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Regional Metamorphism in the Ivrea Zone (Southern Alps, N-Italy): Field and microscopic Investigations [1]

by *André Zingg* [2]

Abstract

High grade metamorphic rocks of the Ivrea zone (Southern Alps) were studied in the region of the Val d'Ossola and the Val Sesia. The following mineral isograds were identified and mapped:

- The muscovite-potassic feldspar isograd in sillimanite- and quartz-bearing metapelites.
- The amphibole-clinopyroxene isograd in impure marbles in the presence of calcite and quartz.
- The first appearance of clinopyroxene and of orthopyroxene in mafic rocks.

The regular isograd zonation indicative of amphibolite to granulite facies metamorphism in the Val d'Ossola region is not matched in the Val Sesia by the rocks of the Mafic Formation (= Basischer Hauptzug) which shows relict magmatic features.

Mineral isograds and regional distribution of cordierite and of the Al_2SiO_5-polymorphs not only indicate increasing pressure and temperature across the Ivrea zone towards NW but also increasing pressure parallel to the strike of the zone towards NE.

1. Geological Setting

The Ivrea zone is part of the Southern Alps and consists of a steeply dipping sequence of pelitic and mafic rocks with small carbonate and ultramafic bodies, metamorphosed under amphibolite to granulite facies conditions. This metamorphism is Caledonian according to Rb-Sr whole rock ages (HUNZIKER and ZINGG, this volume). The monazites of the same rocks give Permian ages (KÖPPEL 1974, KÖPPEL and GRÜNENFELDER 1978/79) whereas the ages of hornblende and micas are lower Mesozoic (McDOWELL and SCHMID 1968, HUNZIKER 1974).

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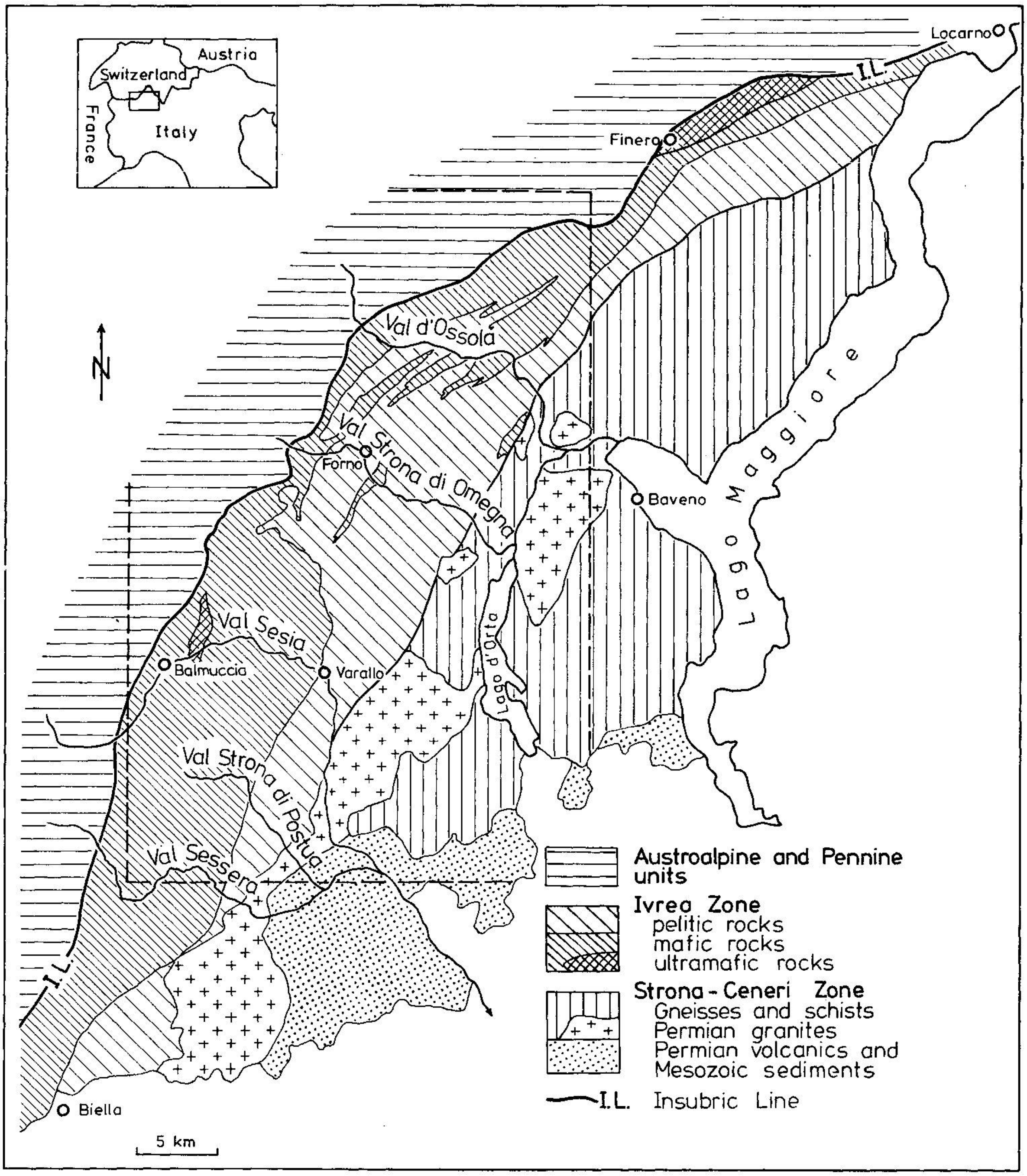

Fig. 1 Sketch map of the Southern Alps west of the Lago Maggiore. □ Area of the mineral distribution maps (Fig. 2, 3 and 4).

In the central part of the Ivrea zone the pelitic and mafic rocks are interlayered, whereas in the SW and NE part of the zone the mafic rocks form a huge mass called Mafic Formation or in German «Basischer Hauptzug» (Fig. 1). According to petrological and geochemical investigations of RIVALENTI et al. (1975) parts of the Mafic Formation show similarities to a stratiform complex and Sr, Pb and S isotope data support a mantle origin for its material (GRAESER and HUNZIKER 1968, HEILMANN and LENSCH 1977).

The Ivrea zone is separated in the NW by the Insubric Line (e.g. GANSSER 1968) from the Alpine «root zones». To the SE the contact to the Strona-Ceneri zone is normal in the region between the Lago Maggiore and the Val Cannobina and tectonic in the other parts (Pogallo Line and other faults) according to BORIANI (1970), BORIANI and SACCHI (1973) and BORIANI et al. (1977).

The region of the Ivrea zone shows a positive Bouger anomaly of up to + 50 mgal (e.g. KAMINSKI and MENZEL 1968, VECCHIA 1968), a magnetic anomaly (e.g. ALBERT 1976) and an inversion of the seismic velocities between 10 and 50 km depth (e.g. ANSORGE 1968, German Research Group for Explosion Seismology 1968, GIESE 1968). To explain these geophysical anomalies a model was proposed which considers the Ivrea zone as a thrusted slice of the deepest crust over rocks of lower density.

2. Aim and Method of Investigation

Based on microscopic studies and radiometric age determinations the metamorphism of the Ivrea zone has been described in the literature as either a single phase or a two phase event. Petrologists who have investigated the central part of the Ivrea zone (Val d'Ossola and Val Strona di Omegna) with the alternation of pelitic and mafic rocks observed only one phase of crystallisation with some retrograde reactions such as kelyphite around garnet and locally recrystallized textures (PEYRONEL PAGLIANI and BORIANI 1967, SCHMID 1967, BERTOLANI 1968). From regions of the Mafic Formation, however, granulite facies metamorphism with a later overprint of amphibolite facies metamorphism was reported (CAPEDRI 1971, KRUHL and VOLL 1976, STECK and TIÈCHE 1976).

As the Ivrea zone has been proposed as a model for the crust-mantle transition (e.g. GIESE 1968, MEHNERT 1975) it seems important to know whether this zone has been overprinted by a second phase of metamorphism, or simply tilted and uplifted to reveal the unmodified physical conditions existing at the base of the crust. To answer this question, modes and textures of pelitic, mafic and carbonate rocks were studied. Regions where one phase and regions where two phases of metamorphism were described were connected by mineral isograds and the relation between the Mafic Formation and the pelites was studied.

3. Petrology

The metamorphism of the Ivrea zone grades from the amphibolite to the granulite facies towards NW as can be seen from the mineral distribution maps (Fig. 2, 3 and 4). These maps include data of ARÉVALO (1980), BERTOLANI (1961

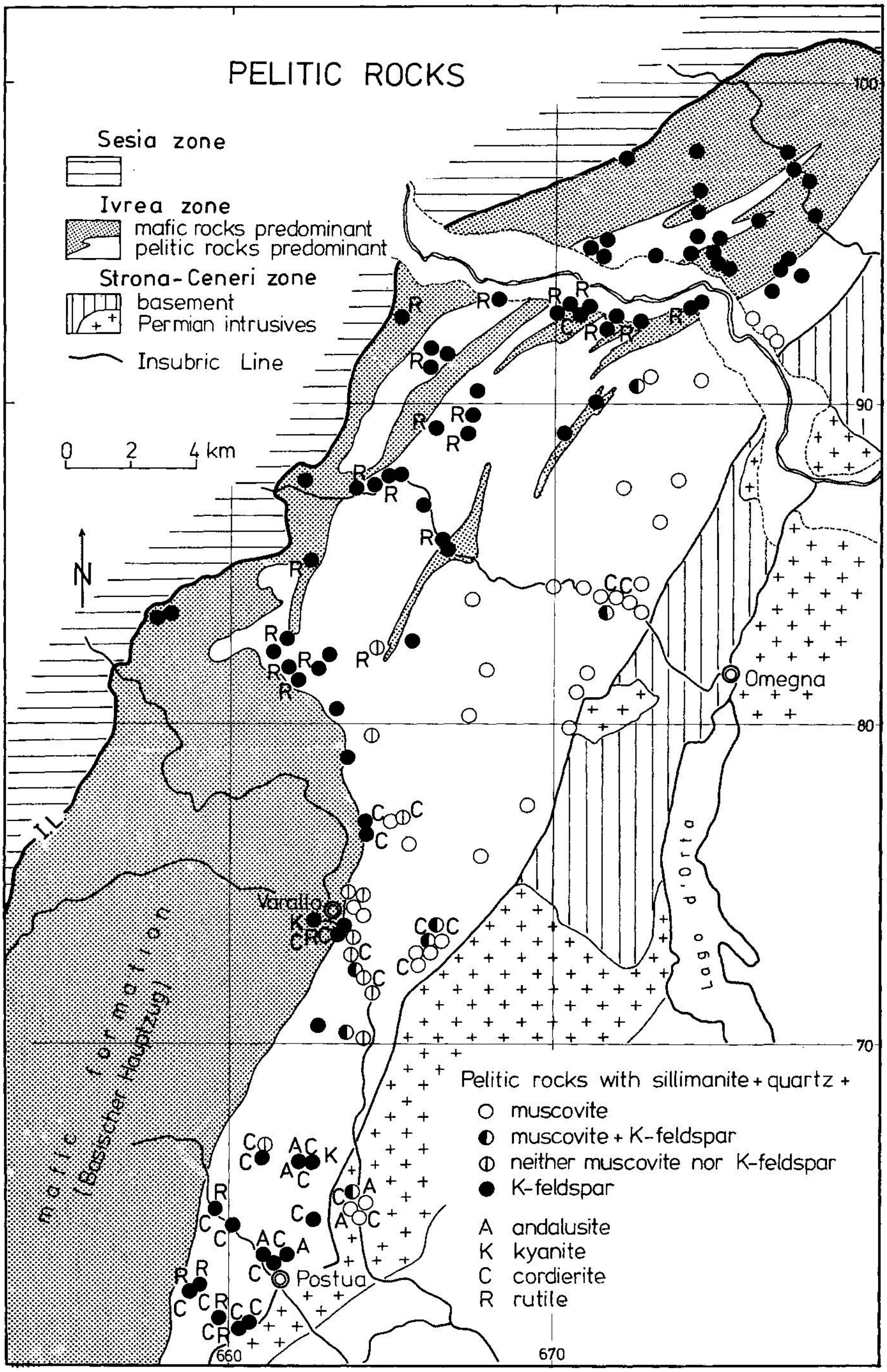

Fig. 2 Regional distribution of the critical minerals in sillimanite bearing metapelites. Representative modes are given in tables 1 and 2.

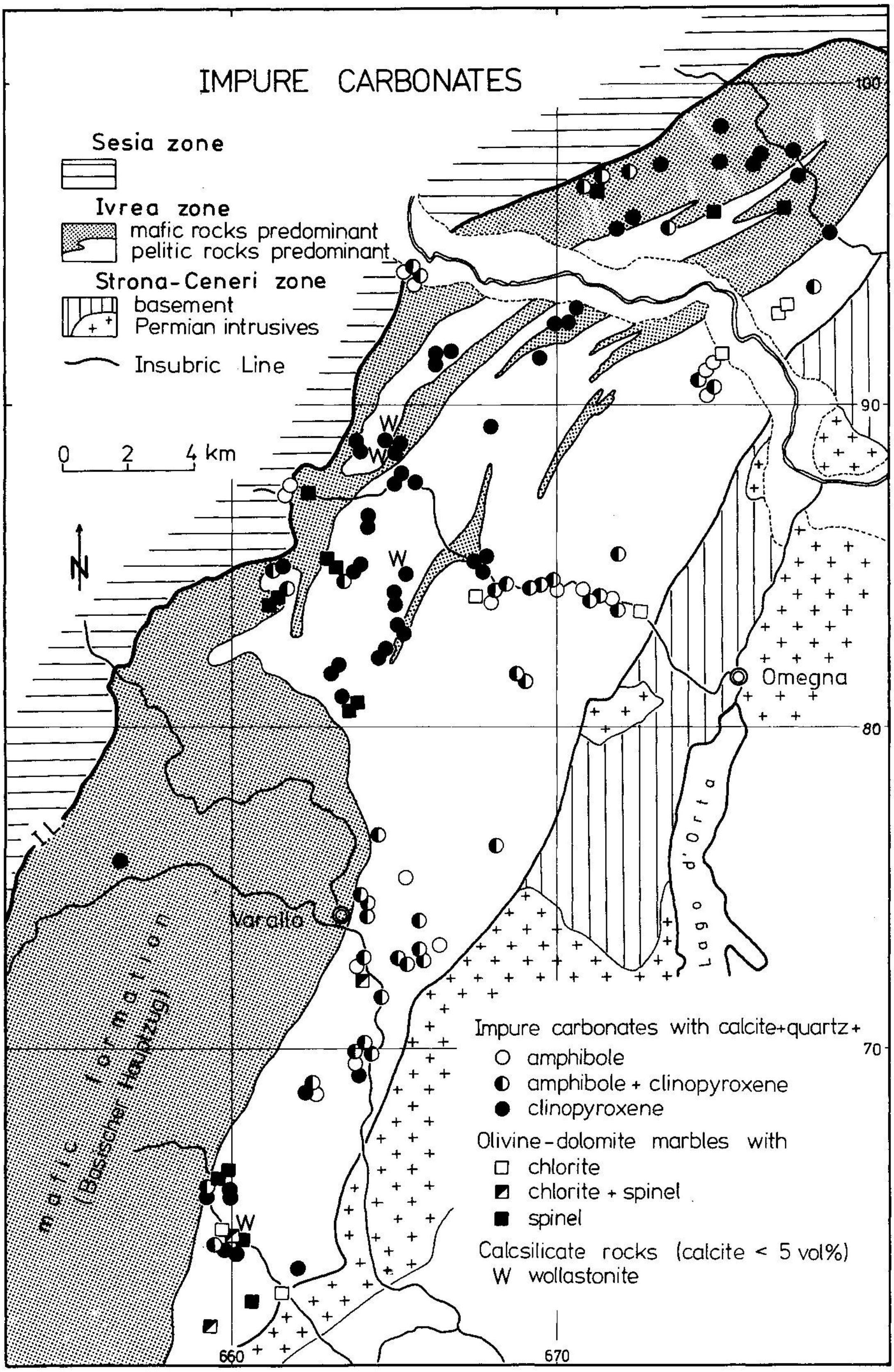

Fig. 3 Regional distribution of some critical minerals in metacarbonates. Representative modes are given in tables 3 and 4.

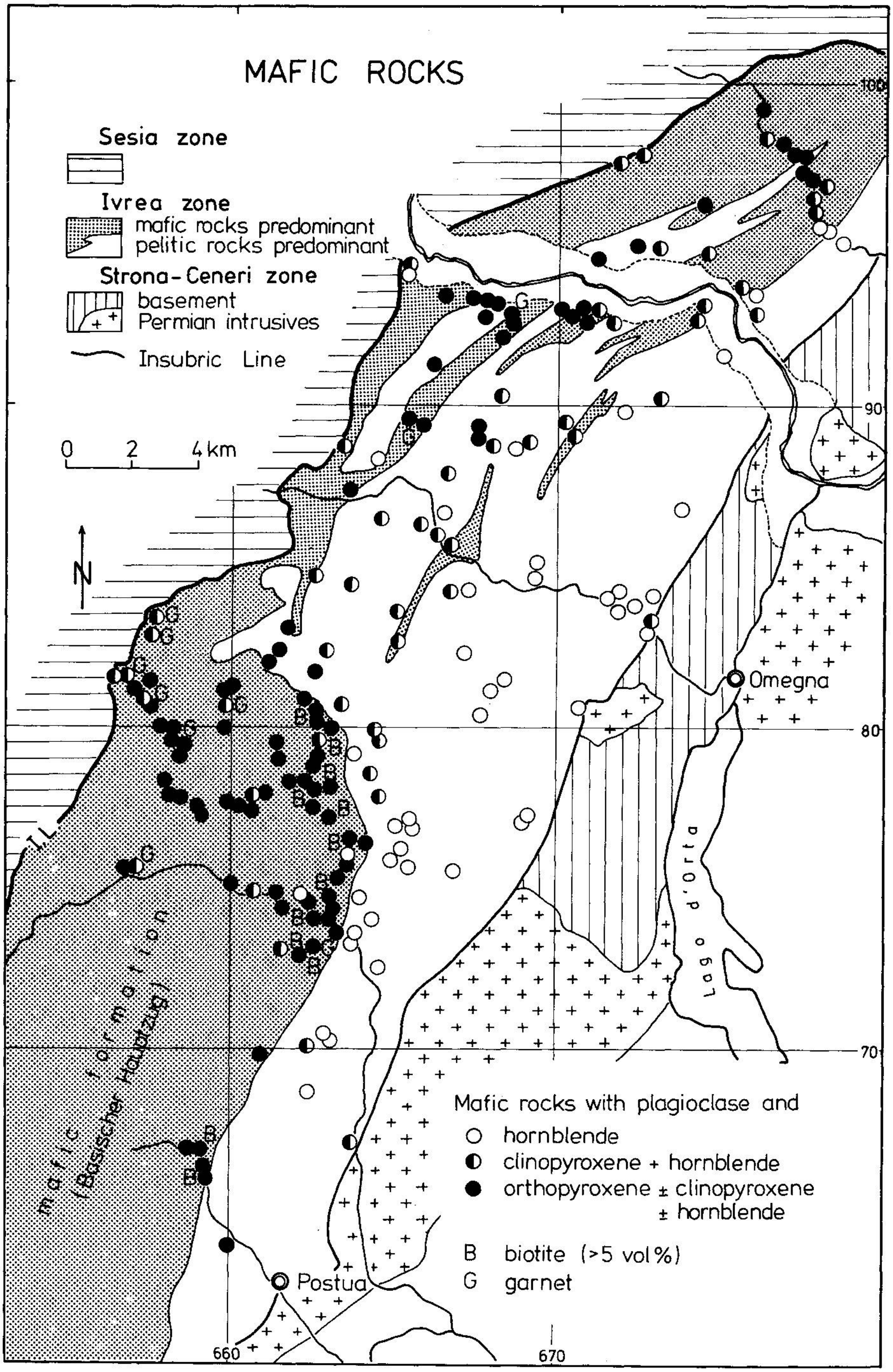

Fig. 4 Regional distribution of clinopyroxene, orthopyroxene and garnet in metabasic rocks. For representative modes consult tables 5 and 6.

and 1968), CAPEDRI (1971), HUTTENLOCHER (1942), PAPAGEORGAKIS (1961), PEYRONEL PAGLIANI and BORIANI (1967), SCHILLING (1957) and SCHMID (1967). Only the occurrence of minerals as disperse phases in the rocks are reported on these maps. Minerals from pegmatitic segregations were omitted.

In addition to the high grade metamorphism considered in this paper, hydrothermal and greenschist alteration is locally observed, especially in the neighbourhood of the Insubric Line and in the marginal parts of the Mafic Formation in the Val Sesia region. This alteration is a late event and seems to be related in the domain of the Insubric Line to Alpine metamorphism (KRUHL and VOLL 1976, STECK and TIÈCHE 1976).

3.1 PELITIC ROCKS

With increasing metamorphic grade the textures of the metapelites change from lepidoblastic to granoblastic because of the replacement of muscovite by K-feldspar and biotite by garnet. At the same time the grain size increases, e.g. fibrolite becomes prismatic sillimanite. To take these changes into consideration the terms «stronalithe» and «kinzigite» were introduced (ARTINI and MELZI 1900, FRANCHI 1905) for the granoblastic metapelites in granulite facies and for the lepidoblastic metapelites in amphibolite facies, respectively.

The metapelites were largely affected by partial melting. Degranitization processes were suggested by SCHMID (1978/79) as the present bulk composition of the metapelite is depleted with respect to granitophile elements.

The granoblastic texture of the granulite facies pelites has been locally overprinted by later mylonitization. Garnet, sillimanite, often also K-feldspar and plagioclase, occur as clasts in an extremely finegrained matrix. Recrystallisation of this matrix as well as the growth of new minerals were observed only in the mylonites outcropping just below Forno, Val Strona di Omegna.

Modes and regional mineral distribution

The modes of representative pelite samples are reported in table 1 and 2 in order of decreasing metamorphic grade. The regional distribution of the alumosilicate polymorphs, of cordierite, muscovite, K-feldspar and rutile is shown on map Fig. 2.

The stable alumosilicate modification is sillimanite over the whole area. Relict andalusite is occasionally found in the lower part of the Val Sesia and in the Val Strona di Postua (Fig. 5). Further SW, in the Biella region, andalusite is very common according to Sacchi (1962). In addition, kyanite has been reported from three localities of the Sesia and Biella region (BERTOLANI 1959, CAPEDRI

Table 1 Mineral assemblages (estimated vol%) of some metapelites from the Val Strona di Omegna. For the abbreviations see table 2.

Sample	Qtz	Kf	Plg	Fsp	Ga	Bi	Mu	Sil	Gr	Ru	Ores	Km from I.L.
Iv 103	25	x	x	15	40	1		18		< 1	1	1.7
Iv 491	35	20	20		18	< 1		5	1	< 1	1	2.5
Iv 545	20	x	x	20	30	2		25	1	2	< 1	3.2
Iv 546	20	x	x	25	26	< 1		26	< 1	2	< 1	4.0
Iv 487	20	10	20		14	20		14	1		1	4.9
Iv 484	30	30	10		5	15		8	1		1	5.1
Iv 444	35		12		2	35	1	15	?			6.5
Iv 45	4		4		6	45	10	30	?		1	8.6
Iv 38	30		10		5	24	10	20			1	9.4
Iv 458	48		13		1	31	3	4	?		< 1	9.9
Iv 27	25		30			25	10	10			< 1	10.4
Iv 459	25		25			30	5	15				10.7

Table 2 Mineral assemblages of metapelites and metagranitoid rocks from the Val Sesia. And: andalusite, Bi: biotite, Cd: cordierite, Fsp: feldspar, Ga: garnet, Gr: graphite, Kf: K-feldspar, Mu: muscovite, Opx: orthopyroxene, Plg: plagioclase, Qtz: quartz, Ru: rutile, Sil: sillimanite, Spi: spinel, Sta: staurolite. I.L.: Insubric Line.

	Sample	Qtz	Kf	Plg	Fsp	Ga	Bi	Mu	Sil	Cd	Gr	Ores	Other	Km from I.L.
metapelites within the mafic formation	Iv 520	25	10	15		15	10		2	20	<1	2	Spi:<1	9.2
	Iv 521	30	15	25		15	15					<1		9.2
contact zone	Iv 608	25	24	20		15	15		10			1		7.7
	Iv 573	25	x	x	35	15	20		2	3	<1	<1		9.0
	AZ 3.11	25	10	25		10	20		8		1	1		10.0
metapelites and metagranitoids from the lower part of the Val Sesia	Iv 289	4		20		15	45		15			1		9.7
	Iv 294	50		2			35	2	10			1		10.0
	Iv 298	35		25		2	25	5	7			1		10.3
	Iv 540	40	2	25			20	2	10	<1	<1	<1		10.9
	Iv 541	30		30		10	20		10		<1	<1		11.0
	AZ 3.80	30		35		10	15					1	Opx: 9	13.3
	AZ 3.72	25	20	10		10	16		1	15		1	Spi:2, Sta: 1	14.5
	AZ 3.73	30	1	25			20	10	10			1	And:3, Sta:<1	14.5
	AZ 3.74	50		15		1	15	5	13	1		<1		14.5
	AZ 3.75	35		20		2	20	<1	18			<1	And:4	14.5
	AZ 3.64	15	10	15		10	20	1		26		2	Spi:1, Sta:<1	15.0
	AZ 3.65	20	15	15		10	10	1	<1	23		2	Spi:2, Opx: 2	15.0

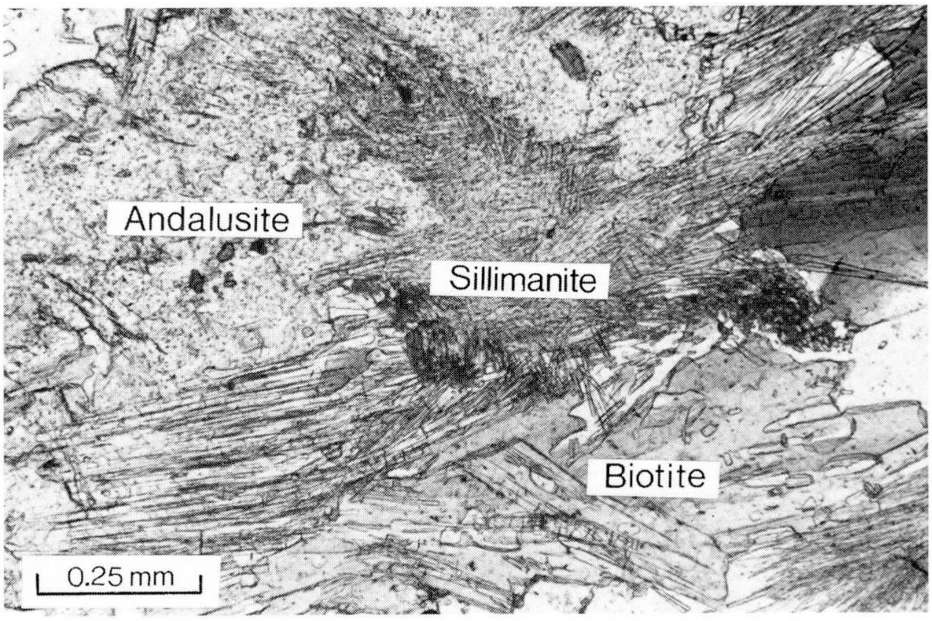

Fig. 5 Sillimanite needles grown in andalusite blast and replacement of biotite by sillimanite documenting the prograde transition from the andalusite to the sillimanite field in the lower part of the Val Sesia and in the Val Strona di Postua. Sample AZ 3.75, locality: Isolella, Val Sesia. Andalusite is also found in the contact aureoles of the Permian intrusions and in some related pegmatitic dikes indicating that during Permian time PT conditions were again those of the andalusite field.

1971 and BORIANI and SACCHI 1973) indicating a PT path close to the triple point for these regions.

Cordierite is abundant in the lower part of the Val Sesia and in the Val Strona di Postua. In the Val Strona di Omegna the presence of cordierite is restricted to the lower part of the valley (muscovite + quartz zone) and in the Val d'Ossola only one occurrence of cordierite is known from a rock with a rather high Mg content (PEYRONEL PAGLIANI and BORIANI 1967). Green spinel shows a similar regional distribution to cordierite and is always included in cordierite, staurolite and seldom in garnet or sillimanite.

In the lower part of the Val Sesia, staurolite might be found but is completely surrounded by cordierite and no longer coexists with quartz. Some granitic gneisses of this region contain orthopyroxene.

The regional distribution of the alumosilicates and of cordierite indicates, in addition to increasing temperature and pressure towards the Insubric Line, increasing pressure parallel to the strike of the Ivrea zone towards NE. This pressure increase corresponds to the axial dip of the «bird head» of the Ivrea body towards SW as recorded by geophysical investigations (German Research Group for Explosion Seismology, Fig. 7 and 11, 1968).

A striking change in the metapelites of the K-feldspar zone is the progressive replacement of biotite by garnet (SCHMID 1967, SCHMID and WOOD, Fig. 3, 1976, HUNZIKER and ZINGG, Fig. 5, this volume), e.g. according to the continuous reaction

Biotite + Sillimanite + Quartz = Garnet + K-feldspar + H_2O (1)

The appearance of rutile as an additional phase in the K-feldspar zone is related to this replacement of biotite that contains up to 6 weight% TiO_2.

In Fig. 2 the occurrence of muscovite + quartz and K-feldspar in the presence of sillimanite is shown. The limit of these two fields can be described by the reaction

Muscovite + Quartz = K-feldspar + Sillimanite + H_2O (2)

and is referred to as muscovite-K-feldspar isograd. Close to this mineral isograd several samples have neither muscovite nor K-feldspar. So additional reactions involving biotite and garnet or cordierite must be responsible for the disappearance of muscovite.

In the Val d'Ossola and Val Strona di Omegna, the muscovite-K-feldspar isograd runs roughly NE-SW, that means parallel to the strike and compositional banding of the Ivrea zone. But SW of the Val Strona di Omegna the isograd turns south and follows approximately the border of the Mafic Formation up to Varallo. The lower part of the Val Sesia is in the muscovite zone whereas in the adjacent Val Strona di Postua only K-feldspar was found. This (apparent?) increase of the metamorphic grade in the direction of the strike of the zone is also shown by the mineral assemblages of the mafic and carbonate rocks (Fig. 3 and 4). In this region the mineral isograds are discordant to the compositional banding of the zone and run more or less N-S.

The geometry of the mineral isograds can be explained at least in part by the decreasing pressure towards SW related to the axial dip of the zone. In the Val Strona di Postua region muscovite is replaced by K-feldspar in the transition field of andalusite to sillimanite. In the Val Strona di Omegna and in the Val d'Ossola, however, the muscovite-K-feldspar isograd runs within the sillimanite field. So this mineral isograd is obviously not an isotherm.

Textures

Disequilibrium textures are seldom and mostly due to retrograde reactions. The only frozen prograde reaction observed in the metapelites is the andalusite/sillimanite transition in the SW part of the area. An example of a texture indicating a retrograde reaction is the replacement of garnet by quartz and fibrolite (compare Fig. 6 of SCHMID and WOOD 1976). In general, equilibrium is suggested by the textures. Only features like embayed minerals, inclusions, large difference of grain size of the same mineral (e.g. sillimanite) and partial recrystallisation of quartz, cordierite and biotite indicate that equilibrium was not perfect or afterwards disturbed. This is true for all rocks not affected by strong deformation after the peak of the amphibolite to granulite facies metamorphism.

Large muscovites which are oblique to the schistosity and overgrow older textures and large garnets which appear to be zoned because of inclusions were put forward as arguments for polymetamorphism. But these garnets turned out to be chemically homogenous (ZINGG 1978). The large muscovites which were found only in the SE part of the area might be related to the Permian magmatic and hydrothermal activity.

Where the relation between crystallisation and deformation suggests different periods of mineral growth (CAPEDRI and RIVALENTI 1973) detailed microprobe work showed that the composition of the minerals varies only in response to the host rock chemistry and is independent of the period of formation (ZINGG 1978). So the previous history of the metapelites was almost completely erased by the amphibolite to granulite facies metamorphism.

3.2 IMPURE CARBONATES AND CALCSILICATE ROCKS

Carbonate bearing rocks make up less than 2% of the Ivrea zone and occur in lenses and bands up to 40 m thick. Due to variations in bulk chemistry the number of different mineral assemblages is large. Three rock types are distinguished: dolomite bearing calcsilicate marbles, dolomite free calcsilicate marbles and calcsilicate rocks with less than 5 vol% calcite. The mineral assemblages of the impure carbonates are reported in tables 3 and 4 for the Val Strona di Omegna and the regional distribution of amphibole, diopside, chlorite, spinel and wollastonite is shown on the map, Fig. 3.

The fluid phase

The fluid of the dolomite bearing calcsilicate marbles seems to have been controlled by the mineral reactions because most of the assemblages are isobaric univariant. This rock type sometimes shows monomineralic zonations at the contact to the pelites. In the dolomite free calcsilicate marbles the variance of the assemblages is usually higher showing that the fluid of these rocks was not rigorously internally controlled. But x_{CO_2} must have remained high in these rocks as calcite + quartz is stable even in the granulite facies domain. Wollastonite was only found in calcsilicate rocks with minor or no calcite.

Table 3 Modes of some dolomite free calcsilicate marbles from the Val Strona di Omegna. Am: amphibole, Bi: biotite, Cc: calcite, Cpx: clinopyroxene, Clz: clinozoisite, Ga: garnet, Kf: K-feldspar, Opq: opaques, Plg: plagioclase, Qtz: quartz, Scp: scapolite, Sph: sphene. Estimated vol%: · <3, o 3–10, x 10–20, X >20 vol%.

Sample	Cc	Qtz	Kf	Plg	Cpx	Am	Clz	Bi	Scp	Ga	Sph	Opq	Km from I.L.
Iv 138	X			·		·					·	·	0.1
Iv 405	X	x		o	o	o	o			·	·	·	1.0
Iv 92	X	·		·	x				x		·	·	2.4
Iv 113	X	·		o	x				x		·	·	3.2
Iv 114	X	o		o	x		·		x		·	·	3.2
Iv 115	X	o		o	x				x		·	·	3.2
Iv 378	X	·			·	o		·	·				4.7
Iv 410	X	o		o	x				x		·	·	4.7
Iv 381	X		·	o	o	o			x		·		4.9
Iv 482	X	o	o		x	o			o	o	·	·	4.9
Iv 476	X	x		o		x	·		·		·	·	8.7
Iv 477	X	o		o	x	x			o	·	·	·	8.7
Iv 449	X	o	x	x	o	x	o	x	o		·	·	9.6
Iv 461	X	o		x		x					·	·	11.0

Table 4 Modes of olivine-dolomite marbles from the Val Strona di Omegna. Chl: chlorite, Do: dolomite, Ol: olivine, Spi: spinel, for the other abbreviations and symbols for the estimated vol% of the modes see table 3.

Sample	Cc	Do	Ol	Cpx	Am	Bi	Chl	Spi	Opq	Km from I.L.
Iv 141	X	x	x	.		o		.	.	0.8
Iv 400	X	o	x	o		o			.	1.4
Iv 401	X	o	o	o		o		.		1.4
Iv 100	X	o	x	o		o		.	.	2.3
Iv 375	X	X	X	x				.	.	4.7
Iv 445	X	x	X		o	o	.		.	6.8
Iv 447	X	X	X	o	.		.		.	6.8
Iv 442	X	x	X		o	o			.	7.4
Iv 463	X	o	x	o	x	x	.		.	11.0

Modes, textures and mineral distribution

In the granulite facies, most of the calcsilicate marbles are tectonized. The calcite matrix is strongly deformed or recrystallized to a fine grain size. The silicate minerals are partially rounded and deformed (Fig. 6). Only quartz, plagioclase, clinopyroxene and scapolite clasts occasionally show polygonal recrystallisation.

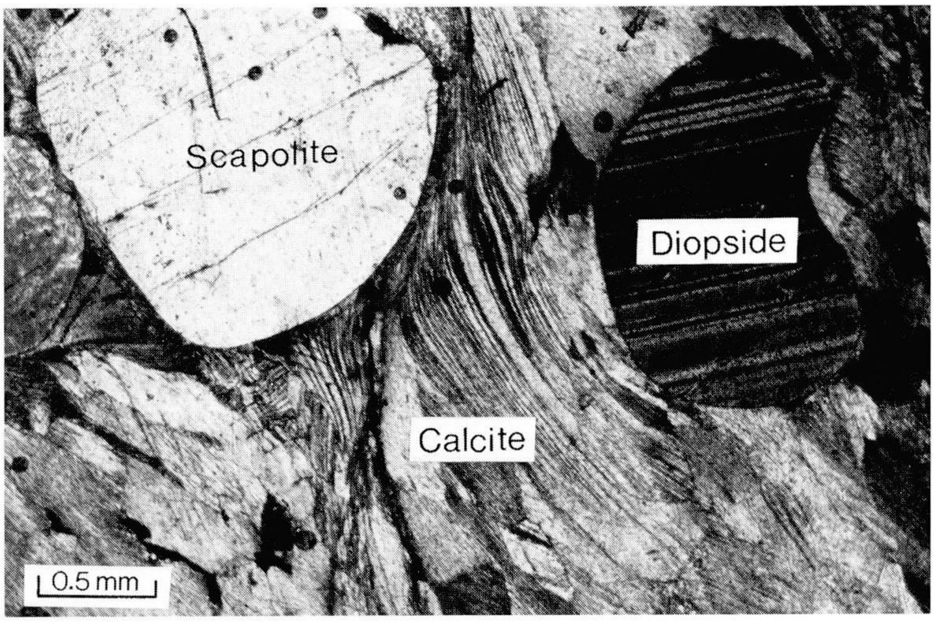

Fig. 6 Strongly deformed calcsilicate marble from the granulite facies domain. Rounded clinopyroxenes (twinned) and scapolites in deformed calcite matrix. Sample Iv 92, Alpe Ravinella, Val Strona di Omegna.

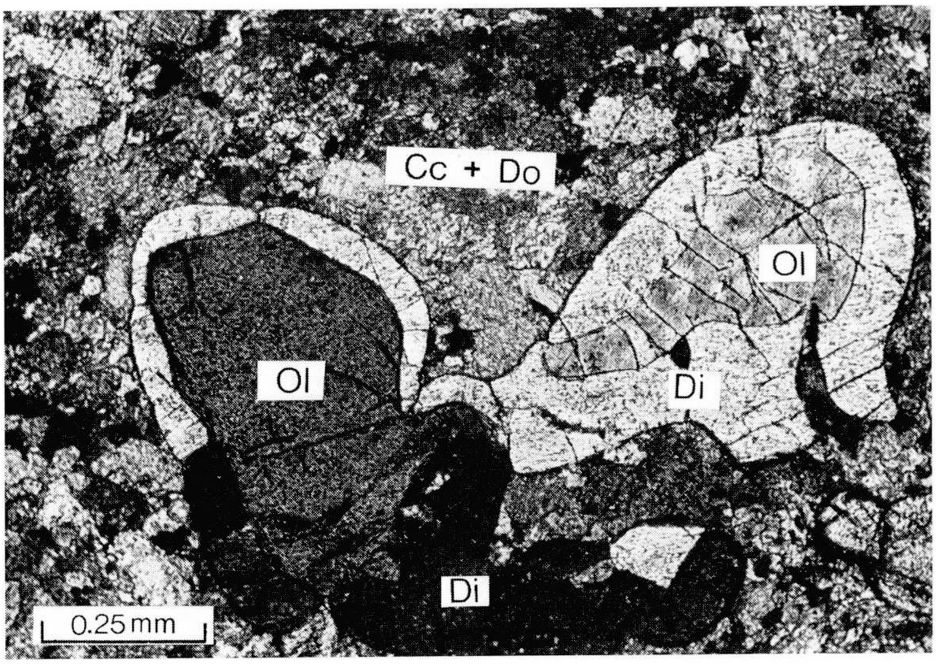

Fig. 7 Olivine with rim of clinopyroxene in recrystallized calcite and dolomite matrix. For this rim the reaction

$$\text{olivine} + \text{calcite} + CO_2 \rightarrow \text{clinopyroxene} + \text{dolomite}$$

might be formulated. Sample Iv 141, Campello Monti, Val Strona di Omegna.

Some samples exhibit reaction textures: Olivine might be rimmed by clinopyroxene (Fig. 7), clinopyroxene by quartz, amphibole or exceptionally by scapolite and scapolite by plagioclase or garnet. These rims reflect decreasing temperature (except garnet around scapolite, compare ELLIS 1978) or change in the fluid composition. Close to the Insubric Line retrograde rims are larger and in a few samples clinopyroxene is completely replaced by poikiloblastic amphibole.

In the dolomite bearing calcsilicate marbles olivine, clinopyroxene and biotite are stable over the whole area. Chlorite is replaced by spinel in the uppermost part of the amphibolite facies domain (Fig. 3). Clinopyroxene, scapolite, plagioclase and sphene coexisting with calcite + quartz are stable in the dolomite free marbles of the whole region. The assemblage colourless to pale green amphibole + calcite + quartz is restricted to the amphibolite facies part of the Ivrea zone, as well as biotite and K-feldspar (bulk chemistry controle?).

Olivine and the assemblage amphibole + calcite + quartz were found in samples from the same localities, indicating that the reactions

$$\text{amphibole} + \text{dolomite} = \text{olivine} + \text{calcite} + H_2O + CO_2 \quad (3)$$

and

$$\text{amphibole} + \text{calcite} + \text{quartz} = \text{clinopyroxene} + H_2O + CO_2 \quad (4)$$

have, in a T-x diagram, an indifferent crossing at the pressure conditions prevailing in the Ivrea zone, as in the Central Alps (TROMMSDORFF 1972) confirming also the trend predicted from experiments and calculations (SKIPPEN 1974). The distribution of clinopyroxene and of amphibole in the presence of calcite and quartz in Fig. 3 gives the approximate position of reaction (4) in the field.

3.3 MAFIC ROCKS

General aspects

In the Val d'Ossola and the Val Strona di Omegna region, where mafic and pelitic rocks alternate, the changes in the modes and the evolution from nematoblastic to granoblastic textures is more or less continuous. In the Val Sesia region, however, modes and textures change suddenly on entering the Mafic Formation. The mafics which are intercalated as lenses within the pelites are fine-grained amphibolites (Fig. 8), whereas the rocks of the Mafic Formation are

Fig. 8 Fine grained nematoblastic amphibolite occurring as lense within the metapelites of the lower Val Sesia. Sample Iv 610, near Varallo.

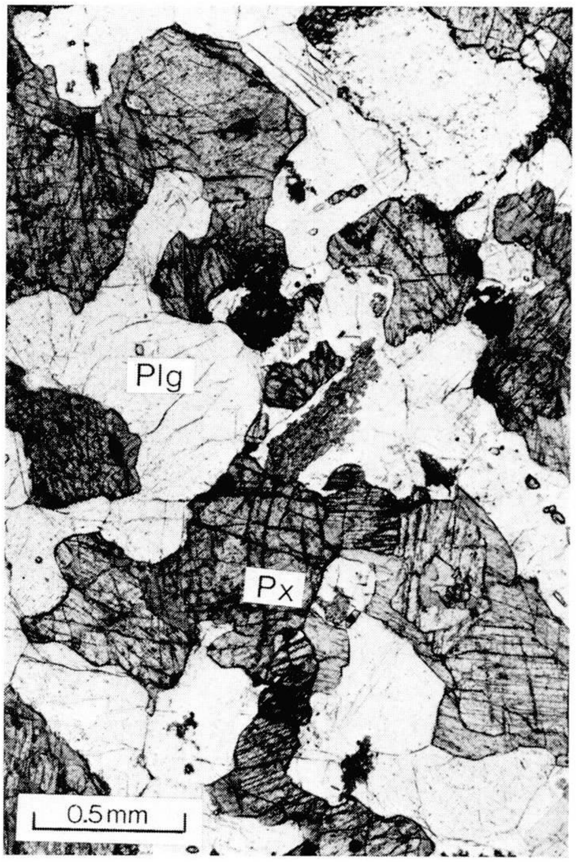

Fig. 9 Coarse grained orthopyroxene bearing mafic rock from the SE border of the Mafic Formation. Sample AZ 4.16, near Varallo.

granoblastic and medium to coarse grained (Fig. 9). The presence of orthopyroxene in Val Sesia is restricted to the Mafic Formation (compare Fig. 4 and table 6) and features like current bedding, intrusive breccia and magmatic textures were locally preserved. These differences are in part explained by the axial dip of the Ivrea zone and by the fact that different levels of the Mafic Formation are exposed in the mentioned valleys.

Modes and mineral distribution

Table 5 gives the modes of mafic rocks from the Val Strona di Omegna where igneous features have completely been obliterated by subsolidus reequilibration to metamorphic conditions. Table 6 shows the mineral assemblages of mafic rocks from the Val Sesia where the igneous origin of the Mafic Formation is locally still recognizable. The regional distribution of clinopyroxene, orthopyroxene, biotite and garnet in mafic rocks of the Ivrea zone is presented in Fig. 4.

In the *Val d'Ossola* and the *Val Strona di Omegna* three fields roughly parallel to the strike of the Ivrea zone are defined by the first appearance of clinopyroxene and orthopyroxene in mafic rocks containing plagioclase and hornblende. Quartz disappears with increasing grade in the amphibole field, sphene in the clinopyroxene field and minor amounts of biotite are still present in some mafic rocks of the orthopyroxene field. Garnet is common in many samples of the orthopyroxene field, but occurs already earlier, especially at the contact between mafics and other rock types. Spinel is missing in most samples except as exsolution product in pyroxenes and in kelyphite rims around garnets (e.g. SCHMID 1967).

Although the mineral distribution is fairly regular and the evolution of the textures is more or less continuous at the regional scale, local changes in grain size and large variation of the amphibole content are very striking. These local variations could be primary or could be due to deformation followed by recrystallisation under amphibolite facies conditions as at Finero (KRUHL and VOLL 1976, STECK and TIÈCHE 1976). For the amphibole rich mafic rocks close to the Insubric Line between Val d'Ossola and Val Strona di Omegna, postmetamorphic intrusion is proposed by BORIANI (1966).

Orthopyroxene is rare in the typical mafic rocks of the Val Strona di Omegna (assemblage: plagioclase, clinopyroxene, hornblende, ± orthopyroxene, ± garnet and opaques). However, it is common in quartz bearing mafics («granuliti piroxeniche» of BERTOLANI 1968) with the assemblage plagioclase, orthopyroxene and minor amounts of quartz, K-feldspar, biotite, garnet and opaques. The latter rocks were not included in the mineral distribution map Fig. 4. It must be mentioned that the distribution fields of the minerals given in Fig. 4

Table 5 Mineral assemblages of mafic rocks from the Val Strona di Omegna. Ap: apatite, Bi: biotite, Cpx: clinopyroxene, Ga: garnet, Hbl: hornblende, Opx: orthopyroxene, Opq: opaques, Plg: plagioclase, Px: pyroxene: Sph: sphene.

Sample	Plg	Opx	Cpx	Px	Hbl	Ga	Bi	Sph	Opq	Other	Km from I.L.
Iv 105	15		20		65						0.2
Iv 552	50	x	x	20	24	5			1		1.1
Iv 91	60				30	10	< 1		< 1		1.3
Iv 542	55	x	x	25	15	5			< 1		1.7
Iv 547	60	x	x	25	15		< 1		< 1		3.7
Iv 615	44	x	x	30	25		< 1		1		3.9
Iv 488	45		10		43		< 1	1	< 1		4.2
Iv 443	40		20		37			1	2		5.3
Iv 620	47		2		50				1	Ap < 1	5.5
Iv 420	42				55		1		2		6.4
Iv 30	48				50		< 1		2	Ap < 1	9.3
Iv 464	30				60		< 1	2	2	Qtz : 5, Ap < 1	10.5

Table 6 Modes of mafic rocks from the Val Sesia. Cu: cummingtonite, Ol: olivine, Spi: spinel, for the other abbreviations see table 5.

	Sample	Plg	Opx	Cpx	Px	Hbl	Ga	Bi	Sph	Opq	Other	Km from I.L.
mafic formation	71.134	65	x	x	20		14			1		0.5
	71.133	65	x	x	25	4	5			1		0.5
	71.130	70	x	x	20	10				<1		1.3
	71.129	60	x	x	10	2	25			3	Ap<1	1.3
	71.121	70	x	x	15	13				2		3.3
	AZ 4.1	65	x	x	25	6		<1		2	Ol:2,Spi<1,Ap<1	4.4
	AZ 4.2	60		15			5	4		1	Ol:15,Ap<1	4.8
	AZ 4.3	60	x	x	25	14				1	Spi<1	5.1
	AZ 4.4	64	x	x	25	10				1		5.7
	AZ 4.7	75	x	x	18	5		2		<1	Ap<1	5.8
dioritic to grano-dioritic margin of the mafic formation	AZ 4.21	60	x	x	15	15		10		<1		6.3
	AZ 4.20	54	x	x	8	12	8	12		3	Ol:3	6.7
	AZ 4.9	65	x	x	12	3	2	12		1	Kf:5	7.2
	Iv 576	54	x	x	15	10		20		1		8.5
	AZ 4.16	55	x	x	25	20				<1		8.8
	AZ 3.1	55	x	x	3	12		18		<1	Kf:10,Ap,Zr<1	9.3
	AZ 3.3	65					4	20		<1	Qtz:10,Ap<1,Zr<1	9.4
	Iv 508	55	x	x	20	8		15		1	Ap<1,Zr<1	8.8
amphibolite lenses within the metape-lites	Iv 290	60				15		9		1	Cu:15	9.2
	Iv 610	63				30		1		2	Cu:4	10.2
	Iv 506	30				50	3	3		4	Qtz:10,Ap<1	9.7
	AZ 3.15	35		10		36		1		3	Qtz:15,Ap<1	9.7
	AZ 3.16	55				43		<1		2		9.7
	Iv 525	20				50		3		2	Qtz:25,Ap<1	10.8
	Iv 527	35		3		50	<1			2	Qtz:10	10.5
	Iv 306	48				50			1	1		11.3
	AZ 3.81	30		10		60				<1		13.4

and 14 might be affected by sampling because field and microscopic study did not allow sufficient control of the bulk chemistry.

The fairly regular isograd zonation observed in Val d'Ossola and Val Strona di Omegna is not matched by the Mafic Formation in the lower part of the *Val Sesia*. Orthopyroxene is restricted to the rocks of this mafic body and enters a domain of amphibolite facies conditions as defined by the pelite assemblages and the few amphibolite lenses within these pelites (Fig. 4 and table 6). Orthopyroxene and most of the other minerals of the Mafic Formation are therefore considered to be of magmatic origin. This is also suggested by the mineral compositions (CAPEDRI 1971). In the rocks of the Mafic Formation close to the contact with the metapelites hydration reactions are observed. Orthopyroxene is partially replaced by hornblende (Fig. 10). These reactions occur only in the Val Sesia region and are interpreted as partial reequilibration of the magmatic assemblage to the more hydreous conditions of the amphibolite facies. Considering these reactions, CAPEDRI (1971) postulated a second phase of metamorphism.

In addition to these hydration reactions some rocks of the Mafic Formation exhibit coronas around the mafic minerals, e.g. olivine is rimmed by opaques, pyroxene, hornblende, biotite and finally by garnet (CAPEDRI 1971). Often, only parts of this succession are present.

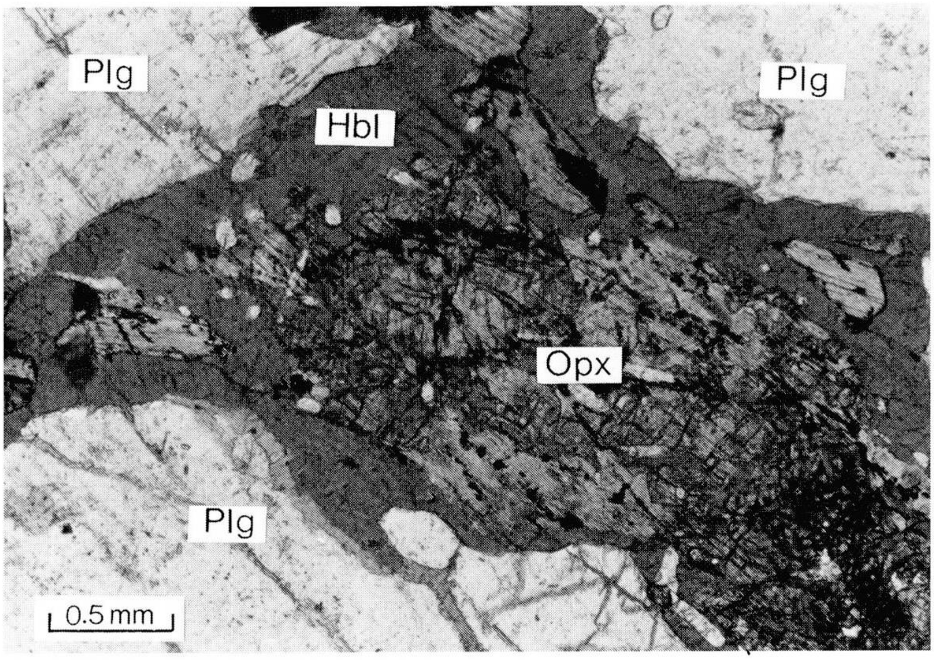

Fig. 10 Partial replacement of orthopyroxene by greenish amphibole in mafic rocks form the SE border of the Mafic Formation. This amphibole has the same optical properties as that in the amphibolite lenses within the pelites. This hydration reaction is regarded as partial reequilibration of the magmatic assemblage to the amphibolite facies conditions in the lower Val Sesia. Sample AZ 4.16, near Varallo.

The Mafic Formation in Val Sesia

The series of the Mafic Formation were brought into subvertical position after the intrusion according to steeply dipping magmatic structures. Therefore a whole profile through this metaigneous body can be studied. RIVALENTI et al. (1975) observed the following sequence in Val Sesia, starting from the Insubric Line:

1) Alternation of mafic and ultramafic rocks (0.5 km)
2) Ultramafic rocks (mainly spinel-lherzolite, 0.5 km)
3) Alternation of mafic and ultramafic rocks locally with current bedding (about 2 km)
4) Gabbroic rocks (3.5 km)
5) Biotite bearing dioritic and granodioritic rocks (2 km)
6) Metapelites

The repetition of the alternation between mafic and ultramafic rocks (series 1 and 3) might be due to an antiform structure like that in the Val d'Ossola or in Finero (SCHMID 1967, LENSCH 1968, KRUHL and VOLL 1976, STECK and TIÈCHE 1976). The contact between 4) and 5) is fairly sharp and is locally formed by an intrusive breccia (Fig. 11). The dioritic to granodioritic rocks of series 5) form a mineralogically and geochemically continuous sequence

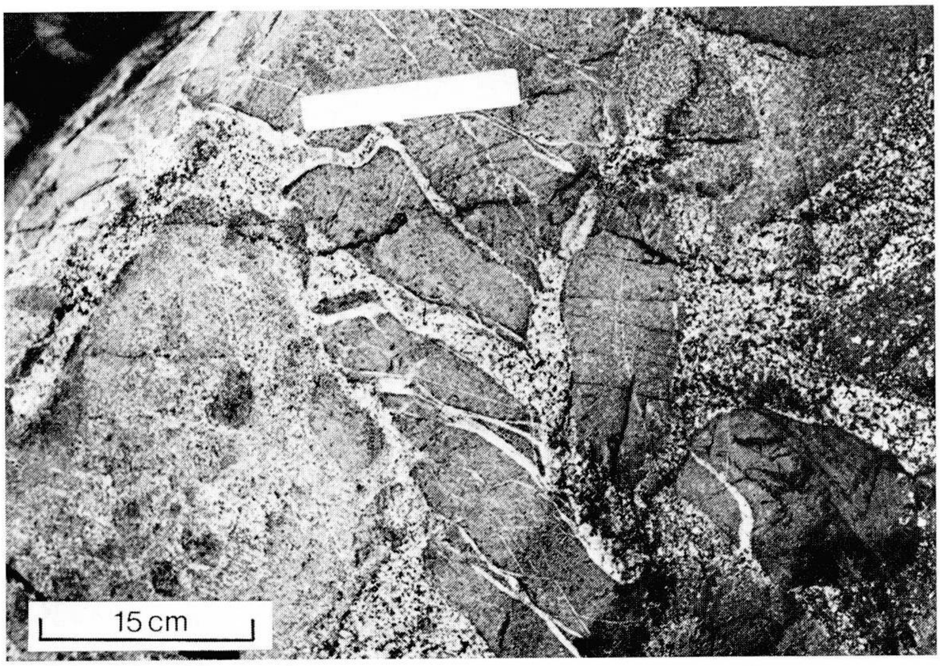

Fig. 11 Intrusive breccia within the Mafic Formation at the contact between the metagabbro (dark and fine grained) and the biotite bearing dioritic rocks (light and medium grained). Val Strona di Postua.

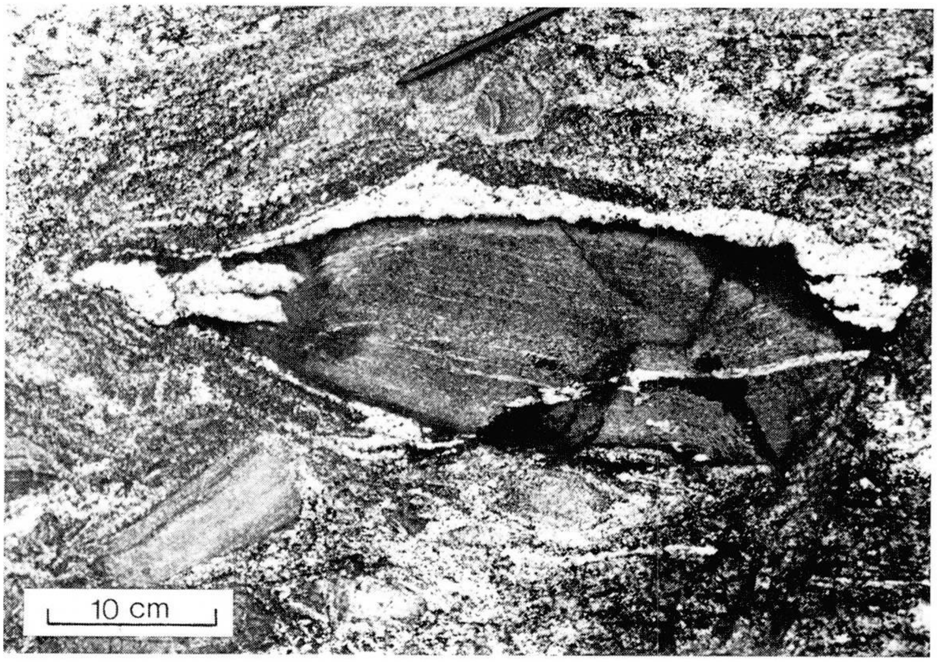

Fig. 12 Granitic melt concentrated around amphibolite boudin in the metapelite from the contact zone to the Mafic Formation at Crevola-Varallo. Such features of partial melting in the contact zone are restricted to the Val Sesia.

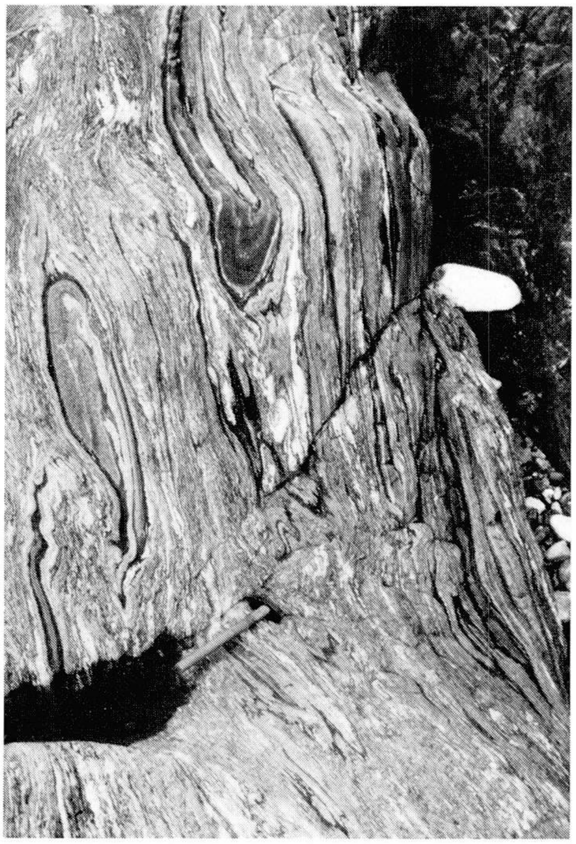

Fig. 13 Plastic deformation of the metapelites with amphibolite lenses at the contact to the Mafic Formation. The amphibolite lenses show garnet rich metasomatic rims. Crevola-Varallo, Val Sesia.

derived from the gabbros by magmatic differentiation and by assimilation of pelitic material (compare CAPEDRI 1971 and BIGIOGGERO et al. 1978/79).

In the contact zone between the Mafic Formation and the metapelites a convergence of both rock series is observed. The rocks of the Mafic Formation get more silica and potassium rich and a foliation develops. The metapelites show partial melting in a large extent (Fig. 12) and extreme plastic deformation (Fig. 13). In the metapelites from this contact zone only one phase of crystallisation has been observed both with the microscope and the microprobe. Contact phenomena are found only in the Val Sesia region where the roof of the intrusion is exposed.

In the Val Strona di Omegna and Val d'Ossola no magmatic features were observed in the mafic rocks. The reequilibration to metamorphic conditions is complete and the metamorphic grade deduced from the mafic rocks is the same as in the metapelite (PEYRONEL PAGLIANI 1967, SCHMID 1967, BERTOLANI 1968) indicating that the high temperature metamorphism has largely outlasted the intrusion of the mafic rocks.

4. Summary and conclusions

The region of the Val d'Ossola and of the Val Strona di Omegna is characterized by the alternation of mafic and pelitic rocks exhibiting a metamorphism grading from the amphibolite to the granulite facies towards the Insubric Line.

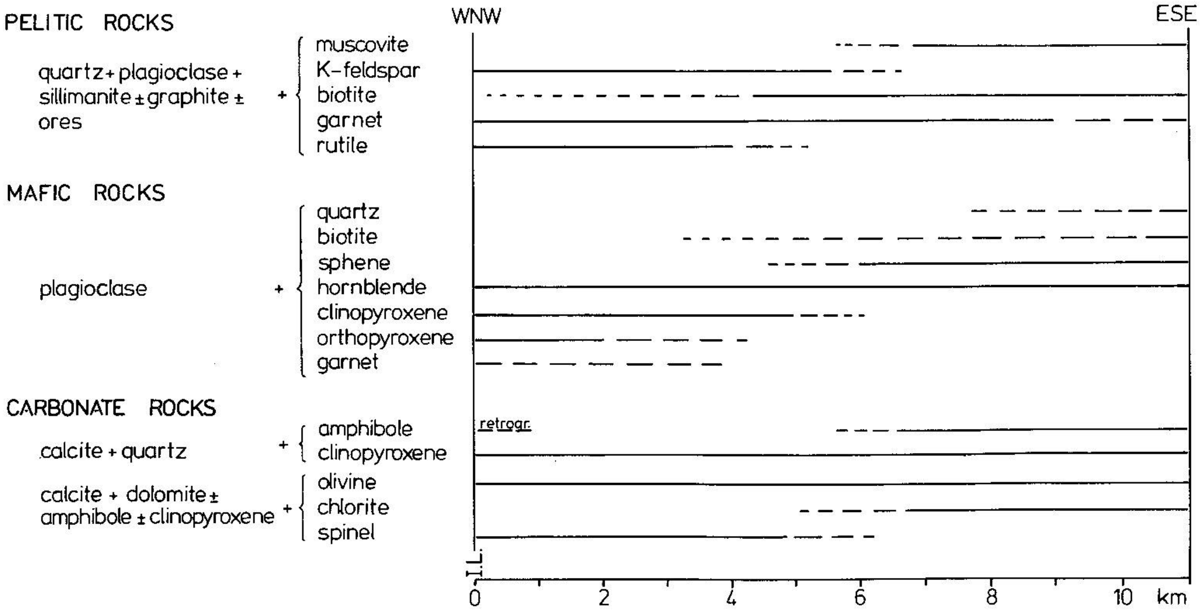

Fig. 14 Changes in the mineral assemblages at the transition from the amphibolite to the granulite facies in the Val d'Ossola and the Val Strona di Omegna.

The evolution of the assemblages in the pelitic, mafic and carbonate rocks is summarized in Fig. 14. Most of the textures and mineral assemblages point to equilibrium. Retrograde rims are occasionally observed around minerals of the mafic and carbonate rocks. These rims are inferred to be due to the cooling phase of metamorphism. A later overprint of rocks of the granulite facies domain by amphibolite facies metamorphism as at Finero (KRUHL and VOLL 1976, STECK and TIÈCHE 1976) has been observed only in tectonized rocks, as only these rocks were reaccessible for H_2O. This overprint presumably occurred in some cooling stage of the Caledonian amphibolite to granulite facies metamorphism. The rocks not affected by deformation and therefore not permeable to fluids adjusted partially to decreasing temperature by retrograde cation exchange among the various phases (ZINGG 1978). For the time-temperature evolution of the Ivrea zone see HUNZIKER and ZINGG (this volume).

The regular mineral isograd zonation which runs more or less parallel to the strike of the Ivrea zone in the Val d'Ossola and the Val Strona di Omegna region runs N-S in the lower part of the Val Sesia, that means discordantly to the compositional banding of the zone. The mineral isograds might be explained by the axial dip of the Ivrea zone and by the (presumably synmetamorphic) intrusion of the Mafic Formation. These mafic rocks intruded a deeper crustal level in the Ossola region and the magmatic assemblages have completely reequilibrated to metamorphic conditions. In the lower part of the Val Sesia, however, the intrusion reached a higher level of the crust so that the roof intruded the amphibolite facies domain of the regional metamorphism. In this area the reequilibration to metamorphic conditions is only partial and magmatic features are preserved.

From the observations presented in this paper and the studies of the Mafic Formation by RIVALENTI et al. (1975) and CAPEDRI et al. (1976), the evolution of the Ivrea zone region during Caledonian time can be sketched as follows: The lower part of a predominantly pelitic series situated at a depth between 20 and 40 km and therefore already under high temperature conditions was intruded by mafic and ultramafic rocks originating from the upper mantle. Through this intrusion additional heat for metamorphism was provided. During subsequent slow cooling the magmatic assemblages of the mafic and ultramafic rocks reequilibrated partially under the new crustal conditions (CAPEDRI et al. 1976, ENGI 1978, ZINGG 1978, GARUTI et al. 1978/79, SHERVAIS 1979). Current beddings (stop 10 and Fig. 7a in RIVALENTI 1978/79) as well as pressure gradients estimated by HUNZIKER and ZINGG (this volume) indicate that the whole Ivrea zone was in a horizontal position during metamorphism and the intrusion of the Mafic Formation. Later the zone was tilted to the subvertical position observed today and thrusted over rocks of lower density (e.g. GIESE 1968).

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SMPM = Schweiz. mineral. petrogr. Mitteilungen

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