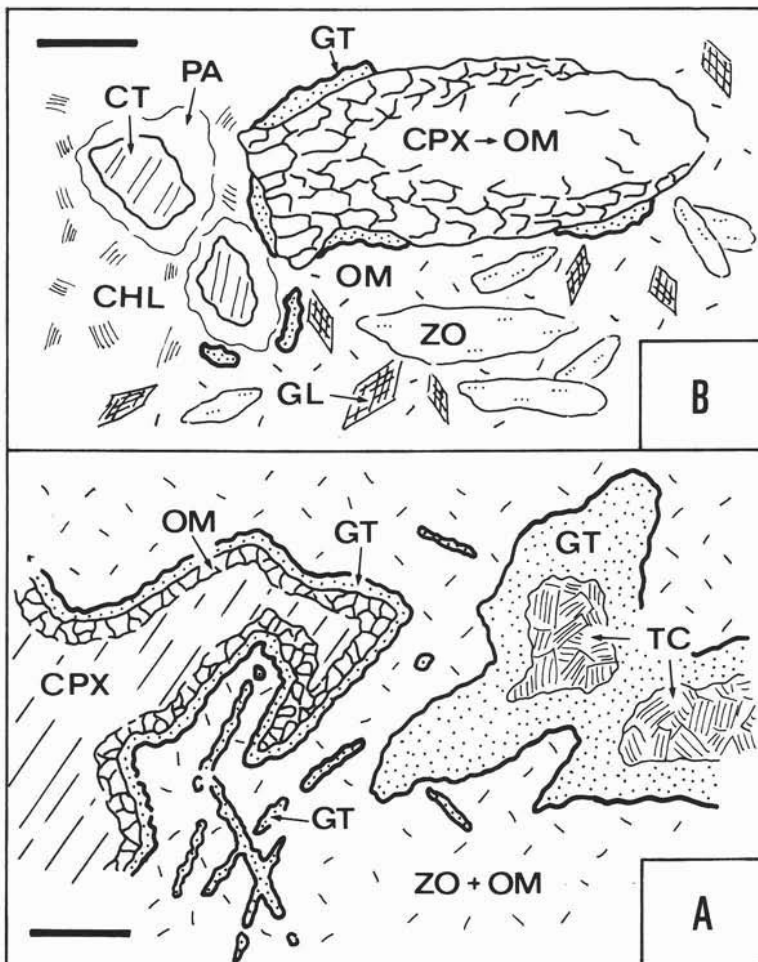


Fig. 2. — A: coronitic Mg-metagabbro from Rocciavré (sample R 299) showing a composite corona of garnet (GT) and omphacite (OM) around metastable magmatic diopside (CPX), and a thick reaction rim of garnet between domain of plagioclase transformed to zoisite (ZO), omphacite \pm garnet and domain of olivine transformed to talc (TC). B: Mg-metagabbro from Rocciavré (sample OF 469) showing transformation of magmatic pyroxene to omphacite and replacement of plagioclase by zoisite, fine grained omphacite and Na/Ca amphiboles (GL); chlorite (CHL) and Mg chloritoid (CT), partly replaced by paragonite (PA), transform probable magmatic olivine. Bars are 0.5 mm long.

Petrography

Mg-metagabbros

Like most of the ophiolite metagabbros of the Western Alps, the Mg-metagabbros are characterized by the close association of little-deformed rock-volumes displaying eclogite coronitic or pseudomorphic transformations (and in places magmatic relics) with blastomylonites showing complete syntectonic eclogite recrystallization (e.g. KIENAST, 1983; POGNANTE, 1985). The rare little-deformed samples showing incomplete eclogitisation, indicate derivation from medium- to coarse-grained rocks consisting of labradoritic plagioclase, Cr-diopside \pm Mg-olivine (BEARTH, 1967; LOMBARDO et al., 1978; POGNANTE and TOSCANI, 1985; POGNANTE et al., 1985). As for the bulk-chemistry, the Mg-gabbros are characterized by high MgO, Al_2O_3 , Cr and Ni, and by low Fe_2O_3 tot, TiO_2 and Zr (POGNANTE and Piccardo, 1984, with references therein, Table 1).

Two samples of little-deformed Mg-metagabbro from the *Rocciavré* massif were studied in detail in the present work. Sample R 299 was collected near Fonte Neiretto (Val Sangone) and was interbedded with metagabbro-norites and Fe-Ti metagabbros; sample OF 469 was collected near Rocca Vergia (Val Chisone), where it was part of a thick sequence of Mg-metagabbros. In sample R 299 (Fig. 2A), magmatic structure is very well preserved but, except for clinopyroxene, the magmatic minerals are pseudomorphed by eclogite minerals and reaction coronas develop at the boundaries between the magmatic domains. Plagioclase is transformed to fine-grained zoisite and Na-pyroxene; the plagioclase domain contain also vein-like aggregates of small garnet crystals. Olivine is replaced by talc and rare pyroxene, and shows a thick reaction rim of garnet near the contact with the plagioclase domain. Magmatic clinopyroxene is partly preserved, but a composite reaction corona consisting of an inner rim of Na-pyroxene and an outer rim of garnet develops at the contact with the plagioclase domain.

In sample OF 469, eclogite recrystallization is more advanced than in sample R 299, and it is not always easy to recognize the original shape of the magmatic domains (Fig. 2B). The magmatic clinopyroxene is largely transformed to pale green Na-pyroxene also forming a recrystallized corona, and is bordered by a discontinuous rim of garnet. Magmatic plagioclase displays a heterogeneous transformation that includes fine-grained Na-pyroxene, zoisite, colourless amphibole and paragonite. Other pseudomorphs consisting of chlorite and chloritoid corroded by flakes of paragonite may derive from original olivine.

The foliated metagabbros associated with the two samples described above display eclogitic assemblages rich in pale blue-green amphibole and zoisite/clinozoisite, and poor in garnet and omphacite. In addition these foliated rocks rich in hydrous eclogitic minerals show advanced low-pressure transformations with the growth of albite and green actinolite which post-date the most pervasive deformation.

The transformations described here for the *Rocciavré* samples are compared to those occurring in Mg-metagabbros from the Lanzo peridotite body and the Allalin massif (Fig. 1).

The *Lanzo* body occurs west of Torino (Italy) and consists of lherzolites crosscut by minor dykes of gabbro and basalt (POGNANTE et al., 1985, with references therein); it is separated by other Piemonte metaophiolites by a major thrust. A few Mg-metagabbros from Lanzo show assemblages including chloritoid, talc, garnet, Na-pyroxenes, Ca/Na amphiboles \pm chlorite (KIENAST and POGNANTE, 1988). In these rocks talc, chloritoid \pm chlorite and a thick reaction rim of garnet form the pseudomorphs after magmatic olivine, while Na-pyroxenes and minor garnet transform plagioclase.

The *Allalin* massif, in the Zermatt-Saas metaophiolites (Valais, Switzerland), consists of a thick body of metagabbro (BEARTH, 1967; MEYER, 1983; BARNICOAT and FRY, 1986). The Allalin metagabbros display peculiar assemblages including: talc, garnet, kyanite, chloritoid \pm chlorite \pm Na-pyroxene in the olivine domain; Na-pyroxene \pm garnet after magmatic clinopyroxene; and an aggregate

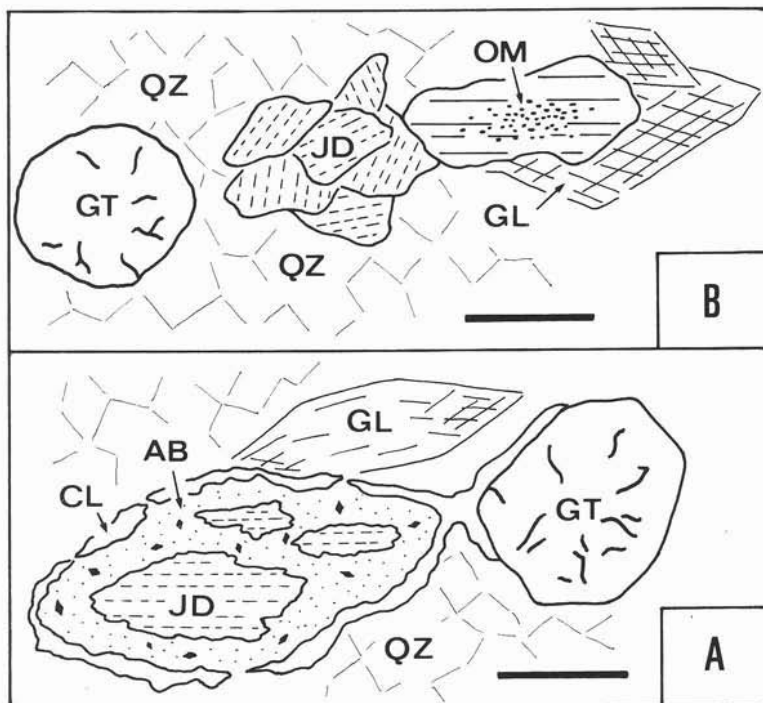


Fig. 3. — A: metatrandhjemite OF 1803b consisting of quartz (QZ), ferro-glaucophane (GL), garnet (GT) and jadeite (JD); jadeite is partly replaced by albite + white mica + Fe-oxides (AB) and shows chloromelanite (CL) reaction rim. B: metatrandhjemite OF 1803a consisting of jadeite, ferro-omphacite (OM), ferro-glaucophane, quartz, garnet. Bars are 0.5 mm long.

including zoisite \pm kyanite \pm Na-pyroxene \pm quartz \pm chloritoid after plagioclase (BEARTH, 1967; CHINNER and DIXON, 1973; MEYER, 1983).

Metatrandhjemites

Trondhjemites are very rare in the Western Alps ophiolites. They represent leucocratic rocks formed in the later stages of differentiation of the tholeiitic magma which produced the gabbroic suite (POGNANTE and PICCARDO, 1984, with references therein). Their bulk-chemistry is characterized by high SiO_2 , Na_2O and Zr, and by low MgO , Cr and Ni (Table 1).

Metatrandhjemite OF 1803a was sampled in the lower *Val Susa* near Colle del Lys, close to the tectonic boundary with the Lanzo body (Fig. 1). It represents a foliated layer associated with eclogitised Fe-Ti gabbros, has a fine-grained granoblastic structure, and

consists of closely associated blasts of colourless jadeite and green Na-pyroxene, quartz, garnet, blue amphibole with a dark blue/green rim, sphene, ilmenite, zircon, apatite (Fig. 3). Here jadeite is partly transformed to albite \pm white micas \pm pale green amphibole, while the green Na-pyroxene and garnet are rimmed by green amphibole. The core of the green Na-pyroxene is usually crowded with opaque inclusions suggesting derivation from magmatic pyroxene by pseudomorphic replacement. With respect to OF 1803a, the adjacent sample 1803b is richer in quartz and lacks green Na-pyroxene, while jadeite is partly replaced by albite \pm white mica \pm epidote and by a reaction corona of dark green pyroxene at the contact with quartz (Fig. 3a).

Jadeite - quartz \pm Na-amphibole \pm garnet assemblages in metatrandhjemites have also been found in *Val d'Ala di Lanzo* (SANDRONE et al., 1986), in the *Monte Nero* eclogitised

TABLE 2
Representative microprobe analyses of minerals from Rocciavré Mg-metagabbros

mineral sample domain	magmatic diopside, omphacites				garnets				chloritoids		talc	chlorite
	R299	OF469			R299	OF469			OF469	ol?	R299	OF469
	di relic	di-pl corona	di-pl corona*	pl	ol-pl corona	ol-pl corona*	di-pl corona	near ct	ol? core	ol? rim	ol	ol?
SiO ₂	50.99	55.05	55.50	57.22	41.64	39.42	38.80	39.91	25.88	26.38	62.93	27.20
TiO ₂	0.92	0.10	0.10	-	0.09	0.06	0.07	0.02	-	0.04	-	0.03
Al ₂ O ₃	2.59	5.28	9.39	9.44	19.26	18.90	18.48	21.01	41.06	40.00	0.30	20.18
FeO tot	6.04	3.05	2.59	1.04	16.99	22.68	24.59	17.39	11.94	13.95	1.23	15.02
MnO	0.15	0.06	0.15	0.02	0.37	0.50	0.52	0.58	-	0.18	0.11	0.13
MgO	15.72	13.50	10.72	11.12	14.78	10.57	4.87	11.36	12.05	10.89	31.50	24.07
CaO	22.94	18.96	15.52	15.50	6.74	7.09	13.19	9.07	0.03	0.04	0.07	0.11
Na ₂ O	0.73	3.70	6.03	5.91	0.05	-	0.02	0.10	-	-	-	0.04
Total	100.08	99.76	100.05	100.25	99.92	99.22	100.54	99.44	90.96	91.49	96.14	86.78
Si	1.890	1.987	1.976	2.009	3.076	3.018	3.011	2.995	2.039	2.088	7.931	5.486
Ti	0.026	0.003	0.003	-	0.005	0.003	0.004	0.001	-	0.003	-	0.004
Al	0.113	0.225	0.394	0.391	1.678	1.706	1.691	1.860	3.812	3.731	0.044	4.796
Fe	0.187	0.092	0.077	0.031	1.050	1.453	1.596	1.090	0.787	0.923	0.130	2.533
Mn	0.005	0.002	0.005	0.002	0.023	0.032	0.034	0.037	-	0.012	0.012	0.023
Mg	0.869	0.727	0.569	0.582	1.627	1.206	0.564	1.271	1.416	1.285	5.918	7.235
Ca	0.911	0.733	0.592	0.583	0.534	0.582	1.097	0.730	0.003	0.004	0.010	0.023
Na	0.053	0.259	0.416	0.403	0.007	-	0.003	0.015	-	-	-	0.018
Total	4.055	4.031	4.034	3.999	8.000	8.000	8.000	8.000	8.057	8.047	14.051	20.118

Structural formulae on basis of 6 oxygens for clinopyroxenes, 12 oxygens for garnets and chloritoids, 22 oxygens for talc and 28 oxygens for chlorite. Asterisk: corona near plagioclase domain. Abbreviations: di=diopside, pl=plagioclase, ol=olivine and ct=chloritoid.

TABLE 3
Representative microprobe analyses of minerals from Val Susa metatrandjemites

mineral sample	Fe-omphacites, jadeites, chloromelanite				garnets		Fe-glaucophane riebeckite	
	OF1803a		OF1803b		OF1803a		OF1803a	
	core	rim	core	rim	core	rim	core	rim
SiO ₂	53.24	54.69	58.37	59.17	52.76	38.03	56.00	42.69
TiO ₂	0.02	0.12	-	-	0.16	-	-	-
Al ₂ O ₃	10.42	11.72	23.23	22.26	4.30	21.84	11.59	9.98
FeO tot	14.03	11.28	3.31	4.01	21.82	31.66	19.81	27.78
MnO	-	-	-	0.08	0.38	1.69	-	0.13
MgO	2.56	3.35	0.24	0.14	2.88	0.19	3.54	4.27
CaO	10.83	9.57	0.67	0.61	9.87	8.18	0.07	6.56
Na ₂ O	8.22	8.60	14.28	14.66	7.16	0.06	7.40	5.49
K ₂ O	-	0.04	0.03	-	0.13	0.02	-	0.57
Total	99.32	99.37	100.13	100.93	99.46	101.67	98.41	97.47
Si	1.961	1.986	1.990	2.002	2.058	3.008	7.966	6.750
Ti	0.001	0.003	-	-	0.005	-	-	-
Al	0.454	0.503	0.933	0.888	0.198	2.037	1.944	1.861
Fe	0.432	0.343	0.094	0.114	0.712	2.095	2.357	3.674
Mn	-	-	-	0.002	0.013	0.113	-	0.017
Mg	0.140	0.182	0.012	0.007	0.167	0.022	0.751	1.006
Ca	0.427	0.373	0.024	0.022	0.413	0.693	0.011	1.112
Na	0.588	0.606	0.944	0.962	0.542	0.009	2.041	1.683
K	-	0.002	0.001	-	0.007	0.002	-	0.115
Total	4.003	3.998	4.000	3.996	4.115	7.980	15.069	16.218

Structural formulae on basis of 6 oxygens for clinopyroxenes, 12 oxygens for garnets and 23 oxygens for amphiboles.

Fe-Ti gabbros from Valle di Champorcher (North-Western Alps; Novo and POGNANTE, personal observations), and in decimetric dykes crosscutting the Lanzo peridotites (personal observations); additionally, pseudomorphs after jadeite occur in a few pods associated with the Rocciavré Fe-Ti metagabbros (POGNANTE, 1981) (Fig. 1).

Metamorphic mineral chemistry

Chemical analyses were obtained with an ARL-SEM-Q microprobe using natural minerals as standard and converting counts to weight per cent employing the MAGIC IV program. Representative analyses are reported in Tables 2 and 3. Fe^{2+} in Na-pyroxenes was calculated by assuming that $\text{Fe}^{3+} = \text{Na-Al}$ and then $\text{Fe}^{2+} = \text{Fe}_{\text{tot}} - \text{Fe}^{3+}$ (CARPENTER, 1979); pyroxene end-members were calculated in the following order: jadeite, acmite, augite. Fe^{3+} in garnets was calculated by the relation: $\text{Fe}^{3+} = 2\text{-Al}$. Fe^{3+} in chloritoids was evaluated by the relation: $\text{Fe}^{3+} = 4\text{-Al}$.

The eclogitic minerals are usually zoned and

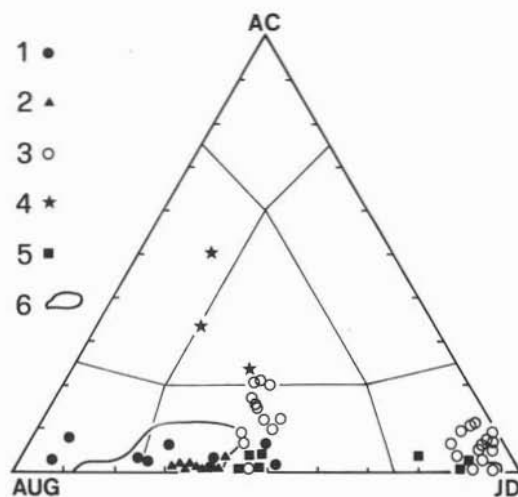


Fig. 4. — Augite (AUG) - jadeite (JD) - acmite (AC) diagram showing pyroxene compositions. Rocciavré metagabbros; 1: omphacites and magmatic diopside from sample R 299, 2: sample OF 469. Val Susa metatrandhjemites, 3: jadeites and ferro-omphacites, 4: chloromelanite or aegirin-augite in reaction rim after jadeite. 5: Lanzo Mg-metagabbro (data from KIENAST and POGNANTE, 1988). 6: Allalin Mg-metagabbros (data from MEYER, 1983).

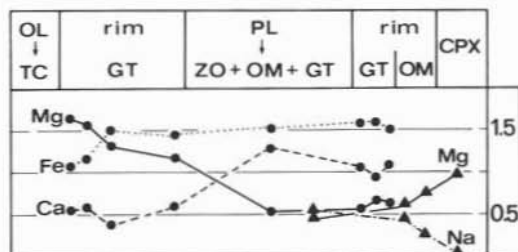


Fig. 5. — Zoning of pyroxenes (triangles) and garnets (circles) across different domains of R 299 Mg-metagabbro from Rocciavré. Vertical scale is cation per 6 oxygen for pyroxenes and cations per 12 oxygens for garnets. OL: olivine, TC: talc, PL: plagioclase, ZO: zoisite, OM: omphacite, GT: garnet, CPX: magmatic clinopyroxene. The GT rim between OL and PL domain is about 0.5 mm thick.

their composition is related to the domain of the magmatic phase in which they crystallized; in the little-deformed rocks the magmatic domains are usually preserved and represent partly independent chemical sub-systems.

Mg-metagabbros

In samples R 299 and OF 469 from Rocciavré, Na-pyroxenes are usually omphacites (Fig. 4) with lower acmite content in the plagioclase domain than in the reaction rims around magmatic diopside; in the reaction rims, Na-pyroxene composition grades from omphacite to sodian augite approaching magmatic diopside (Fig. 5). Pyroxenes which crystallized in the olivine domain plot in the field of sodian augite. In other closely associated Mg-metagabbros with less advanced eclogitisation, jadeite, zoisite \pm quartz were revealed by X-ray diffraction and microprobe analyses in the very fine grained aggregates replacing plagioclase.

In sample R 299 garnets show a wider range of compositions than in sample OF 469 (Fig. 6). Garnets occurring at the boundary between plagioclase and diopside domains are rich in almandine (41-46 mole per cent) with lower amounts of grossular (20-35 mole per cent) and pyrope (18-25 mole per cent); across this boundary garnet compositions display irregular fluctuations (Fig. 5). Garnets rimming the pseudomorphed olivine in sample R 299 are richer in pyrope (29-54 mole per

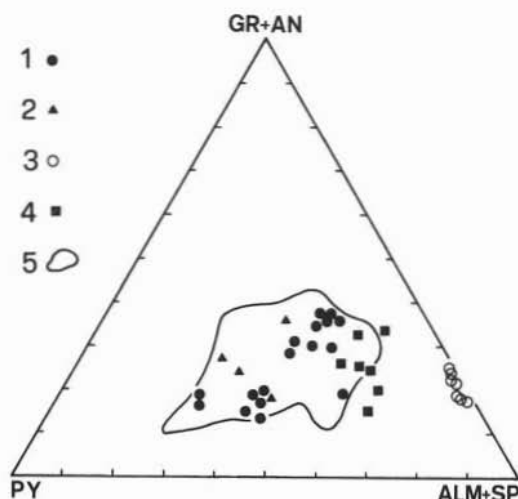


Fig. 6. — Garnet compositions in (grossular (GR) + andradite (AN)) — pyrope (PY) — (almandine (ALM) + spessartine (SP)) diagram. Rocciavré Mg-metagabbros, 1: sample R 299, 2: sample OF 469. 3: Val Susa metatrodhjemites. 4: Lanzo Mg-metagabbros (KIENAST and POGNANTE, 1988). 5: Allalin Mg-metagabbros (MEYER, 1983).

cent) than in almandine (27-41 mole per cent) and grossular (7-25 mole per cent); across this boundary pyrope decreases and almandine increases near the plagioclase domain (Fig. 5). Garnets from the plagioclase domain are always rich in grossular (up to 35 mole per cent). All the analyzed garnets show values of andradite between 1 and 11 mole per cent, and very low values of spessartine (1-2 mole per cent).

Chloritoids from sample OF 469 are rich in Mg with $Mg/Mg + Fe^{2+} = 0.63-0.75$; they are zoned, with rims enriched in Fe relative to cores.

The other minerals from the analysed Rocciavré Mg-metagabbros are Fe-poor talc ($FeO < 1.30$ wt per cent), paragonite, Na-Ca amphiboles and Mg-rich chlorite (ripidolite).

The composition of the eclogitic phases of the Mg-metagabbros from Lanzo (KIENAST and Pognante, 1988) are only partly similar to those from Rocciavré. Among the Na-pyroxenes, at Lanzo jadeite occurs instead of omphacite in the core of the plagioclase domain (Fig. 4); garnets are richer in almandine and poorer in pyrope (Fig. 6);

chloritoids are slightly richer in Fe ($Mg/Mg + Fe^{2+} = 0.65-0.70$) relative to the Rocciavré Mg-metagabbros.

In the Allalin Mg-metagabbros (BEARTH, 1967; CHINNER and DIXON, 1973; MEYER, 1983) Na-pyroxenes are mostly omphacites rich in Cr_2O_3 (up to 2.4 wt per cent) in the pseudomorphs after magmatic Cr-diopside, while jadeite and quartz (\pm kyanite) occur in some fine grained pseudomorphs replacing plagioclase (Fig. 4). Garnets show a wide compositional range that overlaps those of the Rocciavré and Lanzo rocks (Fig. 6). Chloritoids are richer in Fe than those from Rocciavré and Lanzo ($Mg/Mg + Fe^{2+} = 0.45-0.66$).

Metatrodhjemites

Jadeite-rich pyroxenes (82-95 mole per cent of jadeite; Fig. 4) were analysed in samples OF 1803a and OF 1803b from Val Susa. Jadeites are zoned, with rims often enriched in acmite and depleted in jadeite with respect to cores, although opposite zoning patterns also occur. On the contrary, the green Na-pyroxenes of sample 1803a are zoned ferro-omphacites (and minor omphacites) (Fig. 4) with rims enriched in jadeite and augite, and strongly depleted in acmite relative to cores (Fig. 7); in the Western Alps ferro-omphacite has been described in the northern Sesia-Lanzo zone by LARDEAUX et al. (1983). The dark green pyroxenes forming a reaction rim between quartz and jadeite are chloromelanites or aerigin-augites (Fig. 4) that grew in equilibrium with albite at the expense of jadeite.

Garnets are almandines (62-80 mole per cent), relatively poor in grossular (13-24 mole per cent), with variable amounts of andradite (0-14 mole per cent) and spessartine (1-11 mole per cent), and very poor in pyrope (1-2 mole per cent) (Fig. 6). They are zoned with rims enriched in almandine and sometimes in pyrope, and depleted in spessartine and grossular relative to cores (Fig. 7).

Following the classification of LEAKE (1978), the amphiboles are ferro-glaucophanes rimmed by riebeckite.

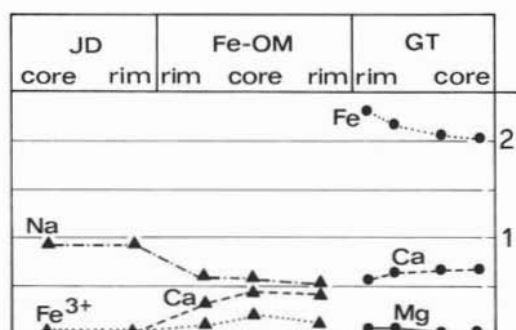


Fig. 7. — Zoning of pyroxenes (triangles) and garnets (circles) in metatrandhjemite OF 1803a from Val Susa. Vertical scale is cations per 6 oxygens for pyroxenes and cations per 12 oxygens for garnets. Abbreviations as in Fig. 5. Ferro-omphacite (Fe-OM) domain is 0.6 mm long.

Thermobarometry

Minimum pressure values for the eclogitic peak in the Rocciavré and Val Susa rocks are confined above the albite = jadeite + quartz curve (HOLLAND, 1980; Fig. 8) by the coexistence of jadeite and quartz. Maximum pressure values around 20 kb are constrained by the presence of paragonite and the lack of omphacite-kyanite assemblages in the Rocciavré Mg-metagabbros, considering the equilibria: omphacite (jd50) + kyanite + H_2O = paragonite, calibrated by HOLLAND (1979) (Fig. 8). The crystallization of omphacite and talc in sample R 299 allows to consider the curve: omphacite (jd50) + talc + H_2O = glaucophane (Fig. 8), recalculated by MEYER (1983) using an ideal mixing model from the experimental curve: jadeite + talc + H_2O = glaucophane (KOONS, 1982). However, in sample R 299 omphacite and talc never occur in mutual contact and they crystallize in different microstructural domains (chemical sub-systems); this suggests that omphacite and talc were probably not able to react to give glaucophane and thus the curve recalculated by MEYER is tentatively considered an upper pressure limit.

As to the evaluation of temperatures, a classical approach for eclogitic rocks is to consider the exchange of the Fe^{2+} -Mg in coexisting garnet-omphacite pairs. For the analyzed rocks, the calibrations of ELLIS and GREEN (1979) and POWELL (1984) considering

the effect of X_{Ca} in garnet were used. In the two Rocciavré Mg-metagabbros temperatures are $500 \pm 90^\circ C$ and $480 \pm 90^\circ C$ (at 15 kb) using the ELLIS and GREEN and POWELL calibrations respectively (mean of 11 pairs and standard deviations). In the metatrandhjemite OF 1803a, temperatures are $410 \pm 45^\circ C$ and $390 \pm 45^\circ C$ (at 15 kb) with the ELLIS and GREEN, and POWELL calibrations respectively (mean of 9 pairs). These values were obtained on minerals in mutual contact.

Temperatures inferred for the Rocciavré Mg-metagabbros are 30-50°C higher than those given for the adjacent Fe-Ti

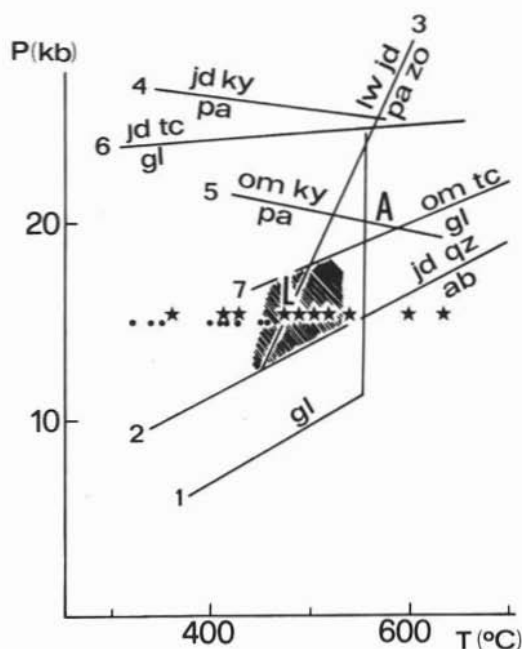


Fig. 8. — P-T diagram showing the conditions of early Alpine eclogite metamorphism in the Rocciavré and Val Susa rocks (shaded area, defined on the basis of garnet-pyroxene thermometry and on other equilibria discussed in the text), and in the Lanzo (L) and Allalin (A) rocks. Stars and dots: temperatures inferred employing garnet-pyroxene thermometry (ELLIS and GREEN calibration, 1979) in Rocciavré Mg-metagabbros and Val Susa metatrandhjemites, respectively. Curves: 1: stability limits of natural glaucophane (MARESCH, 1977); 2: albite = jadeite + quartz (HOLLAND, 1980); 3: lawsonite + jadeite = zoisite + paragonite + quartz + H_2O (HEINRICH and ALTHAUS, 1980); 4: jadeite + kyanite + H_2O = paragonite and 5: omphacite + kyanite + H_2O = paragonite (HOLLAND, 1979); 6: glaucophane = jadeite + talc (KOONS, 1982); 7: glaucophane = omphacite + talc (calculated by MEYER, 1983).

metagabbros (POGNANTE and KIENAST, 1987). This might reflect lower blocking temperatures of the garnet-omphacite geothermometer for Fe-rich systems relative to Mg-rich systems. The large spectrum of values reflects the marked compositional gradients maintained for most elements in these coronitic rocks. In metatrandhjemite OF 1803a the relatively low inferred temperatures may record errors in determination of Fe^{2+} , non-ideal behaviour in the participating solid solution (i.e. N-pyroxenes) and/or lower blocking temperatures in a tectonically active zone close to the tectonic boundary with the Lanzo body.

The above lines of evidence together with the stability of glaucophane, the scarcity of lawsonite (which was found, completely pseudomorphed, only in a few calcschists associated with the metaophiolites), all points to temperatures around 500°C at pressures between 13 and 18 kb for the eclogitic peak of the Rocciavré and Val Susa metaophiolites (Fig. 8).

In the Lanzo body, P-T evaluations for eclogite crystallization using the garnet-omphacite thermometer and other equilibria (POGNANTE and KIENAST, 1987; KIENAST and POGNANTE, 1988), are similar to previous estimates (Fig. 8). On the contrary, remarkably higher temperatures (550-600°C) and pressures (> 20 kb) have been derived for the Allalin metagabbros on the basis of the garnet-omphacite thermometer and the stability of omphacite/jadeite - kyanite - quartz (MEYER, 1983) (Fig. 8).

Petrologic discussion

Reaction mechanisms in Mg-metagabbros

In the little-deformed metagabbros of the Western Alps metaophiolites, the high-pressure reactions often started at the boundaries between the magmatic minerals. Along these boundaries, diffusion occurred in response to gradients in chemical potential of the components and produced distinct reaction zones. Further metamorphic recrystallization proceeded from the boundaries inward, through progressive

TABLE 4

Composition of phases used in reaction (1)

phase	composition
pl	$\text{Ca}_{0.55}\text{Na}_{0.45}\text{Al}_{1.55}\text{Si}_{2.45}\text{O}_8$
cpx	$\text{Ca}_{0.95}\text{Mg}_{0.85}\text{Fe}_{0.20}\text{Al}_{0.05}\text{Si}_{1.95}\text{O}_6$
ol	$\text{Mg}_{0.82}\text{Fe}_{0.18}\text{Si}_{0.50}\text{O}_2$
om	$\text{Na}_{0.35}\text{Ca}_{0.65}\text{Mg}_{0.65}\text{Fe}_{0.05}\text{Al}_{0.30}\text{Si}_{2.06}$
gt	$\text{Ca}_{0.80}\text{Fe}_{1.20}\text{Mg}_{1.00}\text{Al}_{2.00}\text{Si}_{3.00}\text{O}_{12}$
zo	$\text{Ca}_{2.00}\text{Fe}_{0.10}\text{Al}_{2.90}\text{Si}_{3.00}\text{O}_{12}(\text{OH})$
tc	$\text{Mg}_3\text{Si}_4\text{O}_{10}(\text{OH})_2$

reduction of the chemical gradients. In the various magmatic minerals (domains) reactions occurred at different rates and with different mechanisms: plagioclase transformed at higher rates and in the early stages it is replaced by very-fine-grained minerals (e.g. jadeite - zoisite \pm quartz), while in the later stages it is replaced by coarser-grained minerals characterized by a composition indicating a closer interactions with the adjacent domains (e.g. omphacite - zoisite - paragonite - glaucophane); clinopyroxene is preserved in several samples even when the other magmatic phases are completely replaced, and it is often

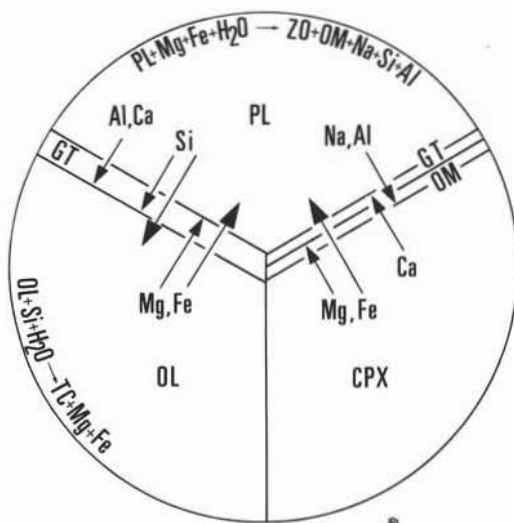
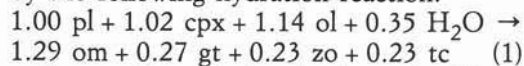


Fig. 9. — Sub-reactions and component-exchange between plagioclase (PL), olivine (OL) and clinopyroxene (CPX) domains in R 299 Mg-metagabbro from Rocciavré. PL breaks down completely; OL is replaced by talc and has a reaction rim of garnet; CPX is partly preserved with composite reaction rim of garnet and omphacite; no reaction rim occurs between OL and CPX. Abbreviation as in Fig. 5.

re-equilibrated through topotactic reactions.

On the basis of the composition of the metamorphic minerals and of the magmatic relics analyzed in adjacent, more preserved, Mg-metagabbros, eclogitisation of sample R 299 from Rocciavré is tentatively described by the following hydration reaction:



Composition of minerals of reaction (1) are reported in Table 4. In sample R 299 the compositional control of the magmatic domains on the kind and composition of the eclogite minerals and the preservation of chemical gradients in the reaction coronas, are obvious from the mineral chemistry (Fig. 5). As already emphasized for Fe-Ti metagabbros (POGNANTE and KIENAST, 1987), this points to eclogite recrystallization governed by local equilibrium. It is therefore possible to subdivide the rock into three sub-systems (plagioclase, clinopyroxene and olivine), each characterized by a peculiar sub-reaction; the sub-systems were not completely closed to component-exchange and the main diffusing components were Mg, Fe, Ca, Si, Na \pm Al (Fig. 9). Reaction (1) also involves infiltration of H₂O into the bulk-rock system.

The kind of metamorphic recrystallization which began at the interface between the magmatic domains (e.g. omphacite-garnet rim) or in cracks within the domains (e.g. vein-like aggregates of garnet in the plagioclase domain), supports the hypothesis that grain-boundary (intercrystalline) diffusion was prevalent over lattice (intracrystalline) diffusion during eclogitisation. Consequently, grain-boundary diffusion and the low dissolution rate of the reactants (recorded by the relics of magmatic diopside) were probably the main mechanisms that governed eclogitisation in sample R 299 from Rocciavré and in many other little-deformed coronitic rocks of the Alpine belt. Because intercrystalline diffusion and dissolution rates of the relics are strongly enhanced by the existence of a fluid phase (BRADY, 1977), infiltration of a H₂O-rich fluid, as implied by reaction (1), is necessary for the various sub-reactions to proceed. Indeed sample OF 469, which is richer in hydrous phases (chlorite,

paragonite, amphibole, chloritoid) and probably sustained a higher interaction with H₂O-rich fluids than sample R 299, displays more advanced eclogitic recrystallization and less marked chemical gradients.

Together with the syn-metamorphic fluid phase, the other factor that favors a closer approach to eclogitic equilibration is pervasive deformation. For the Rocciavré metagabbros, the catalytic effect of deformation on reaction rates and on enlargement of equilibrium domains, has recently been discussed (POGNANTE, 1985; POGNANTE and KIENAST, 1987).

Interpretation of zoning

Two types of zoning are usually recognized in metamorphic minerals (TRACY, 1982): growth zoning, controlled by slow intracrystalline diffusion and depending on the change in composition of the material supplied to the surface of the mineral; and diffusion zoning, imposed upon a pre-existing composition and developed through intracrystalline diffusion. In order to apply zoning for the interpretation of P-T histories, it is thus necessary to interpret the mechanisms of zoning and to know the relative sequence of growth of minerals in the rock.

In the incompletely equilibrated Mg-metagabbro R 299, zoning of garnet and omphacite from the reaction coronas (Fig. 5), are interpreted as the result of incomplete elimination of chemical potential gradients during growth in conditions of sluggish and selective diffusion between the chemical sub-systems. The Ca-depletion in garnet rims from metatrandhemite OF 1803 is rather common in low grade rocks (TRACY, 1982) and is interpreted as growth zoning. On the contrary, the Ca-depletion (and enrichment in jadeite molecule) in the ferro-omphacite rims of sample OF 1803a (Table 3; Fig. 7) is diffusion zoning imposed on probable ferro-augite during pressure increase; indeed, the abundance of rutile and opaque inclusions in ferro-omphacite cores supports derivation from a relatively Ti-rich ferro-augite of probable magmatic origin according to the

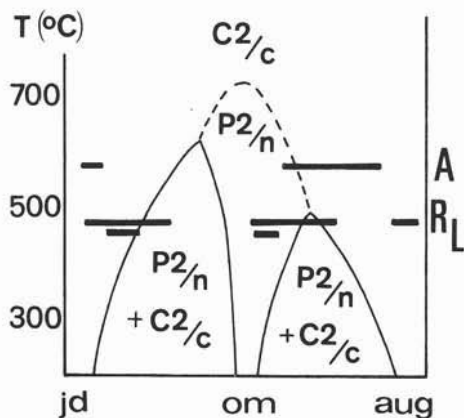


Fig. 10. — Equilibrium phase diagram along jadeite-augite join (CARPENTER, 1980). Diagram shows composition of pyroxenes from Rocciavré Mg-metagabbros and Val Susa metatrandhjemites (R, this work), Lanzo Mg-metagabbros (L, KIENAST and POGNANTE, 1988) and Allalin Mg-metagabbros (A, MEYER, 1983).

coupled reaction: $\text{Ca, Fe} = \text{Na, Al}^{\text{VI}}$. The enrichment of jadeite molecules in the rims of ferro-omphacite is in agreement with the parallel depletion of jadeite molecules in the rims of the adjacent blasts of jadeite that grew at the expense of sodic plagioclase.

In conclusion, zoning of metamorphic minerals from low-grade rocks that were split into several sub-systems during metamorphism must be carefully evaluated and, at times, may be useless for interpretation of P-T paths. In these rocks zoning may record: 1) incomplete topotactic re-equilibration through intracrystalline diffusion of a pre-metamorphic phase; 2) incomplete elimination of chemical gradients during growth of minerals in response to the complex sequence of sub-reactions proceeding in the rock at different rates.

Pyroxene immiscibility

Fig. 4 shows two well defined compositional groups for Na-pyroxenes that crystallized in metatrandhjemite OF 1803a. The two groups include ferro-omphacite (with minor omphacite and chloromelanite) and impure jadeite, and testify to two different magmatic domains, i.e. probable ferro-augite and sodic

plagioclase, respectively. Because ferro-omphacite and jadeite are in mutual contact and are not separated by a syn-eclogite reaction rim, their coexistence is interpreted as the result of the miscibility gap existing along the omphacite-jadeite joint at temperatures lower 600°C (CARPENTER, 1980). In the low temperature eclogites of the Western Alps this gap has been already recognized in the metagabbros from Rocciavré and Lanzo (POGNANTE and KIENAST, 1987; KIENAST and POGNANTE, 1988). Detailed study of pyroxene immiscibility in the Val Susa metatrandhjemites is currently in progress with J.R. Kienast.

In the equilibrium phase diagram of CARPENTER (1980) (Fig. 10), the composition of Na-pyroxenes from the metatrandhjemite OF 1803 is plotted and compared to the composition of Na-pyroxenes from the Mg-metagabbros. The distribution of Na-pyroxenes in Carpenter's diagram is partly consistent with the geothermometric estimates discussed above.

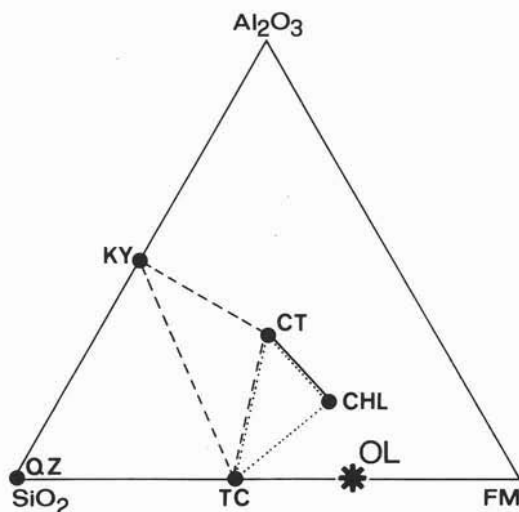


Fig. 11. — Al_2O_3 - FM (FeO + MgO) - SiO_2 (+ H_2O) diagram describing eclogitic assemblages crystallized in olivine domain of the Mg-metagabbros: KY-TC-CT at Allalin, CT-CHL at Rocciavré and TC-CT at Lanzo. Abbreviations: KY: kyanite, CT: chloritoid, CHL: chlorite, TC: talc, QZ: quartz. Asterisk: average composition of the magmatic olivine from Alpine Mg-gabbros.

TABLE 5
Composition and equilibria used in
Schreinemakers analysis

phase	composition
ct	(Fe,Mg) ₂ Al ₄ Si ₂ O ₁₀ (OH) ₄
ky	Al ₂ SiO ₅
tc	(Fe,Mg) ₆ Si ₈ O ₂₀ (OH) ₄
chl	(Fe,Mg) ₉ Al ₆ Si ₅ O ₂₀ (OH) ₁₆
qz	SiO ₂
V	H ₂ O

equilibria	
(ct)	2chl + 20qz = 3tc + 6ky + 10V
(ky)	2chl + 12 qz = 2tc + 3ct + 6V
(tc)	9ct + 4qz = 2chl + 12ky + 2V
(chl)	1tc + 6ky + 4V = 3ct + 8qz
(qz)	15ct + 1tc = 4chl + 18ky

Phase relations in Mg-metagabbros

The thermobarometry discussed above yields partly different P-T conditions for the eclogite recrystallization in the Rocciavré, Lanzo and Allalin Mg-metagabbros. These Mg-metagabbros also differ as to eclogite mineralogy in the domain of the magmatic olivine: chlorite and chloritoid crystallized in sample OF 469 from Rocciavré, talc-chloritoid ± chlorite formed at Lanzo, and talc - chloritoid - kyanite occur at Allalin. In all these rocks the olivine domain is rimmed by a corona of pyrope-rich garnet. In sample R 299 from Rocciavré, interaction with the adjacent domains was less marked than in the above rocks and consequently only talc grew in the olivine domain.

Minerals formed in the olivine domain (except garnet) are described by the system Al₂O₃ - FM (FeO + MgO) - SiO₂ - H₂O (Fig. 11). Because this system has been experimentally investigated for Mg composition by MASSONE et al. (1981) and CHOPIN and SCHREYER (1983), it is considered here in order to explain the different eclogite assemblages of the olivine domain, and in order to check the consistency of the thermobarometric estimates. Assuming that H₂O is externally buffered and starting from the three-component system Al₂O₃-FM - SiO₂, a Schreinemakers analysis (ŽEN, 1966)

was derived for the five equilibria reported in Table 5 ((ct), (ky), (tc), (chl) and (qz)). Employing the available experimental data to define the approximate slopes of the two equilibria (ct) (MASSONNE et al., 1981) and (qz) (CHOPIN and SCHREYER, 1983), a qualitative P-T diagram was constructed (Fig. 12).

From the P-T diagram of Fig. 12 it is apparent that: 1) the stability of Mg-chloritoid confines the metamorphic recrystallization at relatively high pressures (P tot = P H₂O); 2) the talc - kyanite - chloritoid assemblage of the Allalin Mg-metagabbros is typical of higher temperatures relative to the assemblages of the Rocciavré and Lanzo rocks.

However, the P-T diagram does not consider the composition of chloritoid that is actually slightly different in the three Mg-metagabbros. In order to take into account the influence of P-T conditions and mineral assemblages on chloritoid composition, the tentative isothermal P-X_{Mg} and isobaric T-X_{Mg} diagrams constructed by CHOPIN (1983) are reported in Fig. 13. Chopin's diagrams were derived for the Al₂O₃ - FM - SiO₂ - H₂O system using the same equilibria reported in Tab. 5, except for equilibria (qz) that is replaced here by equilibria: (O) chloritoid + kyanite + H₂O = chlorite + quartz. On the basis of equilibria (O) reported in Fig. 13. and for X_{Mg} in chloritoid lower

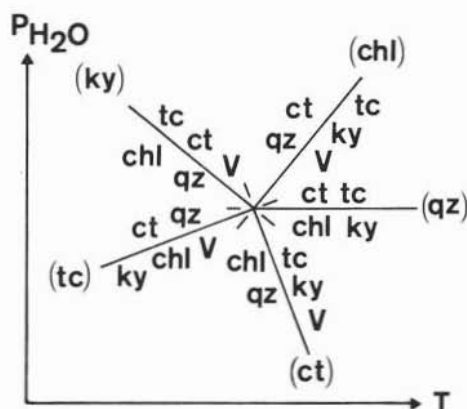


Fig. 12. — Qualitative P-H₂O - T diagram constructed to describe phase relations in Al₂O₃ - FM - SiO₂ (+ H₂O) system. Equilibria and abbreviations as in Table 5.

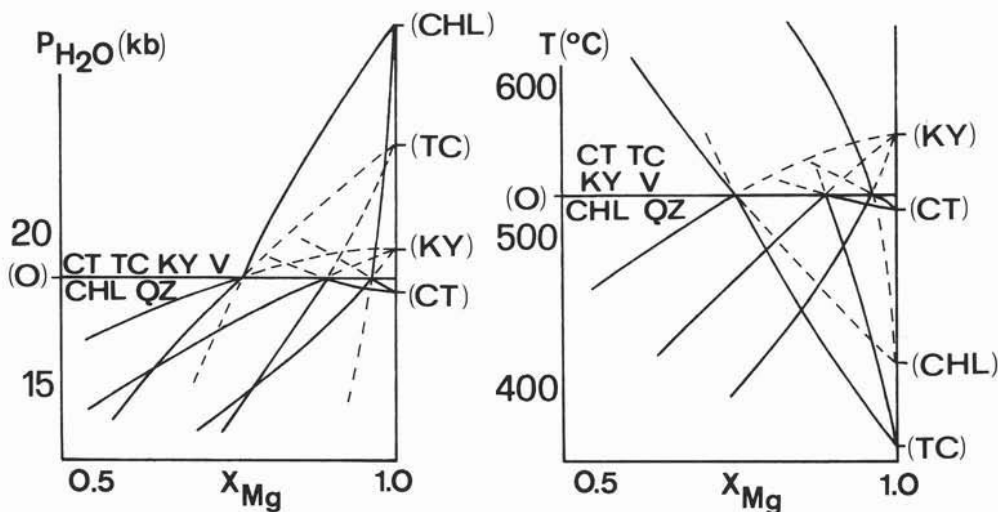


Fig. 13. — Tentative isothermal $P - X_{Mg}$ (at 540°C) and isobaric $T - X_{Mg}$ (at 19 kb) diagrams constructed by CHOPIN (1983) to describe the effect of P - T conditions on phase relations and on chloritoid composition (X_{Mg}). Equilibria as in Fig. 12 and Table 5, except for equilibria (O) $ct + tc + ky + v = chl + qz$.

than 0.75, temperatures and pressures in excess of approximately 530°C and 18 kb should characterize eclogitization in the talc - kyanite - chloritoid - bearing metagabbros from Allalin; on the contrary, the previous estimates should be regarded as maximum values for the Rocciavré and Lanzo rocks. This is consistent with the independent thermobarometric estimates reported previously in this paper.

In the above discussion it is assumed that $P_{H_2O} = P_{tot}$. However, it has been suggested that fluid-deficient conditions accompanied eclogitisation in a few little-deformed Fe-Ti metagabbros rich in magmatic relics (POGNANTE and KIENAST, 1987). $P_{H_2O} < P_{tot}$ conditions may (at least during limited periods of time) have attained the eclogitisation of sample R 299 from Rocciavré and of some Lanzo rocks, but this is probably not the case of sample OF 469 from Rocciavré which is rich in hydrous phases and shows less defined magmatic domains and less marked chemical gradients.

Hydration- versus dehydration-reactions in Mg-gabbro - Fe-Ti gabbro eclogitised suites

Starting from the evidence that the distribution of deformation and syn-

metamorphic fluid phase was heterogeneous during eclogitisation of the Rocciavré metagabbros (POGNANTE, 1985; POGNANTE and KIENAST, 1987), a comprehensive model is proposed here to explain the eclogite evolution in the interlayered ophiolite suites consisting of Fe-Ti metagabbros and Mg-metagabbros.

In many Mg-metagabbros and notably in the mylonitic Mg-metagabbros, H_2O must have been introduced into the anhydrous magmatic system in order to give the hydrous eclogitic minerals (see reaction (1)). Such interaction with H_2O is less obvious in the Fe-Ti metagabbros which, in many mylonitic zones, recrystallized according to reaction (POGNANTE, 1985):

1 augite + 1.4 plagioclase + 0.9 Fe-Ti oxides \rightarrow 1.6 omphacite + 0.7 garnet + 0.7 rutile + 0.3 quartz + 0.2 O_2 (2). The bulk chemistry thus favors the stabilization of more hydrous assemblage in Mg-metagabbros than in Fe-Ti metagabbros (CIMMINO et al., 1981).

Because the magmatic assemblages were characterized by anhydrous phases (except, perhaps, a few late magmatic hornblendes), there are two possible origins of the H_2O -rich fluid. It may be inherited from ocean-floor metamorphism that followed crystallization of the gabbros from tholeiitic magma but pre-dated the early Alpine

metamorphism, or it infiltrated during the early Alpine eclogitisation from an external reservoir. At Rocciavré ocean-floor metamorphism (or a late magmatic stage) is documented in a few samples by the growth of brown amphiboles at the expense of the magmatic pyroxenes (POGNANTE, 1981), but no evidence of syn-eclogite infiltration of a fluid in large amounts, for example through syn-eclogite metamorphic veins, are preserved.

Although infiltration of H_2O from an external reservoir during eclogitisation of the thick suite of metagabbros from Rocciavré cannot be excluded, it is more likely that at least part of the fluids responsible for the growth of the hydrous eclogite minerals infiltrated prior to the early Alpine metamorphism, during an ocean-floor event (see also POGNANTE and KIENAST, 1987). During eclogitisation, fluids diffused at the scale of the outcrop in response to hydration reactions in the Mg-metagabbros (similar to reaction (1)), and to prevalent reactions that did not involve significant amounts of H_2O (similar to reaction (2)), or dehydration reactions in the case of previous ocean-floor hydration, in some Fe-Ti metagabbros. On the contrary, in small bodies of metagabbro included in water-rich metasediments (calcschists), more important contribution of H_2O through infiltration from adjacent metasediments must be expected during the Alpine metamorphism.

Summary

The main conclusions provided by this paper are summarized as follows:

- 1) Ophiolite Mg-metagabbros from the Rocciavré massif have omphacite - garnet - zoisite - talc or omphacite - garnet - zoisite - Mg-chloritoid - Mg-chlorite - amphibole eclogite assemblages of early Alpine age.

- 2) Ophiolite metatrandhjemites from Val Susa are characterized by jadeite - quartz - garnet - ferro-glaucophane - sphene \pm ferro-omphacite eclogite assemblages.

- 3) P-T estimates based on the garnet-pyroxene geothermometer and on other equilibria point to temperatures around 500°C at pressures between 13 and 18 kb for

the eclogite peak of the Rocciavré and Val Susa rocks (Fig. 8). This is in agreement with previous estimates in this part of the Alpine metaophiolites.

- 4) Eclogitisation of the little-deformed Mg-metagabbros was not always complete and was governed by local equilibria and slow reaction kinetics which, at least during limited periods of time, were favored by $P H_2O < P_{tot}$ conditions.

- 5) In little-deformed low-grade rocks characterized by a local equilibrium reaction mechanism, zoning of metamorphic minerals must be carefully evaluated in order to unravel P-T histories; zoning may be the result either of incomplete reequilibration of a pre-metamorphic phase, or of incomplete elimination of chemical gradients during growth of the minerals in response to the relative sequence of sub-reactions which proceeded in the rock at different rates.

- 6) The coexistence in the Val Susa metatrandhjemites of jadeite and ferro-omphacite in mutual contact is ascribed to the miscibility gap existing at low temperatures on the jadeite-omphacite join.

- 7) In little-deformed metagabbros rich in MgO and Al_2O_3 study of phase compatibilities in the Al_2O_3 - FM - SiO_2 (+ H_2O) system may be an alternative or complementary method to the classical thermobarometry used in eclogites.

- 8) A tentative model is proposed for eclogitisation in the interlayered intrusive suites of the Western Alps metaophiolites. According to this model, hydration reactions occurred in the Mg-metagabbros, while prevalent reactions that did not involve significant amounts of H_2O , or possibly dehydration reactions, characterized a few Fe-Ti metagabbros; the sequence of reactions in adjacent volumes of Mg-metagabbro and Fe-Ti metagabbro favored the diffusion of H_2O and contributed to a heterogeneous distribution of fluids during eclogitisation. In this view, the existence of rock-volumes that sustained eclogitisation under water-deficient conditions and display only an incipient (or in very few samples lack) metamorphic recrystallization, may be due to the faster progress of hydration reactions in certain rock-

volumes producing a marked depletion of the fluid phase in adjacent volumes. Additionally, the heterogeneous distribution of the fluid phase possibly influenced (but in turn may have been constrained by) the location of pervasive deformation along shear zones.

Acknowledgements. — This paper was improved by critical comments of two referees and by discussion with B. Lombardo. The Centro di Studio sui Problemi dell'Orogeno delle Alpi Occidentali (C.N.R., Torino) financially supported this work. The C.N.R. (C.S. Stratigrafia e Petrografia delle Alpi Centrali, Milano) is acknowledged for installation and operation of the electron microprobe laboratory in the Dipartimento di Scienze della Terra di Milano.

This work is part of a C.N.R. (Centro di Studio sui Problemi dell'Orogeno delle Alpi Occidentali, Torino) programme.

REFERENCES

- BALDELLI C., DAL PIAZ G.V., LOMBARDO B. (1985) - *Ophiolite eclogites from Verres, Val d'Aosta, Western Alps, Italy*. Chem. geol. 50, pp. 87-98.
- BARNICOAT A.C., FRY N. (1986) - *High pressure metamorphism of the Zermatt-Saas ophiolite zone, Switzerland*. J. Geol. Soc., London 143, pp. 607-618.
- BEARTH P. (1967) - *Die Ophiolite der Zone von Zermatt-Saas Fee*. Betr. geol. Karte Schweiz 130, pp. 132.
- BRADY J.B. (1977) - *Metasomatic zones in metamorphic rocks*. Geochim. Cosmochim. Acta 41, pp. 113-125.
- CARPENA J., POGNANTE U., LOMBARDO B. (1986) - *New constraints for the timing of the alpine metamorphism in the internal ophiolitic nappes from western Alps as inferred from fission-track data*. Tectonophysics 127, pp. 117-127.
- CARPENTER M.A. (1979) - *Omphacites from Greece, Turkey and Guatemala: composition limits of cation ordering*. Am. Mineral. 64, pp. 102-108.
- CARPENTER M.A. (1980) - *Mechanism of exsolution in sodic pyroxenes*. Contrib. Mineral. Petrol. 71, pp. 289-300.
- CHINNER G.A., DIXON J.E. (1973) - *Some high pressure parageneses of the Allalin gabbro, Valais, Switzerland*. J. Petrol. 14, pp. 185-202.
- CHOPIN C. (1983) - *Mg-chloritoid, a key minerals for the petrogenesis of high grade pelitic blueschists*. Bull. Mineral. 106, pp. 715-717.
- CHOPIN C., SCHREYER W. (1983) - *Magnesio-carpholite and magnesio-chloritoid: two index minerals of pelitic blueschists and their preliminary phase relations in the model system $MgO - Al_2O_3 - SiO_2 - H_2O$* . Am. J. Sci. 283A, pp. 72-96.
- CIMMINO F., MESSIGA B., PICCARDO G. (1981) - *Le caratteristiche paragenetiche dell'evento eclogitico di alta pressione nei diversi sistemi (pelitici, femici, ultrafemici) delle ofioliti metamorfiche del Gruppo di Voltri (Liguria occidentale)*. Rend. Soc. Ital. Mineral. Petrol. 37, pp. 419-446.
- DAL PIAZ G.V. (1974) - *Le metamorfisme de haute pression et basse temperature dans l'evolution structurale du bassin ophiolitique alpine-apenninique*. Schweiz. Mineral. Petrogr. Mitt. 54, pp. 399-424.
- ELLIS D.J., GREEN D.H. (1979) - *An experimental study of the effect of Ca upon garnet-clinopyroxene equilibria*. Contrib. Mineral. Petrol. 71, pp. 13-22.
- ELTER G.I. (1971) - *Schistes lustrés et ophiolites de la zone piémontaise entre Orco et Doire Baltee (Alpes Graies)*. Geol. Alpine 47, pp. 147-169.
- ERNST W.G., DAL PIAZ G.V. (1978) - *Mineral parageneses of eclogitic rocks and related mafic schists of the Piemonte Ophiolite nappe, Italian Western Alps*. Am. Mineral. 63, pp. 621-640.
- HEINRICH W., ALTHAUS E. (1980) - *Die obere Stabilitätsgrenze von Lawsonit plus Albit bzw. Jadeit*. Fortschr. Mineral. 58, pp. 49-50.
- HOLLAND T.J.B. (1979) - *Experimental determination of the reaction $\text{paragonite} = \text{Jadeite} + \text{Kyanite} + K_2O$, and internally consistent thermodynamic data for part of the system $Na_2O - Al_2O_3 - SiO_2 - H_2O$, with application to eclogites and blueschists*. Contrib. Mineral. Petrol. 68, pp. 293-301.
- HOLLAND T.J.B. (1980) - *The reaction albite = jadeite + quartz determined experimentally in the range 600°-1200°C*. Am. Mineral. 64, pp. 129-134.
- KIENAST J.R. (1983) - *Le metamorfisme de haute pression et basse temperature (eclogite et schistes bleus): donnees nouvelles sur la petrologie des roches de la croûte oceanique subductee et des sediments associes*. Thesis. Universite de Paris VI, pp. 474.
- KIENAST J.R., MESSIGA B. (1987) - *Cr-rich Mg-chloritoid, a first record in high pressure metagabbros from Monviso (Cottian Alps, Italy)*. Mineral. Mag., 51, 681-687.
- KIENAST J.R., POGNANTE U. (1988) - *Chloritoid-bearing assemblages in eclogitised metagabbros of the Lanzo peridotite body (western Italian Alps)*. Lithos, 21, pp. 1-11.
- KOONS P.O. (1982) - *An investigation of experimental and natural high pressure assemblage from the Sesia zone, western Alps, Italy*. Thesis, ETH Zürich, pp. 260.
- LARDEAUX J.M., LOMBARDO B., GOSSO G., KIENAST J.R. (1983) - *Decouverte de parageneses a ferro-omphacites dans les orthogneiss de la zone Sesia-Lanzo septentrionale (Alpes Italiennes)*. C.R. Acad. Sci. Paris 296, pp. 453-456.
- LARDEAUX J.M., CARON J.M., NISIO P., PEQUIGNOT G., BOUDEULLE M. (1986) - *Microstructural criteria for reliable thermometry in low-temperature eclogites*. Lithos 19, pp. 187-203.
- LEAKE B.E. (1978) - *Nomenclature of amphiboles*. Am. Mineral. 63, pp. 1023-1052.
- LOMBARDO B., NERVO R., COMPAGNONI R., MESSIGA B., KIENAST J.R., MEVEL C., FIORA L., PICCARDO G.B., LANZA R. (1978) - *Osservazioni preliminari sulle ofioliti metamorfiche del Monviso (Alpi occidentali)*. Rend. Soc. Ital. Mineral. Petrol. 34, pp. 253-305.
- MARESCHE W.V. (1977) - *Experimental study on glaucophane: an analysis of present knowledge*. Tectonophysics 43, pp. 109-125.
- MASSONE H.J., MIRWALD P.W., SCHREYER W. (1981) - *Experimentelle Überprüfung der Reaktionskurve Chlorit*

- + Quartz = Talk + Disthen im system $MgO - Al_2O_3 - SiO_2 - H_2O$. Fortschr. Mineral. 59, pp. 122-123.
- MEYER J. (1983) - Mineralogie und Petrologie des Allalngabbros. Thesis, Universitat Basel, pp. 331.
- NISIO P. (1985) - Les domaines d'antiphas des omphacites et la petrologie des eclogites: contribution a l'etude de l'evolution tectonometamorphique du Monviso (Alpes italiennes occidentales). These, Universite Claude Bernarde, Lyon, pp. 117.
- OTTEN M., BROWER H. (1979) - High pressure metamorphism in a ferrogabbro from Fenestrelle (Western Italian Alps). Schweiz. Mineral. Petrogr. Mitt. 59, pp. 281-297.
- POGNANTE U. (1979) - The Orsiera-Rocciavré metaophiolitic complex (Italian Western Alps). Ofioliti 4, pp. 183-198.
- POGNANTE U. (1980) - Preliminary data on the Piemonte ophiolite nappe in the lower Val Susa - Val Chisone area, Italian Western Alps. Ofioliti 5, pp. 221-240.
- POGNANTE U. (1981) - Magmatic and metamorphic evolution of two Fe-Ti gabbroic series from the Piemonte ophiolite nappe in the Susa Valley area, Italian Western Alps. Mem. Sci. Geol. Padova 35, pp. 21-34.
- POGNANTE U. (1984) - Eclogitic versus blueschist metamorphism in the internal Western Alps along the Susa Valley traverse. Sci. Geol. Bull. Strasbourg 37, pp. 29-36.
- POGNANTE U. (1985) - Coronitic reactions and ductile shear zones in eclogitized ophiolite matagabbro, western Alps, north Italy. Chem. Geol. 50, pp. 99-109.
- POGNANTE U., PICCARDO G.B. (1984) - Petrogenesi delle ofioliti delle Alpi Occidentali. Mem. Soc. Geol. Ital. 29, pp. 79-92.
- POGNANTE U., TOSCANI L. (1985) - Geochemistry of basaltic and gabbroic metaophiolites from the Susa Valley, Italian Western Alps. Schweiz. Mineral. Petrogr. Mitt. 65, pp. 256-277.
- POGNANTE U., KIENAST J.R. (1987) - Blueschist and eclogite transformations in Fe-Ti gabbros: a case from the western Alps ophiolites. J. Petrol. 28, pp. 271-292.
- POGNANTE U., LOMBARDO B., VENTURELLI G. (1982) - Petrology and geochemistry of Fe-Ti gabbros and plagiogranites from the Western Alps ophiolites. Schweiz. Mineral. Petrogr. Mitt. 62, pp. 457-472.
- POGNANTE U., ROESLI U., TOSCANI L. (1985) - Petrology of ultramafic and mafic rocks from the Lanzo peridotite body (Western Alps). Lithos 18, pp. 201-214.
- POWELL R. (1985) - Regression diagnostics and robust regression in geothermometer/geobarometer calibration: the garnet-clinopyroxene geothermometer revisited. J. Metam. Geol. 3, pp. 231-243.
- SANDRONE R., LEARDI L., ROSSETTI P., COMPAGNONI R. (1986) - P-T conditions for the eclogitic re-equilibration of the metaophiolites from Val d'Ala di Lanzo (internal Piemonte zone, Western Alps). J. Metam. Geol. 4, pp. 161-178.
- TRACY R. (1982) - Compositional zoning and inclusions in metamorphic minerals. In Ferry J.M. Ed., Characterization of Metamorphism through Mineral Equilibria. Rev. Mineral. 10, pp. 353-397.
- ZEN E.A. (1966) - Construction of pressure-temperature diagrams for multicomponent systems after the method of Schreinemaker - A geometric approach. Geol. Surv. Bull. 1225, p. 1-56.