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The Ivrea and Strona-Ceneri Zones (Southern Alps, Ticino and N-Italy) - A Review

by *André Zingg**

Abstract

The basement of the Southern Alps west of the Lago di Como is represented by segments of the deep and intermediate crust (Ivrea and Strona-Ceneri zones, respectively) which underwent an amphibolite to granulite facies metamorphism during Paleozoic time. The age of this metamorphism is controversial; an Ordovician or Variscan age is proposed in the literature. After the Variscan orogeny, the SE part of the Strona-Ceneri zone was covered by Permo-Carboniferous and Mesozoic sediments. However, the Ivrea zone remained at depth and yields Permian and lower Mesozoic mineral ages.

The literature of the last 20 years is reviewed with special consideration of the geothermometry and geochronology.

Keywords: regional metamorphism, geochronology, geothermometry, Hercynian orogeny, Ivrea Zone.

Zusammenfassung

Das südalpine Grundgebirge westlich des Comersees wird von der Ivrea- und der Strona-Ceneri-Zone aufgebaut. Diese Zonen entsprechen Segmenten der tieferen beziehungsweise der mittleren Kruste. Je nach Interpretation der radiometrischen Altersbestimmungen wird für die Amphibolit- bis Granulitfazies-Metamorphose ein ordovizisches oder ein variskisches Alter angenommen. Nach der variskischen Orogenese wurde der SE-Teil der Strona-Ceneri-Zone diskordant von permokarbonischen und mesozoischen Sedimenten überlagert. Die Ivrea-Zone blieb hingegen in der Tiefe und weist permische und mesozoische Mineralalter auf.

In der vorliegenden Arbeit wird die Literatur der letzten 20 Jahre zusammengefasst, wobei die Ergebnisse der Geothermometrie und der Geochronologie eingehender besprochen werden.

Riassunto

Ad ovest del Lago di Como il basimento delle Alpi meridionali è costituito dalle zone Strona-Ceneri e Ivrea-Verbano che rappresentano segmenti di crosta media rispettivamente profonda. È stata proposta un'età ordoviciana o ercinica per il metamorphismo crescente del facies delle amphiboliti al facies di granuliti. Dopo l'orogenesi ercinica la parte sudorientale della zona Strona-Ceneri

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è stata ricoperta di sedimenti permocarboniferi e mesozoici. La zona Ivrea-Verbano, invece, è rimasta a un livello profondo e i minerali mostrano età radiometriche permiane e mesozoiche.

Questo lavoro è una ricapitulazione delle conoscenze acquisite negli ultimi 20 anni con particolare considerazione dei risultati della geochronologia e geothermometria.

Content

1. Introduction

The present review is an extended version of the talk given at the colloquium "Variscan and Pre-Variscan basement in the Swiss Alps" held in Fribourg. However, the geochemistry of the mafic and ultramafic rocks of the Ivrea zone is not considered in this paper as several works on their isotope geochemistry are forthcoming. A complete bibliography of the Ivrea zone is given by CARRARO & SCHMID (1968) and BORIANI & POTENZA (1978/79). For two reasons a large part of this paper will deal with the Ivrea zone: First, much more data has become available on this zone; and second, the author's previous experience centers on the Ivrea zone.

2. Geological setting

The basement of the W part of the Southern Alps consists of the Ivrea and Strona-Ceneri zones (plate I and fig. 1). These two zones represent segments of

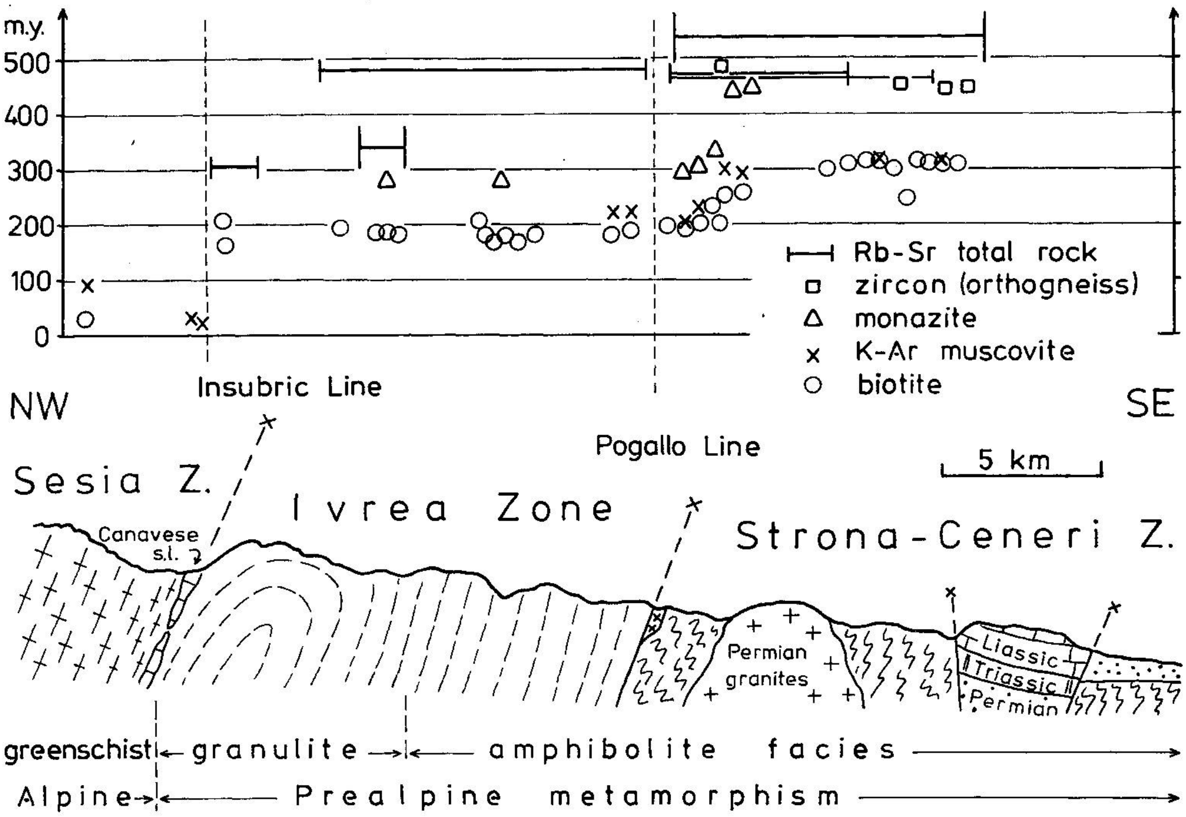

Fig. 1 Composite section across the Ossola and Sesia regions with the radiometric age determinations cited in table 3. All ages were projected into this section causing a considerable distortion in the position the ages determined in the Ticino. Note that the ortho- and paragneiss Rb-Sr whole rock isochrons (large samples) give lower Paleozoic ages both in the Ivrea and Strona-Ceneri zones, whereas the mineral ages become younger from the SE to the NW. The distinction between the SE and NW part of the Strona-Ceneri zone is based solely on the radiometric ages and not on petrological arguments.

the deep and intermediate crust, respectively. Carboniferous, terrigenous sediments and Permian, volcanoclastic and volcanic series yield an upper time limit for the basement evolution in the SE part of the area considered here. However, in the Ivrea zone and the NW part of the Strona-Ceneri zone elevated temperatures prevailed during early Mesozoic time, as shown by the radiometric age determinations (fig. 1 and 5). The change between Variscan and Permo-Mesozoic ages generally does not coincide with the boundary between the Ivrea and Strona-Ceneri zones (see the regional distribution of the biotite and monazite ages, e. g. plate I). The contact between the two zones is tectonic (Pogallo line) in the Val d'Ossola region but gradational in the NE, i. e. in the Lago Maggiore region.

3. Description of the Strona-Ceneri zone

The basement between the Ivrea zone and the Permo-Carboniferous and Mesozoic sediments is subdivided in several ways as shown in table 1. The term Strona-Ceneri zone is used here in the sense of SCHMID (1968, plate 1). General-

Tab. 1 Basement units of the W part of the Southern Alps. In this paper the terminology of Schmid (1968, plate I) is adopted. "Zona Diorito-Kinzigitica" is an equivalent term for the Ivrea-Verbano zone. The latter is often shortened to Ivrea zone.

Reinhard (1953, 1964) (E of Lago Maggiore)	Schmid (1968, plate I)	Boriani et al. (1977)	Novarese (1929)	
	Zone Ivrea-Verbano	Zona Ivrea-Verbano	Formatione diorito-kinzigitica	Massiccio dei Laghi
Ceneri-Zone	Zone Strona-Ceneri	Serie dei Laghi: Strona-Ceneri Serie dei Laghi: Scisti dei Laghi	Gneiss della formatione dei Laghi Micascisti della formatione dei Laghi	
Val Colla-Zone	(Val Colla-Zone)	Zona Val Colla		

ly, two units are distinguished within this zone : Gneisses predominate in the NW while schists are more common in the SE. However, the latter unit includes large bodies of orthogneisses. According to BORIANI et al. (1977), the gneiss and schist units are separated by partly feldspathized amphibolites. The region discussed is almost completely covered by the maps of REINHARD (1953) and of BORIANI et al. (1977). The summary presented here is largely based on the publications of REINHARD and co-workers for the part east of the Lago Maggiore and of PEYRONEL PAGLIANI, BORIANI and co-workers for the western part.

3.1. Lithologies

Gneiss unit

Gneiss varieties of psammitic and granitic composition dominate. BORIANI (1970a) distinguishes several lithologies: medium grained biotite-plagioclase gneisses with transition to K-feldspar augengneisses, flasergneisses, fine grained gneisses which are similar to REINHARD'S "Hornfelsgneise" but do not contain aluminosilicates, and the so called Ceneri gneiss. This latter type is a biotite-plagioclase gneiss with inclusions of fine grained biotite-gneisses and of zoned calcsilicate nodules. For REINHARD (1964) the Ceneri gneiss represents deformed and metamorphosed psammitic sediments with limestone layers. However, according to BORIANI (1968), BORIANI & CLERICI RISARI (1970) the inclusions and nodules within this gneiss were produced by anatectic processes; the inclusions represent deformed restites.

Schist unit

Micaschists of pelitic composition dominate and contain rotated blasts of plagioclase and garnet (BORIANI, 1970a). Concordant orthogneiss bodies of granitic to tonalitic composition are found within these schists (BORIANI et al., 1982/83). For REINHARD (1964) the metasediments grade into the "Mischgesteine" (= migmatites) and the latter into the orthogneisses, whereas for BORIANI et al. (1982/83) an intrusive origin of the orthogneisses is evident. The latter authors relate the "Mischgesteine" to metasomatism during the intrusion. A magmatic origin of the orthogneisses is also suggested by the zircon morphology (KÖPPEL & GRÜNENFELDER, 1971).

Amphibolites and ultramafic rocks

Amphibolites are scarce in the Strona-Ceneri zone and most of them are found as layers or lenses at the contact between the gneiss and schist units (BORIANI, 1970a, BORIANI & GIOBBI MANCINI, 1972) and along the SE border of the Strona-Ceneri zone (REINHARD, 1953). The modes of the amphibolites vary greatly and include plagioclase, hornblende ± quartz ± biotite ± K-feldspar ± garnet and minor components. The southern margin of the lenticular amphibolite layers separating the schist and gneiss units is characterized by the presence of K-feldspar blasts (BORIANI & GIOBBI MANCINI, 1972) and grades into hornblende-biotite-gneisses. Garnet-amphibolites of tholeitic composition crop out E of the Lago Maggiore (BÄCHLIN, 1937, SPICHER, 1940 and BULETTI, 1981). The garnet may be rimmed by kelyphites of hornblende and plagioclase.

Ultramafic rocks are rare and restricted to small lenses. Their assemblages consist of variable amounts of olivine, pyroxenes, hornblende and the corresponding alteration products. In addition, an occurrence each of phlogopite-peridotite and of garnet-serpentinite are reported (BÄCHLIN, 1937, SPICHER, 1940, ROST et al., 1978/79). The mafic-ultramafic rocks of the Strona-Ceneri zone seem very similar to those described by BORIANI & PEYRONEL PAGLIANI (1968) occurring as a lense in paragneiss of the SE margin of the Ivrea zone.

Late-Variscan instrusives

The basement of the Strona-Ceneri zone is intruded by the post-metamorphic granitic suite of Baveno–Mt. Orfano. Granite is by far most common but tonalite, diorite and even olivine gabbros are found (GALLITELLI, 1937, 1941, BORTOLAMI, 1963, GANDOLFI & PAGANELLI, 1974). U-Pb, Rb-Sr and K-Ar determinations on minerals and whole rock give Permian ages for the granites (JÄGER & FAUL, 1960, KÖPPEL, 1974, KÖPPEL & GRÜNENFELDER, 1978/79, HUNZIKER & ZINGG, 1980). The intrusions show contact aureoles with an intense hydrothermal alteration. The Permian granites have lower $^{87}Sr/^{86}Sr$ values than the paragneisses of the Ivrea and Strona-Ceneri zones and therefore cannot have originated from partial melting of these rocks (HUNZIKER & ZINGG, 1980).

Most of the mafic intrusives crop out at the limit between the Ivrea and

Strona-Ceneri zones (SCHILLING, 1957, BORIANI & PEYRONEL PAGLIANI, 1968, BORIANI et al., 1975). These rocks yield upper Carboniferous monazite ages (KÖPPEL & GRÜNENFELDER, 1978/79) and are locally and variably foliated in the vicinity of the Pogallo line. Within the foliated intrusives quartz is dynamically recrystallized to fine grained aggregates and the mineral assemblages have been altered under syntectonic greenschist facies conditions (Mark Handy, personal communication).

3.2. Metamorphism

The Strona-Ceneri zone was metamorphosed under amphibolite facies conditions. Mineral isograds cannot be drawn as few rocks have appropriate assemblages. For the zone taken as a whole, a general trend of increasing metamorphic grade towards the NW is observed by BORIANI et al. (1977). Garnet + staurolite + quartz + muscovite + kyanite coexist within the micaschists. In the gneiss unit the syn- to post-kinematic transformation of kyanite to sillimanite is reported (BORIANI et al., 1977). But the metamorphic history is not simple. The relics of garnet-peridotites and the reactions within the garnet-amphibolites (amphibolized eclogites?) point to an earlier high-pressure stage—at least for parts of the Strona-Ceneri zone. In addition, BÄCHLIN (1937) and BIGIOGGERO & BORIANI (1975) observed aluminosilicate nodules adjacent to deformed pegmatites. In several cases the nodules have the shape of chiastolite. Most of these nodules now consist of kyanite + mica or of sillimanite + biotite + garnet + quartz. A few grains of andalusite were found in a kyanite-bearing nodule by BÄCHLIN (1937). From these chiastolites BORIANI et al. (1982/83) inferred contact metamorphism of very low-grade metasediments during the Ordovician granite to tonalite intrusions. As these intrusives were subsequently transformed to orthogneisses during amphibolite facies metamorphism, the authors conclude that the regional metamorphism is of Variscan age (however, see discussion chapter 7). It is notable that these aluminosilicate nodules are spatially associated with pegmatites and not with the Ordovician granitic to tonalitic intrusions where contact metamorphism should be more pronounced.

No trace of metamorphism has been observed in the Carboniferous and Mesozoic sediments W of the Lago di Como except in the Canavese s. str. (STADLER et al., 1976, ZINGG et al., 1976). However, post-Variscan, very low-grade metamorphism is reported from the Permian Collio formation (CASSINI et al., 1978) and from the basement (CRESPI et al., 1982) of the Southern Alps E of the Lago di Como.

3.3. Deformation

The Strona-Ceneri zone shows two characteristic large-scale features: 1) so-called "Schlingen"; that is, folds with amplitudes in the km range and steeply dipping fold axes (BÄCHLIN, 1937, SPICHER, 1940, REINHARD, 1953 or 1964); and 2) a major angular discordance of the compositional banding and foliation across the Pogallo line in the Ossola region (BORIANI, 1970a, BORIANI et al., 1977). Here the Pogallo line comprises the contact between the Ivrea and Strona-Ceneri zones and is characterized by both mylonites and minor brittle deformation (PEYRONEL PAGLIANI & BORIANI, 1962, BORIANI & SACCHI, 1973 and 1974). The sudden decrease of the mica and monazite ages towards the NW (HUNZIKER, 1974, KÖPPEL, 1974 fig. 7, KÖPPEL & GRÜNENFELDER, 1978/79) coincides in Val d'Ossola with the Pogallo line (see fig. 1).

The mylonites along the Pogallo line were formed under low temperature conditions (Mark Handy, personal communication). Quartz forms partially recrystallized ribbon grains and green biotite grows in the pressure shadows of brown biotite and muscovite clasts.

The Pogallo mylonites cut older mylonites (including flasergneiss) which are concordant to the foliation of the Strona-Ceneri zone (BORIANI et al., 1973). These older mylonites have a polygonized matrix with recrystallized feldspars (fig. 6 and 7 of BORIANI, 1970b) and thus formed under higher temperature conditions than the Pogallo mylonites. Amphibolite facies shear zones are also found within the Ivrea zone (fig. 3 to 6 of BORIANI, 1971). BORIANI (1970a and b, 1971) and BORIANI & SACCHI (1973) recognized these different types of mylonites but unfortunately did not distinguish them in their discussion of the Pogallo line. They conclude that this line must have formed under relatively high temperatures during late Variscan time. However, the Pogallo line formed under geenschist facies conditions and is post-Variscan (early Mesozoic rifting or Alpine tectonic?) according to the time-temperature curve in fig. 5.

Late faults and thrusts divide the Strona-Ceneri zones into several blocks as shown on the maps of REINHARD (1953 or 1964) and of BORIANI et al. (1977). In addition, pseudotachylites (= "Gangmylonite") are mentioned by BÄCHLIN (1937) and SPICHER (1940) in the region E of the Lago Maggiore.

4. Description of the Ivrea zone

The Ivrea zone is related to the geophysical anomalies which follow the internal part of the Alpine arc from Locarno to Cuneo (e. g. gravity map of VECCHIA, 1968). Based on these anomalies, a model was proposed in which a sliver of mantle material overlies crustal rocks as shown in fig. 2 (e. g. German

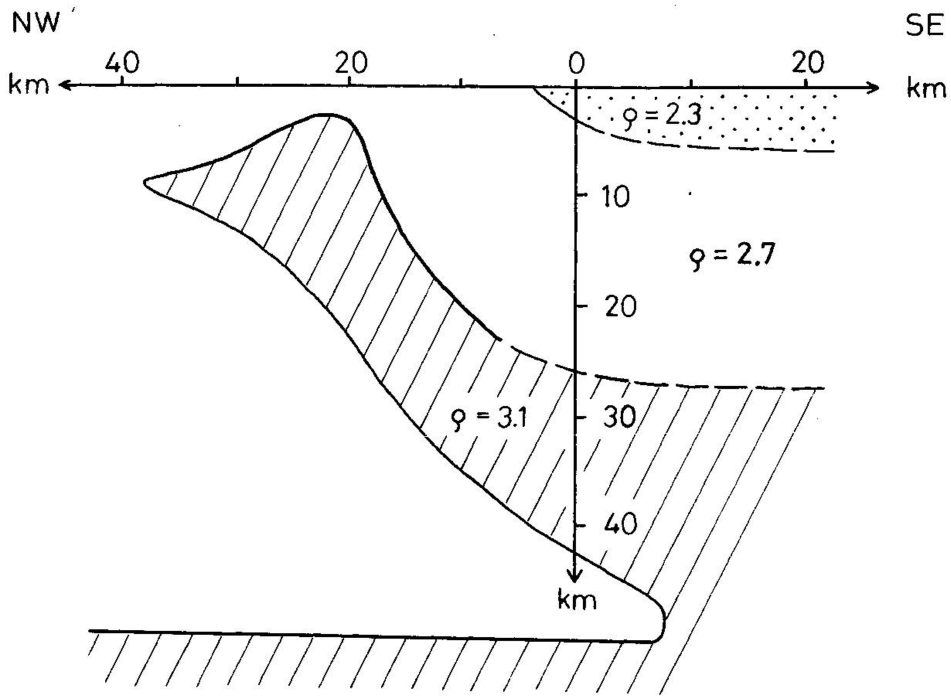

Fig. 2 Model of the crust in the Ivrea zone region according to the German Research Group for Explosion Seismology (1968). The high density wedge overriding granitic crust is called (geophysical) "Ivrea body". The section runs approximately through the Val Sesia.

Research Group for Explosion Seismology, 1968, GIESE, 1968 or KISSLING, 1980). According to this model, the MOHO discontinuity rises from a depth of about 30 km beneath the Po plain to close to the surface in the Ivrea zone region. In conformity with this crustal structure the metamorphic grade increases towards the NW from the amphibolite to the granulite facies. So the Ivrea zone can serve as a model for the deep crust and it may even be for the mantle-crust transition (e. g. MEHNERT, 1975, FOUNTAIN, 1976).

4.1. Lithologies

Four rock types are commonly distinguished on the geological maps. Mafic rocks and paragneisses dominate, while ultramafic rocks and calc-silicate marbles form small bodies and lenses. These four rock types encompass a large variety of lithologies which have been mapped in great detail by SCHMID (1967) in the area east of the Val d'Ossola. The modes of the most common rock types are given in BERTOLANI (1968) and ZINGG (1980). It must be mentioned that plutonic rock names are commonly used in the literature even for the mafic and ultramafic rocks which show a metamorphic reequilibration and overprint.

The II. Kinzigite-Diorite zone and the Valpelline Serie are units with the same lithological association and pre-Alpine metamorphic history as the Ivrea zone. However, the former two units were involved in Alpine orogeny.

Ultramafic rocks

Most of the ultramafic bodies crop out adjacent to the Insubric Line, i. e., in the granulite facies part of the Ivrea zone. They include peridotites s. l. and pyroxenites. Spinel peridotites and lherzolites are the most common types in the Baldissero and Balmuccia bodies (LENSCH, 1971, RIVALENTI et al., 1975, SHERVAIS, 1979). These bodies are regarded as mantle differentiates and must be distinguished from the spinel-bearing dunites and harzburgites which are interlayered with gabbros and norites (layered group of RIVALENTI et al., 1975 and 1981). According to these authors the layered group formed by magmatic differentiation within the lower crust.

Phlogopite- and hornblende-peridotite are characteristic for the Finero body (LENSCH, 1971). The phlogopite-peridotite containing spinel and up to 15 vol% phlogopite shows concentrations of Sr, Rb, Ba and $^{87}Sr/^{86}Sr$ ratios between mantle and crustal values. This contrasts with the values for the normal mantle peridotites. Therefore, a crustal contamination of the Finero peridotite is proposed (LENSCH, 1971, HUNZIKER & ZINGG, 1982, HUNZIKER et al., in prep.).

Kelyphite-peridotites were found only as boulders and scree in two localities (LENSCH & ROST, 1972, HUNZIKER et al., in prep.). The kelyphite textures vary from fibrous to fine grained granoblastic. The granulite facies reequilibration of the mineral assemblage is nearly complete, with spinel as the aluminous phase both in the kelyphite and the olivine matrix.

Mafic rocks

Two types of mafic rock must be distinguished based on occurrence: 1) mafics intimately associated with the paragneiss. This occurrence dominates in the central part of the Ivrea zone. These mafics have crystalloblastic textures and show the same deformational history and metamorphic evolution as the paragneisses (PEYRONEL PAGLIANI & BORIANI, 1967, SCHMID, 1967); 2) the mafic rocks forming the large bodies of the Mafic formation (= "Basischer Hauptzug") which dominate the SW and NE ends of the Ivrea zone. However, these bodies are not as homogeneous as appears on the large scale maps (compare the detailed sketch map of Val Sessera by BERTOLANI & GARUTI, 1970).

In Val Sesia, where the Mafic formation is best developed, the following sequence is described by RIVALENTI et al. (1975) from the WNW (bottom) to the ESE (top of the intrusion):

- Layered group (about 0.5 km) with dunites, harzburgites, norites, gabbros and leucogabbros
- Spinel-peridotite of Balmuccia (about 0.5 km)

- Layered group (about 2 km) with the same lithologies as above
- Main gabbro (about 3.5 km) with banded norites, gabbros and leucogabbros
- Biotite-diorite and granodiorite (about 2 km)
- Paragneisses

The first layered group (WNW of the Balmuccia peridotite) is thought to be a tectonic repetition. The contact of the Mafic formation with the paragneisses is concordant. At the contact, the paragneisses are very locally affected by anatexis, which generated small volumes of granitic melt (fig. 12 of ZINGG, 1980). Magmatic features are preserved within the Mafic formation in Val Sesia[1]: current beds in the layered group (stop 10 and fig. 7a of the excursion guide of RIVALENTI, 1978/79); clusters of mafic minerals in gabbroic rocks; and orthopyroxene found in regions affected only by amphibolite facies metamorphism according to the assemblages of adjacent paragneisses and impure marbles. For a more detailed discussion of the Mafic formation, see GARUTI et al. (1980) and for geochemical data, see CAPEDRI (1971), RIVALENTI et al. (1975, 1981) and BIGIOGGERO et al. (1978/79).

Paragneisses

For practical reasons, all rocks which are not mafics, ultramafics, marbles or calcsilicate rocks were mapped as paragneisses or even as metapelites. So this cartographic unit encompasses a large variety of rocks ranging from metapelites to metagranitoids. However, the most common types are sillimanite-bearing paragneisses which are called "kinzigite" and "stronalite" in the amphibolite and granulite facies, respectively. Charnockitic rocks (see BERTOLANI, 1964, BERTOLANI & GARUTI, 1970) and plagioclase-orthopyroxene-garnet-rich rocks also belong to the paragneiss sequence.

The paragneisses are strongly affected by partial melting. Migmatites are common, especially at the amphibolite-granulite facies transition. Anatectic processes affected the rocks, not only at the outcrop, but also at the regional scale. SCHMID (1972, 1978/79) and SIGHINOLFI & GORGONI (1978) demonstrated that, compared to sedimentary compositions, the bulk composition of the Ivrea paragneisses is strongly depleted with respect to granitophile elements. This implies that the paragneisses are restites. Their mean composition varies systematically at a regional scale with the grade of the amphibolite to granulite facies metamorphism.

[1] According to the description of WALTER (1950), the metamorphic overprint of the Mafic formation in the NE part of the Ivrea zone is complete.

Impure marbles and calcsilicate rocks

The carbonate-bearing rocks occur in lenses and bands mainly within the amphibolite facies part of the Ivrea zone but also close to the Insubric Line. Their mineral assemblages show large variations described by PAPAGEORGAKIS (1961), ARÉVALO et al. (1980) and ZINGG (1980). The most common type is an impure calcite-marble with quartz and diopside ± actinolite as well as other silicate minerals. Olivine-dolomite marbles and calcsilicate rocks ± wollastonite are subordinate.

4.2. Metamorphism

The amphibolite to granulite facies metamorphism has erased most traces of the previous history of the Ivrea rocks. Relics from the evolution before the peak of the metamorphism are the kelyphite structures in two peridotite lenses (LENSCH & ROST, 1972) and in the mafics of Alpe Morello (BORIANI & PEYRONEL PAGLIANI, 1968). These features indicate an early high-pressure evolution, at least for parts of the Ivrea zone. The kyanite which occurs in addition to sillimanite in a few paragneiss samples (BERTOLANI, 1959, CAPEDRI, 1971, BORIANI & SACCHI, 1973) may also represent relics of this event.

The rocks of the Ivrea zone often show equilibrated textures. Locally, reaction rims show a partial reequilibration of the assemblages to lower-temperature conditions. This retrograde reequilibration may be nearly complete in shear zones. Only rocks with crystalloblastic textures were used to determine the conditions of the regional metamorphism and to trace mineral isograds (PEYRONEL PAGLIANI & BORIANI, 1967, SCHMID, 1967, ZINGG, 1980). In general, the metamorphic grade increases from the amphibolite to the granulite facies towards the NW. However, the NW-most part at the Insubric line locally shows amphibolite facies conditions. The regular zonation parallel to the compositional banding shown by the mineral isograds in the central part of the Ivrea zone is not matched by the Mafic formation in Val Sesia. In this region, the occurrence of orthopyroxene does not follow the mineral isograds but is restricted to the Mafic formation (plate I, see also ZINGG, 1980). The magmatic origin of these orthopyroxenes was first recognized by RIVALENTI et al. (1975).

Along strike of the zone, a weak pressure increase from SW to NE is observed—in agreement with the axial dip of the Ivrea body modeled by the geophysists (compare fig. 7 and 11 of the German Research Group for explosion Seismology, 1968). Andalusite and cordierite are common in the SW (Biella and Val Sesia region, respectively) and disappear towards the NE, where sillimanite is the stable aluminosilicate polymorph (ZINGG, 1980).

Remark concerning the muscovite-K-feldspar isograd

Large muscovite blasts which are discordant to all microstructures are found close to the SE boundary of the Ivrea zone (see plate IB). They occur in the same area as aplites and lamprophyres which probably belong to the Permian magmatic suite of Baveno. Close to the muscovite-K-feldspar isograd the muscovite grains are too small to allow determination of their relationship to the microstructure. The fine grain size of these muscovites may be attributed either to their growth near the upper stability limit during regional metamorphism or to their distance from the presumed centers of hydrothermal activity in the SE. Therefore, the mapped muscovite-K-feldspar isograd must be considered with caution.

Retrograde reactions and reaction rims

Except in the shear zones, the retrograde reactions affect single minerals without major change of the original fabric. In thin section it is often not clear what mineral phases are involved in the reaction. Several types of reaction textures can be distinguished: 1) Replacement of individual minerals, e. g. garnet by aggregates of sillimanite and quartz (fig. 6 of SCHMID & WOOD, 1976); 2) Monomineralic rims, observed mainly in impure marbles, e. g. diopside enclosing olivine (foto 1-9 of ARÉVALO et al., 1980, fig. 7 of ZINGG, 1980); 3) Fine grained kelyphites and symplectites around garnet, pyroxene and hornblende in mafic rocks (fig. 45-51 of SCHMID, 1967). Most of these reaction rims formed under decreasing temperature conditions or resulted from a change in the fluid composition. Orthopyroxene found in symplectites around hornblende (SCHMID, 1967, SCHENK, 1981) may represent an exception. In this case a dehydration reaction was active either under decreasing temperature conditions or, more plausible in the regional context, under decreasing pressure conditions.

Within the gabbroic rocks of the Mafic formation in the Val Sesia region, coronas around mafic minerals are observed. For example, olivine might be rimmed by pyroxene, hornblende, biotite and finally, by garnet (fig. 5 of CAPEDRI, 1971, or fig. 32 and 33 of Zingg, 1978). In addition to these coronas, the (magmatic) orthopyroxene reacts to brown hornblende. Because of this hydration reaction found in the SE border of the Mafic formation, BERTOLANI (1968) and CAPEDRI (1971) postulate an older granulite facies metamorphism overprint by a second phase of metamorphism grading towards the NW from the amphibolite to the granulite facies.

High temperature shear zones

The shear zones are located predominantly in the granulite facies part of the Ivrea zone. They affect all rock types, particularly the paragneisses. Large variation in both the grain size and the amount of the recrystallized matrix are observed (e. g. WALTER, 1950). All recrystallized mineral assemblages are characteristic of the amphibolite facies as shown in table 2. This implies retrograde conditions with respect to the granulite facies metamorphism indicated both by

Tab. 2 Modes of the shear zones from the granulite facies part of the Ivrea zone. [1]) Opx recrystallized only after (3). References: (1) KRUHL & VOLL (1976), (2): STECK & TIÈCHE (1976), (3): BRODIE (1980), (4): BRODIE (1981), (5): WALTER (1950), (6): SCHMID (1967), (7): ZINGG (1978 and unpublished).

Rock type	Porphyroclasts and country rocks	Mylonite matrix	References
Ultramafic rocks	orthopyroxene, clinopyroxene, olivine, hornblende, spinel, ±phlogopite	orthopyroxene[1]), olivine, clinopyroxene, hornblende, ±phlogopite	1-3
Mafic rocks	plagioclase, clinopyroxene, hornblende, ±orthopyroxene, ±garnet	plagioclase, clinopyroxene, hornblende	1,2,4-7
Paragneisses	quartz, K-feldspar, plagioclase, garnet, biotite, sillimanite	quartz, K-feldspar, biotite, plagioclase	6,7

the porphyroclasts within the shear zones and by the country rock assemblages. However, this conclusion is not consistent with the mineral chemistry of the sheared mafic rocks. Brodie (1981) observed that the recrystallized hornblende is enriched in Ti, Na + K and Fe (with respect to Mg) and that the recrystallized plagioclase is more anorthitic compared with the clast compositions. According to her favoured interpretation higher temperatures prevailed during the formation of the shear zones than during the formation of the crystalloblastic textures of the country rocks. This discrepancy has yet to be resolved.

4.3. Deformation

Structural data are available for only a few areas of the Ivrea zone. The brief summary presented here pertains to the granulite facies part and is based on the studies of SCHMID (1967), CAPEDRI & RIVALENTI (1973), KRUHL & VOLL (1976), STECK & TIÈCHE (1976) and on unpublished data of the author. For mineral preferred orientation data and textural investigations performed on the ultramafic and associated rocks, the reader is referred to NICOLAS et al. (1971), GARUTI (1977), GARUTI & FRIOLO (1978/79), KRUHL & VOLL (1978/79).

The general strike of the compositional banding and main foliation is parallel to the zone, i. e. ENE–WSW to NNE–SSW. The dip is moderately steep towards the NNW to WNW or towards the SSE to ESE due to large antiforms (SCHMID, 1967, and LENSCH, 1968). The following deformational sequence for the granulite facies part of the Ivrea zone has been observed: Two phases of isoclinal folding were followed by annealing under granulite facies conditions. Textures within the fold hinges are granoblastic, though sillimanite shows a strong preferred orientation parallel to the fold axes. During these early deformational stages, anatectic veins of the paragneisses were boudinaged and folded. Open folds and the shear zones (chapter 4.2.) developed later and under amphibolite facies conditions. This deformation is followed by movements along shear zones formed under greenschist facies conditions. The border of the Ivrea zone is involved to a variable extent in the mylonitization along the Insubric and Pogallo lines. Pseudotachylites are found within the entire Ivrea zone, but are concentrated in the mafic rocks along the Insubric line. The antiform structure of Finero was formed during the amphibolite facies deformation according to STECK & TIÈCHE (1976) but during the greenschist facies deformation according to KRUHL & VOLL (1976). Note that in certain areas additional folding phases can be distinguished (e. g. STECK & TIÈCHE, 1976).

5. Geothermometry in the Ivrea zone

Various geothermometers have been applied to the Ivrea rocks and the temperatures obtained cover a large range as shown in fig. 3. If we neglect the effects of the various calibrations, large temperature differences remain between the various geothermometers. In the ultramafic rocks the highest temperatures are recorded by the olivine-spinel-pyroxene system. The temperatures scatter around 1250 °C and are thought to reflect the approximate conditions of the magmatic crystallization (GARUTI et al., 1978/79, SHERVAIS, 1979). The orthopyroxene-clinopyroxene solvus gives temperatures ranging from about 1200 to 800 °C indicating for several samples a partial reequilibration of the magmatic assemblages to granulite facies conditions (CAPEDRI et al., 1976, ERNST, 1978, GARUTI et al. 1978/79, SHERVAIS, 1979). Finally, temperatures around 700 °C are obtained from olivine-spinel, which are interpreted as a high-temperature reequilibration along the cooling path (ENGI, 1978). Even lower temperatures were obtained from rocks of the granulite facies domain using the rhodonite-bustamite geothermometer in manganese marbles (ABRECHT et al., 1978/79) and the Fe-Mg distribution between garnet-biotite and garnet-cordierite (ZINGG, 1978, HUNZIKER & ZINGG, 1980).

The temperatures plotted in fig. 3 are not only dependant on the choice of the geothermometer and calibration but also on the location and type of measure-

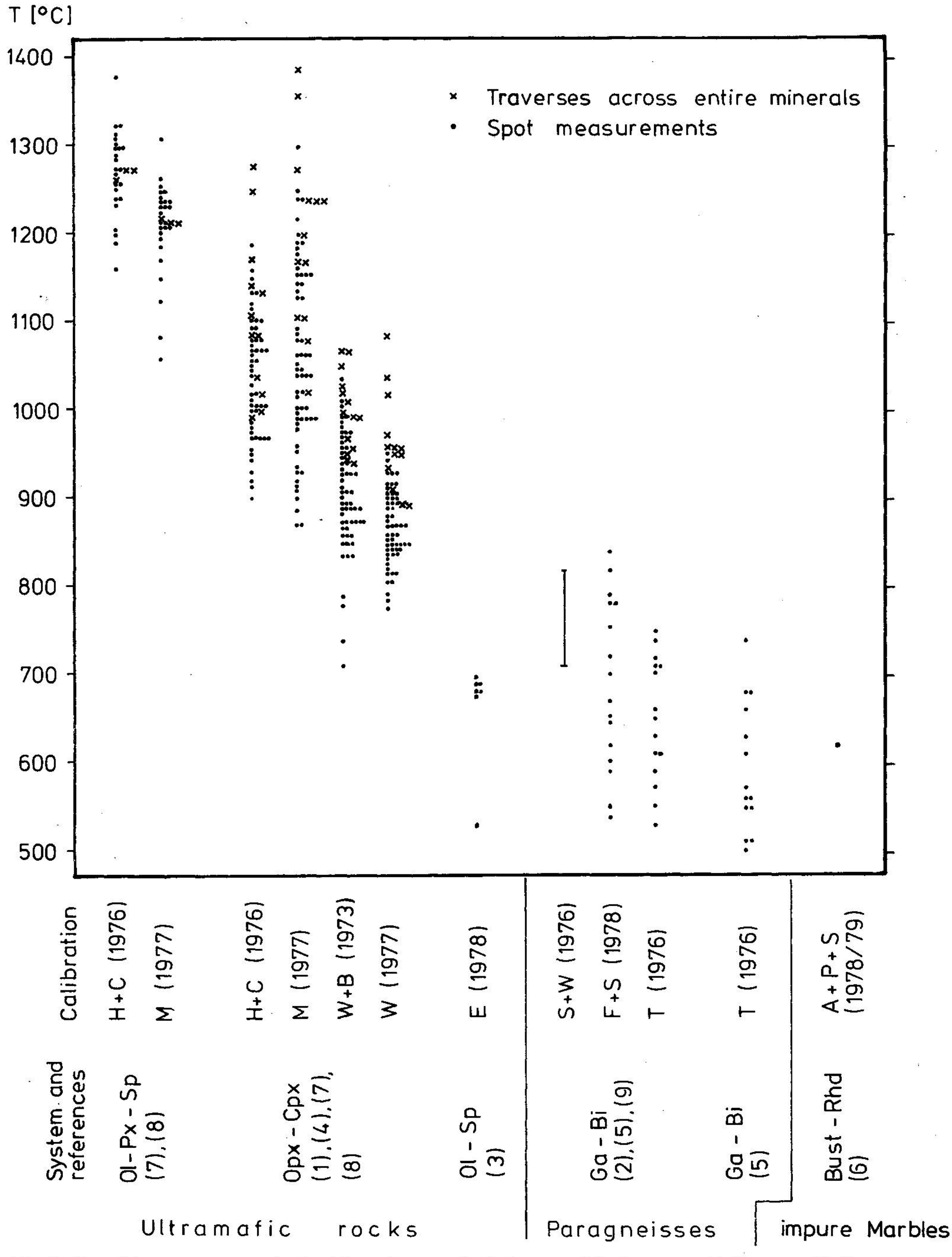

Fig. 3 Plot of the temperatures obtained from the granulite facies part of the Ivrea zone. References: (1): CAPEDRI et al. (1976), (2): SCHMID & WOOD (1976), (3): ENGI (1978), (4): ERNST (1978), (5): ZINGG (1978), (6): ABRECHT et al. (1978/79), (7): GARUTI et al. (1978/79), (8): SHERVAIS (1979), (9): HUNZIKER & ZINGG (1980). Calibrations: W+B: WOOD & BANNO (1973), H+C: HERZBERG & CHAPMAN (1976), S+W: SCHMID & WOOD (1976), T: THOMPSON (1976), M: MORI (1977), W: WELLS (1977), E: ENGI (1978), F+S: FERRY & SPEAR (1978), A+P+S: ABRECHT et al. (1978/79).

ment (traverses across minerals or spot measurements) because of unmixing and retrograde cation exchange among the phases. Fig. 4 summarizes the results of systematic measurements of Fe and Mg in garnet and cordierite of a high-grade paragneiss sample. Garnet and cordierite, if not in contact with each other, are homogeneous. But garnet-cordierite pairs show a zonation with respect to Fe and Mg due to retrograde cation exchange which is well known from other high-grade terrains (e. g. HESS, 1971). As the composition of the mineral pairs changed during cooling, there is no way of determining the conditions of the peak of metamorphism using geothermometers based on the Fe-Mg distribution between these phases. Temperatures ranging from 680 to 500°C can be produced from the same sample, as shown in fig. 4.

Therefore, it is not possible to decide from the PT estimates if the thermal history of the Ivrea zone is polyphase or not. Analogous to radiometric age determinations, geothermometry (and geobarometry) only give us numbers whose geological significance—magmatic crystallization, peak of metamorphism, cooling stage, disequilibrium—is a matter of interpretation.

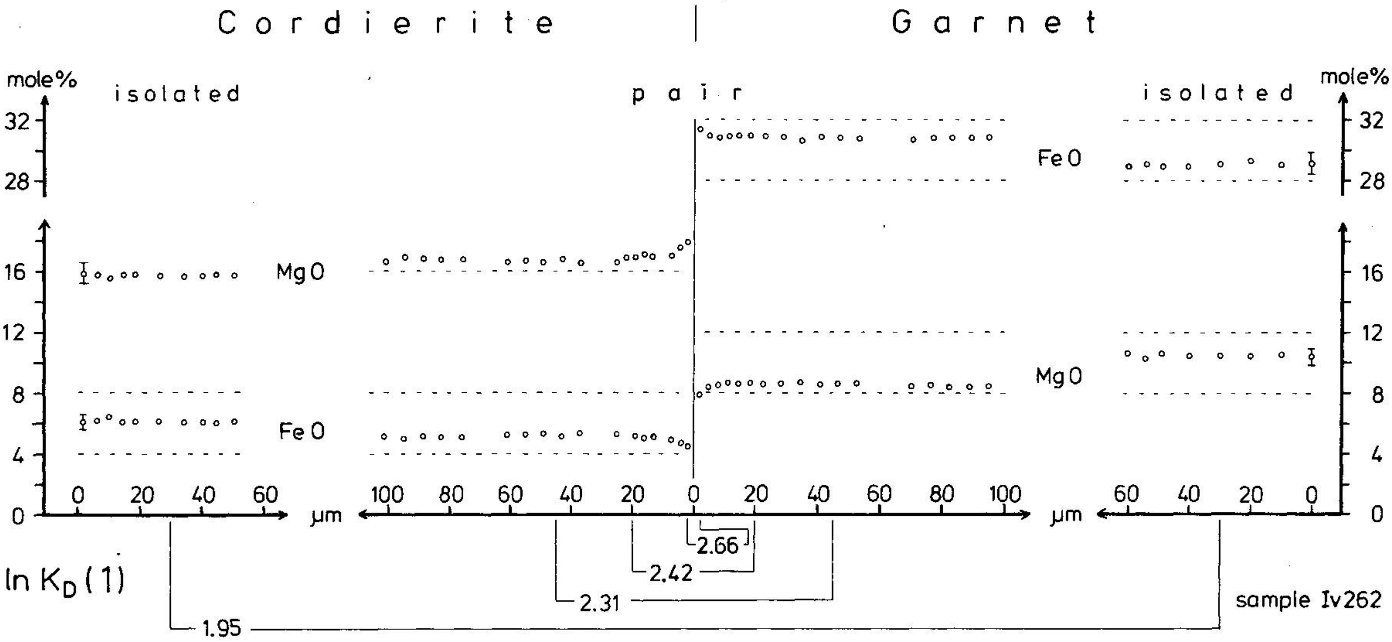

Fig. 4 Partial reequilibration of a garnet-cordierite pair to lower temperature conditions. For the zonation observed at the grain boundary, retrograde cation exchange according to the reaction:
Mg-garnet + Fe-cordierite = Fe-garnet + Mg-cordierite (1)
must apply. The following temperatures are obtained using the calibrations of THOMPSON (1976) and HOLDAWAY & LEE (1977) respectively:

Domain	ln K_D (1)	T	[°C]
Isolated ga and cd	1.950	684	687
ga-cd pairs 40-50 µm	2.306	578	593
ga-cd pairs 20 µm	2.422	548	567
ga-cd pairs 8 µm	2.572	513	535
ga-cd pairs ± 3 µm	2.662	493	516

Note that the isolated garnet and cordierite may not give the temperature of the peak of metamorphism as their compositions presumably are dictated by the local chemistry of the rock.

6. Geobarometry in the Ivrea zone

The pressure estimates for the Ivrea zone scatter between 3 and 20 kb and vary with the geobarometer, calibration and solution model applied as well as with the measured domain. The problems of pressure estimates in the Ivrea ultramafics have been discussed recently by SHERVAIS (1979) and GARUTI et al. (1980). For the Balmuccia peridotite they conclude that the pressure ranged between 12 and 20 kb during the magmatic crystallization. A pressure between 8 and 11 kb is proposed for the reequilibration of the spinel-peridotite after its emplacement in the lower crust. In the paragneisses the reaction

$$\text{plagioclase} = \text{garnet} + \text{sillimanite} + \text{quartz} \qquad (2)$$

can be used for pressure estimates. However, the grossular component in the Ivrea garnets is very low ($x_{Ca} < 0.07$) and the calculated P are highly dependent on the solution data and models used. From reaction (2), P of 9–11 kb were obtained by SCHMID & WOOD (1976) for the granulite facies part of the Ivrea zone. Their calculations both of P and T are strongly affected by their assumption concerning the H_2O activity. HUNZIKER & ZINGG (1980) calculated minimal and maximal P of 6–7 and 9–10 kb, respectively, making extreme assumptions on the grossular solution properties (ideal mixing and regular solution model with Margueles parameters $W_{Ca\,Mg} = 7460{-}4.3T$, $W_{Ca\,Fe} = 0$, $W_{Fe\,Mg} = 0$, respectively).

More promising results are obtained from the paragenesis garnet-pyroxene-plagioclase-quartz. For the granulite facies part of the Ivrea zone P around 8 kb were obtained by NEWTON & SCHMID (in prep.).

7. Age determinations

The published radiometric age determinations are compiled in table 3 and fig. 1. Plate I shows the regional distribution of biotite and monazite ages and in fig. 5 the ages are plotted in a temperature-time diagram. In several cases, the same sample or samples from a given outcrop were used for dating with different methods. Most of these samples show crystalloblastic textures without reaction features. Therefore, the various ages obtained on the rock-forming minerals from the same sample cannot be assigned to different phases of metamorphic crystallization. They must be related to the different behaviour of the age systems during metamorphism and cooling.

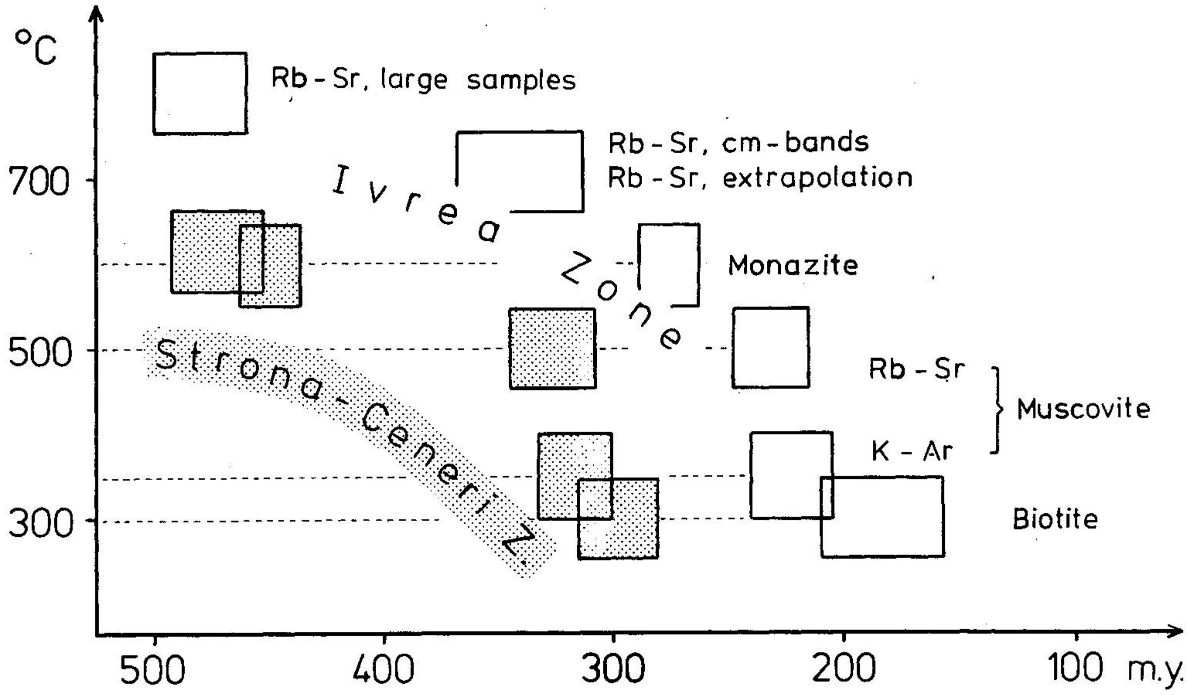

Fig. 5 Plot of the radiometric age determinations (see table 3 for references) against the closing temperatures for the granulite facies part of the Ivrea zone and the SE part of the Strona-Ceneri zone. The Rb-Sr whole-rock isochrons are interpreted according to model III (chapter 7.4). The temperatures applied for the closure of the mineral systems are those of PURDY & JÄGER (1976) and KÖPPEL & GRÜNENFELDER (1975). For a PT-time plot derived from regional considerations see LAUBSCHER & BERNOULLI (1982).

7.1. Rb-Sr whole-rock ages

Paragneiss samples (30–50 kg each) from the Ivrea zone define an isochron of 478 ± 20 m.y. (HUNZIKER & ZINGG, 1980). The samples were collected over the entire metamorphic range. They include migmatites (paleosome + neosome), one sample of neosome alone and restites according to the investigations of SCHMID (1972, 1978/79) and SIGHINOLFI & GORGONI (1978). Therefore, the authors assigne this Ordovician age to the anatexis which is closely related to the regional metamorphism in the Ivrea zone.

An isochron of 338 ± 41 m. y.[2] was obtained by GRAESER & HUNZIKER (1968) on mylonitized paragneiss bands of cm-width from Anzola. All bands taken together as one large sample plot on the Ordovician isochron. This indicates that Sr-homogenization on the cm-scale was still possible during early Variscan time whereas the large-scale Sr-exchange had already ceased during Ordovician time, after the anatexis and dehydration of the rocks.

[2] Age recalculated with the new constant (λ 1.42).

Orthogneiss samples of the Strona-Ceneri zone yield an isochron of 466 ± 5 m. y. (BORIANI et al., 1982/83) with the same Sr-initial ratio of 0.7087 as the Ivrea paragneisses. The authors interpret this isochron as dating the granitic to tonalitic intrusions. These rocks were previously considered to be the product of the degranitization of the Ivrea paragneisses. However, the common lead isotopes do not support such an interpretation (KÖPPEL & SCHROLL, this volume).

Finally, an isochron of 305 ± 10 m. y. was obtained on 20–30 kg samples of phlogopite-peridotite (HUNZIKER & ZINGG, 1982, Hunziker et al., in prep.). A crustal contamination of these peridotites is inferred, with an age of 350 ± 20 m. y. calculated by the linear extrapolation of the $^{87}Sr/^{86}Sr$-values of the phlogopite-peridotites to those of the common (mantle) peridotites of the Ivrea zone using a combined Compston/Jeffery/Nicolaysen diagram.

7.2. U-Pb mineral ages

The orthogneiss zircons of the Strona-Ceneri zone are euhedral and prismatic. Their ages are nearly concordant and yield apparent ages between 429 and 487 m. y.; that is, ages within the same range as the monazites of the paragneisses (PIDGEON et al., 1970, KÖPPEL & GRÜNENFELDER, 1971, 1978/79). The paragneiss zircons are rounded (detrital) or euhedral with habit dominated by pyramides. Their ages are discordant and the lower end of their arrays intercepts the concordia between 450 and 500 m. y. These Ordovician ages are attributed by the authors to the regional metamorphism which attained the amphibolite facies grade in the Strona-Ceneri zone.

In the Ivrea zone, the U-Pb systems yield Permo-Carboniferous ages. The arrays of the paragneiss zircons intersect the concordia at 285 to 300 m. y. and at about 1900 m. y. The monazites from the same samples give concordant ages between 270 and 274 m. y. (KÖPPEL, 1974, KÖPPEL & GRÜNENFELDER, 1978/79). It is notable that Pb-loss in zircon and monazite of the Ivrea zone stopped later than the small-scale Sr-exchange in paragneiss bands (see also Jäger, this volume).

7.3. Hornblende and mica ages

The hornblende and mica ages of the SE part of the Strona-Ceneri zone yield Variscan ages and contrast with the Permo-Mesozoic ages obtained in the Ivrea zone. In the latter zone all mineral ages are younger than the Variscan angular unconformity (prior to Westphal D). An Alpine rejuvanation of Variscan ages, favoured by PIN & VILZEUF (1983) for biotite, is improbable as only low grade Alpine alteration is observed (biotite → chlorite + sphene, garnet → chlorite). I

Tab. 3 Compilation of the radiometric age determinations from the literature. The older ages were recalculated with the new constants (STEIGER & JÄGER, 1977). The subdivision of the Strona-Ceneri zone is based on the mineral ages. A biotite age of 270 m. y. was arbitrarily chosen as the upper age limit for the NW border. References: (1): JÄGER et al. (1967), (2): GRAESER & HUNZIKER (1968), (3): MCDOWELL & SCHMID (1968), (4): MCDOWELL (1970), (5): PIDGEON et al. (1970), (6): KÖPPEL & GRÜNENFELDER (1971), (7): HAMET & ALBARÈDE (1973), (8): HUNZIKER (1974), (9): KÖPPEL (1974), (10): KÖPPEL & GRÜNENFELDER (1978/79), (11): HUNZIKER & ZINGG (1980), (12): BORIANI et al. (1982/83), (13): HUNZIKER et al. (in prep.).

System	Ivrea Zone	Strona-Ceneri Zone NW border	Strona-Ceneri Zone SE part	References
Rb-Sr total rock, paragneisses, large samples	478±20	-		11
Rb-Sr total rock, paragneisses, cm-bands	338±41	-		2
Rb-Sr total rock, phlogopite-peridotite	305±10	-		13
Rb-Sr total rock, basement rocks	-	539±55		7
Rb-Sr total rock, basement rocks	-	473±29		11
Rb-Sr total rock, orthogneisses	-	466± 5		12
Zircon, U-Pb, orthogneisses, ±concordant	-	-	429-487	5,6
Zircon, U-Pb, paragneisses, discordant, lower intersection	285-300	345	450-500	5,6,9
Monazite, U-Pb	270-274	286-330	438-453	9,10
Hornblende, K-Ar	213	332-397	326-353	3,4
Muscovite, Rb-Sr	224,251	311	325	1,8,12
Muscovite, K-Ar	225,230	206-307	316-326	4,8
Biotite, Rb-Sr and K-Ar	162-211	196-270	285-322	1-4,8,12

prefer to interpret the Permo-Mesozoic ages as reflecting the superposition of two thermal regimes, the Variscan cooling and the break-up of the continental margin.

7.4. Radiometric ages and age of metamorphism

The geological meaning of the radiometric ages is still being debated, especially the interpretation of the U-Pb ages and the Rb-Sr whole-rock isochrons. The following models were proposed:

Model I: ALLÈGRE et al. (1974) suggest a Cadomian (520–580 m. y.) event followed by a Variscan event using multistage and/or multiepisodic models for the interpretation of the U-Pb data. This interpretation is supported by the Rb-Sr whole-rock isochron of HAMET & ALBARÈDE (1973) yielding 539 ± 55 m. y. (λ 1.42).

Model II: BORIANI et al. (1982/83) postulate for the Strona-Ceneri zone an Ordovician intrusion of granitic to tonalitic magmas into very low-grade metasediments. These sediments and granitoids were then overprinted by amphibolite facies metamorphism during Variscan time. They suggest that the Rb-Sr muscovite ages around 325 m. y. give the age of the regional metamorphism. This model is extended to the Ivrea zone in BORIANI (1982/83).

Model III: HUNZIKER (1974), KÖPPEL (1974) and HUNZIKER & ZINGG (1980) propose a one phase model with an Ordovician age for the amphibolite to granulite facies metamorphism followed by very slow cooling. In this model, the crustal segments remained at great depth until Permo-Carboniferous time and the different radiometric ages reflect specific properties of the different age systems and their behaviour during this long thermal evolution.

Model IV: KÖPPEL (personal communication) presently prefers a two stage model for the Ivrea zone. During Ordovician time, the paragneisses were dehydrated under amphibolite facies conditions. This dehydration is recorded by the Rb-Sr isochron defined by large samples. The amphibolite to granulite facies metamorphism is then of Variscan age and dated by the U-Pb systems.

These different models require some comments: In models I and II the amphibolite to granulite facies metamorphism is considered to be Variscan. However, only Ordovician and no Variscan monazite and zircon ages have been found in the SE part of the Strona-Ceneri zone. In terms of these two models it is also hard to understand why the orthogneiss zircons of the Strona-Ceneri zone yield nearly concordant Ordovician ages. Under amphibolite facies conditions discordant zircons are observed in orthogneisses (see e. g. the Lepontine area) due to continuous or episodic loss of radiogenic lead (KÖPPEL et al., 1981, and VIDAL & HUNZIKER, in press, respectively).

The quality of the isochron of HAMET & ALBARÈDE (1973) quoted in support of model I is rather poor, as discussed by HUNZIKER & ZINGG (1980). Only 5 of the 7 samples were used to calculate this age.

Model II is based on several debatable interpretations: that the aluminosilicate nodules found adjacent to pegmatites are chiastolites; that these chiastolites were formed in low-grade metasediments during contact metamorphism; and that these pegmaties are related to the Ordovician intrusions. In addition, the possibility that the Rb-Sr orthogneiss isochron dates not the intrusion but the subsequent metamorphic overprint is not considered[3], even though it would explain the nearly concordant Ordovician orthogneiss zircons.

The interpretation of the Ordovician Rb-Sr paragneiss isochron in model III is based on the following considerations: 1) the isochron, furnished by restites, migmatites and neosome, dates the anatexis, as partial melting will homogenize the Sr; 2) according to the studies of SCHMID (1972 and 1978/79) and SIGHINOLFI & GORGONI (1978) the anatexis and "degranitization" of the paragneisses is closely related to the amphibolite to granulite facies metamorphism. However, it is remarkable that the arrays of the paragneiss zircons from the Ivrea zone still have an upper intercept with the concordia of about 1900 m. y. and seem not to reflect an Ordovician event. In addition, one thermal peak is proposed in

[3] In the Central Alps, several isochrons on Variscan granitoids yield Alpine ages, i. e. the time of upper Cretaceous metamorphism (HANSON et al., 1969, HUNZIKER, 1970, FREY et al., 1976, STEINITZ & JÄGER, 1981, OBERHÄNSLI et al., in press).

model III, although there is not direct evidence for (or against) the persistence of high temperatures between the Ordovician and Variscan cycles. Such an assumption implies temperatures around 700 °C persisting over 150 m. y. at a depth of about 30 km. This thermal implication has not yet been tested by model calculations.

Model IV is based on the assumption that the lower intercept of zircon arrays with the concordia dates approximately the peak of the amphibolite to granulite facies metamorphism. If so, the peak of metamorphism was at 450–500 m. y. in the SE part of the Strona-Ceneri zone, at about 345 m. y. in the NW part of the Strona-Ceneri zone and at 285–300 m. y. in the Ivrea zone. In model IV an amphibolite facies metamorphism is followed by an amphibolite to granulite facies metamorphism. But petrological studies always point to the inverse, i. e. a granulite facies stage followed by an amphibolite facies stage (chapter 4.3.).

Personally, I favour an Ordovician age for the regional metamorphism in both the Ivrea and Strona-Ceneri zones, these crust segments remaining at depth until the Variscan orogeny (model III). The monazite ages are interpreted as formation ages in the SE part of the Strona-Ceneri zone and as "cooling" ages in the higher tempered Ivrea zone.

8. Discussion of some aspects of the evolution of the Ivrea and Strona-Ceneri zones

Several reasons make it difficult to establish valid models for the evolution of the Ivrea and Strona-Ceneri zones:

1) At the deep crust level represented by the Ivrea zone, magmatic and metamorphic features (subsolidus reequilibration, anatexis) converge. In addition anorogenic metamorphic processes are possible at this depth.

2) Recrystallization and reequilibration of the assemblages after the peak of metamorphism might be complete and erase evidence of previous stages of the history. Thus far, criteria for distinguishing among Ordovician and Variscan features have not been established.

3) Most laboratory data (PT-estimates, radiometric ages) are not self-evident. The geological meaning of these numbers must be interpreted in the context of many other data.

In addition to these general remarks, it must be pointed out that until recently most of the workers were petrologists interested in the Ivrea zone as a model for the deepest crust. To reconstruct the prevailing conditions at these depths they intensionally avoided mylonites and fault zones. Therefore, our knowledge of the postmetamorphic history and especially of the tectonic evolution is fragmentary.

A crucial point in the history of the Ivrea and Strona-Ceneri zones is the age of the climax of the amphibolite to granulite facies metamorphism. An Ordovician age is favoured for both the Strona-Ceneri and the Ivrea zones (model III in chapter 7.4). We do not know the geotectonic environment of this thermal event and therefore the term "Caledonian" is avoided.

Only few features predating the culmination of the regional metamorphism have been preserved. The kelyphite-peridotites and amphibolitized eclogites indicate an early high-pressure stage in the evolution of at least a part of the basement rocks. Discordant zircon populations point to source rocks older than 1900 m. y. (KÖPPEL & GRÜNENFELDER, 1971). Extrapolations of the Sr-evolution of the Ivrea paragneisses give a sedimentation age between 480 and 700 m. y. (HUNZIKER & ZINGG, 1980). The substratum of these sediments is unknown according to HUNZIKER & ZINGG (1980) and is thought to have been consumed by subduction as the sediments were brought to depth. For NICOLAS (1983) the Mafic formation represents oceanic crust on which these sediments were deposited. However, in light of field and analytical work the Mafic formation is more likely to represent a deep seated intrusion (e. g. GARUTI et al., 1980).

The emplacement age of the Mafic formation is still being debated. GARUTI et al. (1980) propose an intrusion after the peak of the amphibolite to granulite facies metamorphism. For this case two generations of mantle-derived rocks have to be distinguished: 1) an older generation of mafics with a complete reequilibration of the assemblages under the conditions of the regional metamorphism. This type is predominant in the Val d'Ossola region (e. g. Anzola); 2) the Mafic formation with magmatic relics and only partially reequilibrated assemblages, mainly found in the Val Sesia region.

Alternatively, the difference in reequilibration of the mafics observed in the two aforementioned valleys could reflect the different crustal level exposed (ZINGG, 1978, 1980). In agreement with the regional distribution of cordierite in the paragneisses, geobarometry indicates a pressure increase towards the NE, i. e. parallel to the strike of the zone. According to this finding, the mafics in Val d'Ossola intruded a deeper crustal level than in Val Sesia where the roof of the intrusion is exposed. Based on these considerations, HUNZIKER & ZINGG (1980) proposed an emplacement of the Mafic formation during the regional metamorphism. The intrusion would have provided additional heat and caused the climax of metamorphism.

The Mafic formation is subject to isotope work by several groups. These studies will allow a more substantial discussion of the genesis of these mantle rocks.

The evolution of the paragneisses during amphibolite to granulite facies metamorphism is better known. SCHMID (1972 and 1978/79) and SIGHINOLFI & GORGONI (1978) demonstrate that anatexis and "degranitization" of the paragneisses were very important during regional metamorphism. These processes depleted the Ivrea zone in granitophile elements, forming paragneisses with mean densities of 2.95–3.05 g/m^3 (FOUNTAIN, 1976, KISSLING, 1980). The resulting melts consumed considerable amounts of water and thereby caused the dry conditions of the granulite facies.

Granitoids of Ordovician age (BORIANI et al., 1982/83) are found today as orthogneisses in the Strona-Ceneri zone. They have the same Sr-initial as the paragneisses of the Ivrea zone and were considered to be possible degranitization products until KÖPPEL & SCHROLL (this volume) provided common lead data which preclude a genetic relationship. Nevertheless, the degranitization of the Ivrea paragneisses is an important process of crustal differentiation: The lower crust is depleted and the medium crust enriched with respect to granitophile elements.

The physical conditions of the peak of metamorphism (9–11 kb and 800–900 °C for the granulite facies part of the Ivrea zone) are uncertain, as the PT-estimates might reflect a later reequilibration. Parts of the pressures and temperatures are strongly affected by retrograde cation exchange and constrain the conditions of the cooling path.

The pressure increase determined by geobarometry in a profile from the amphibolite to the granulite facies coincides approximately with the lithostatic pressure produced by the rock sequence (HUNZIKER & ZINGG, 1980). In the layered group of the Mafic formation, magmatic structures (e. g. flow bedding) are observed in subvertical position (RIVALENTI, 1978/79). Therefore, one may assume that the Ivrea zone was in a horizontal position during the regional metamorphism and the intrusion of the Mafic formation. Subsequent movements brought it into its present-day, steeply dipping position.

Between Ordovician time and the Variscan cycle there is a large information gap. In the model favoured, high-temperature conditions persist during this time span, and the crust has remained essentially in its original horizontal position.

At the onset of the Variscan cycle granulite facies conditions still persisted according to the interpretation of the Rb-Sr whole-rock data and the petrological investigations of the Finero phlogopite-peridotite (STECK & TIÈCHE, 1976, HUNZIKER & ZINGG, 1982, HUNZIKER et al., in prep.). The inferred crustal contamination of the Finero peridotite 350 ± 20 m. y. ago could be related to tectonic activity which brought the Ivrea and Strona-Ceneri zones to a higher level and initiated the cooling phase. This cooling is well documented by the closure of the different mineral age systems as shown in fig. 5. At the same time, shallow portions of the crust, e. g. the lower Paleozoic sediments of the E part of the Southern Alps, underwent a prograde metamorphism attaining the anchizone and locally the greenschist facies[4] in the Carnian Alps. So one must assume

[4] The relation between lower Paleozoic sediments, Edolo schists, Morbegno gneisses and the Strona-Ceneri zone is not known. So it may be that the prograde metamorphism was even higher than greenschist facies.

thrusting during the Variscan orogeny which simultaneously generated prograde and retrograde metamorphism depending on the crustal level affected.

After the Variscan orogeny the Ivrea zone remained at a considerable depth, whereas the SE part of the Strona-Ceneri zone was discordantly covered by Permo-Carboniferous sediments and volcanics and intruded by the granitoids of the Baveno suite. The Mesozoic evolution of the Southern Alps is marked by Triassic volcanic activity and by the fragmentation of the continental margin during Liassic time (e. g. BERNOULLI et al., 1979, BALLY et al., 1981, WINTERER & BOSELLINI, 1981). The thermal regime of the rifted continental margin was superimposed on the Variscan cooling of the Ivrea zone. Accordingly, the upper Triassic and Liassic mica ages are interpreted either as cooling ages (HUNZIKER, 1974) or are thought to reflect a thermal event related to rifting (FERRARA & INNOCENTI, 1974, see also LAUBSCHER & BERNOULLI, 1982). Work is in progress (by Mark Handy) to distinguish rifting tectonics from Alpine tectonics in the basement.

The question still most debated is the age of emplacement of the Ivrea body. Variscan, Cretaceous and Paleogene ages have been proposed for the generation of the "bird head" structure shown in fig. 2.

For a Variscan emplacement age it was argued that the subhorizontal position of the Permo-Mesozoic sediments covering the SE part of the Strona-Ceneri zone preclude an Alpine "tilting" of the Ivrea zone. - However, the crustal profile exposed between the Ivrea zone and the sediments is not continuous (see fig. 1). During Permian time the Ivrea Zone was still at depth, with temperature around 600 °C (monazite ages). So important movements have occurred between this zone and the sediments since Permian time (Pogallo and Cremosina line). In addition, not all Mesozoic sediments are in their original position. In several places they are tilted and thrusted (e. g. fig. 5 of Novarese, 1929).

A second argument commonly put forward for a Variscan emplacement is based on the interpretation of the radiometric age data shown in fig. 5. These ages were interpreted as reflecting the cooling of continental crust after the Variscan orogeny. During Liassic time 300 °C (biotite ages) was reached, an unlikely temperature for a crustal level close to the continental MOHO. Therefore, it was concluded, that the Ivrea zone must have been detached from the upper mantle before Mesozoic time, i. e. during the Variscan orogeny. - For this argumentation, normal continental crust is assumed. But the Southern Alps were affected by rifting during early Mesozoic time and the Ivrea zone was situated at the continental margin, a region of thinned crust (LAUBSCHER & BERNOULLI, 1982). The second assumption is that the Ivrea zone was originally located at the crust-mantle boundary. However, the amphibolite-granulite facies transition and the relatively low pressures obtained for the granulite facies part indicate that the Ivrea zone represents not the transition to the upper mantle but a segment of deep crust.

Arguments generally advanced for an Alpine emplacement of the Ivrea body are the presumed instability of such a density inversion over a period of more than 300 m. y. and the position of the Ivrea body within the arc of the Western Alps and its kinematic implications. Laubscher (1970) relates the mise en place of the Ivrea body to Neogene dextral strike-slip movements along the Insubric line. For the II. Kinzigite-Diorite zone (and the Valpelline Serie) Laubscher (personal communication) postulates an earlier emplacement, as this unit was involved in the upper Cretaceous (Eo-alpine) orogeny (Dal Piaz et al., 1971). The II. Kinzigite-Diorite zone and the Valpelline Serie have the same lithological association and the same thermal evolution as the Ivrea zone—at least until 180 m. y. ago (biotite ages, Hunziker, 1974).

Alternatively, all 3 units were emplaced during the Eo-Alpine orogeny (Hunziker, 1974). During this event, basement rocks of the Sesia zone s. str. were subducted (e. g. Compagnoni et al., 1977). This wedge of felsic rocks could be responsible for the density inversion observed today. Note that the morphology of the Ivrea body may have changed significantly since the emplacement due to the subsidence of the Po basin and to the root zone tectonics.

These problems are subject of a joined NF project at the Basel and Zürich institutes and will be discussed in detail elsewhere.

9. Summary

Special tectonic circumstances permit the study of lower continental crust in the Ivrea zone. This zone consists of paragneisses, marbles, mafic and ultramafic rocks. During the Paleozoic amphibolite to granulite facies metamorphism, the paragneisses were depleted in granitophile elements. This "degranitization" is a large-scale differentiation process producing dense lower curst and a granitic intermediate crust. The Strona-Ceneri zone with amphibolite facies micaschists, psammitic and granitic gneisses represents a segment of intermediate crust. However, the profile from the Mesozoic sediments to the intermediate and lower crust is disrupted by the Cremosina and Pogallo lines.

The basement evolution of the SE part of the Strona-Ceneri zone ended with the Variscan orogeny, whereas the Ivrea zone remained at depth and yields Permian and lower Mesozoic mineral ages.

The ages and temperatures obtained from the Ivrea zone vary systematically as a function of the dating method and the geothermometer applied. The different ages either reflect different metamorphic phases or are controlled by the blocking conditions of the applied system. The latter possibility is favoured by the author and a thermal evolution with high temperatures persisting from Ordovician time to the Variscan orogeny is proposed.

Several problems are still in discussion and are the topic of current research:

the age of the mafics, the interpretation of the radiometric ages, the postmetamorphic evolution and the emplacement history of the Ivrea body.

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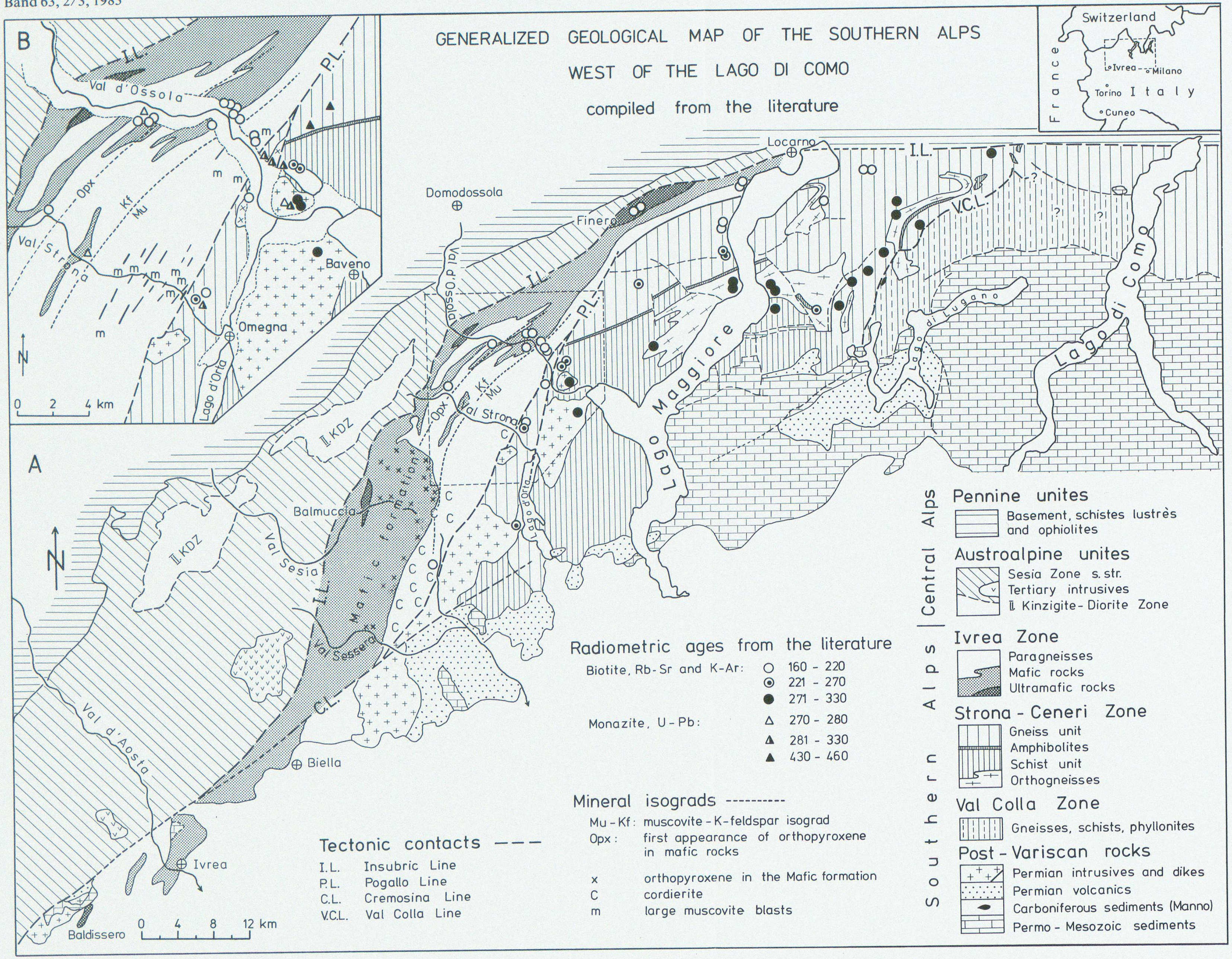

Plate 1 A: Sketch map of the Southern Alps west of the Lago di Como and B: detailed map of the Ossola region. In the Ossola region there is a discordance in the compositional banding between the Ivrea and Strona-Ceneri zones. The limit between the two zones is formed by the Pogallo line. Further NE, along the Lago Maggiore, the boundary between the Ivrea and Strona-Ceneri zones is transitional and is placed according to the map of BORIANI et al. (1977). In the region of the Lago di Como, the Strona-Ceneri zone and the Val Colla zone are not distinguished on the available maps. Note that the mica ages (quoted in table 3) change within the Strona-Ceneri zone from Variscan in the SE to Permo-Mesozoic in the NW part. The regular isograd zonation observed in the Val d'Ossola region is not matched by the occurrence of orthopyroxene in the Mafic formation (= "Basischer Hauptzug") in the Val Sesia. m: location on map B of the large muscovite blasts (see chapter 4.2.). Their spacial occurrence is the same as that of dikes which presumably belong to the Baveno suite.