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Pre-Alpine metamorphism of the Southern Alps west of the Giudicarie Line

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Abstract

This paper concerns the pre-Alpine metamorphic evolution in the basement of the Southern Alps west of the Giudicarie Line. In the western part, the basement comprises two main units separated by the Cossato-Mergozzo-Brissago (CMB) and Pogallo Lines. The westernmost unit (Ivrea-Verbano Zone) is composed of a volcano-sedimentary sequence intruded by a large Mafic Complex. To the east of CMB and Pogallo Lines, the basement comprises a sedimentary sequence with interlayered thin volcanic horizons that was intruded during the Ordovician by large plutons, mainly granitic in composition. To the east of Ivrea-Verbano Zone the basement is commonly divided into the Serie dei Laghi, the Val Colla Zone and the Orobic Basement.

The main metamorphism of the Ivrea-Verbano Zone occurred under amphibolite (T = 730 ± 50 °C; P = 5.5 ± 1 kbar) and granulite (T = 850 ± 100 °C; P = 8–9 kbar) facies conditions. The high-temperature event was mainly due to the emplacement of the Mafic Complex during Early-Permian age. The other unit of the Southern Alps suffered the main regional metamorphism under amphibolite (T ~ 600 °C; P = 6–9 up to 11 kbar) and/or greenschist facies conditions. The easternmost portion of the Orobic Basement records only greenschist facies conditions and contains palynomorphs of Silurian-Ordovician age. Relics of high pressure associations (P > 15 kbar; T = 700 ± 50 °C) are locally recognised within the northern part of the Serie dei Laghi, overprinted by amphibolite facies metamorphism(s). The main metamorphic event (amphibolite facies conditions) is considered Variscan in age (thermal peak between 320 and 350 Ma), although for the Serie dei Laghi unit Ordivician ages are also proposed for another and older amphibolite facies event. All the Southern Alpine domain (except the Ivrea-Verbano Zone) seems to have suffered the same metamorphic evolution but the different units record different structural levels: intermediate in the central Alps, high crustal level near Adamello and east of the Giudicarie Line. After the main regional event, the metamorphic evolution of the Southern Alps is instead different in P-T conditions and age.

Keywords: Pre-Alpine metamorphism, Southern Alps, basement, Serie dei Laghi (Strona Ceneri Zone), Orobic basement.

1. Introduction

The Southern Alpine domain occurs to the south of the Periadriatic Line. It comprises a metamorphic pre-Alpine basement and Permo-Mesozoic volcanic and sedimentary cover rocks. It is incorporated in the Alpine orogen and so has been affected by south-verging folds and thrust systems. The pre-Alpine basement is constituted by two main metamorphic units: an amphibolite to granulite facies volcano-sedimentary sequence with a large intrusive Mafic Complex (the Ivrea-Verbano Zone, IVZ) and an amphibolite to greenschist unit, mainly composed of metapelites, minor metabasite lenses and large metagranitoid bodies (basement to the east of the Ivrea-Verbano Zone, commonly divided in the Serie dei Laghi, the Val Colla Zone and the Orobic Basement).

We will describe the basement of the Southern Alps from the town of Ivrea in the west to the Adamello massif in the east (Fig.1).

2. The Ivrea-Verbano Zone

The Ivrea-Verbano Zone (Fig. 1) occurs over a distance of 140 km along the inner arc of the west-

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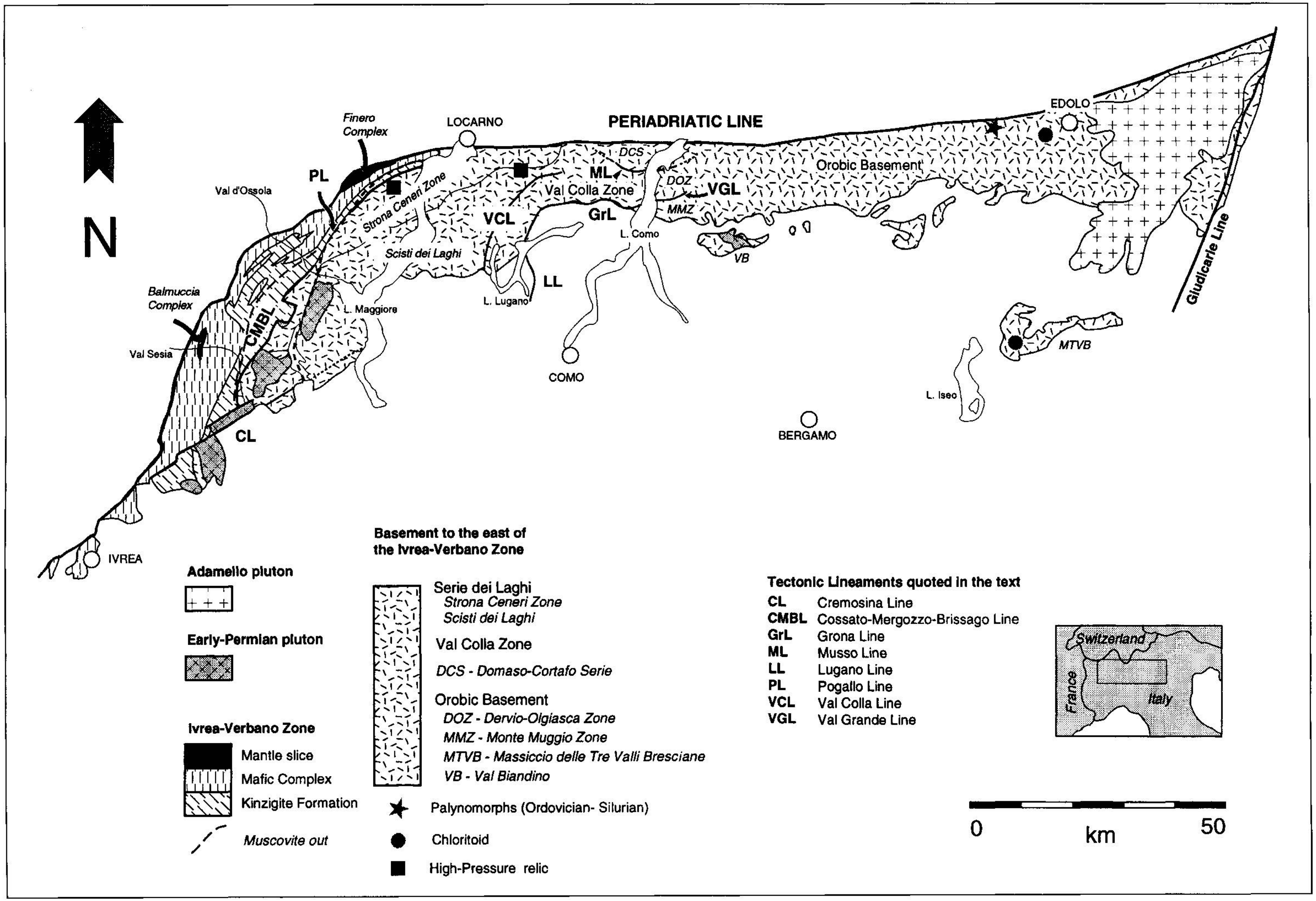

Fig. 1 Sketch map of the basement units in the Southern Alps west of the Giudicarie Line.

ern Alps from Ivrea to Locarno (CH). It ranges in width between 5 and 15 km. The Ivrea-Verbano Zone is tectonically bounded by two important tectonic lineaments: to the north and west the Periadriatic Line (in this region known as Canavese Line), a greenschist mylonitic belt that separates the IVZ from the Alpine nappes, and to the south-east, the Cossato-Mergozzo-Brissago Line (CMBL) separating the Ivrea-Verbano Zone from the Serie dei Laghi.

The Ivrea-Verbano Zone (BORIANI and RIVALENTI, 1984) is a peculiar structural unit in the Alpine chain with mantle slices, as well as ultramafic rocks and mafic bodies (Mafic Complex) intruded into a metamorphosed volcano-sedimentary sequence (Kinzigite Formation) during Early Permian time (VOSHAGE et al., 1990). All the Ivrea-Verbano Zone strikes SW–NE and dips steeply to the north-west and in the Kinzigite Formation, the metamorphic grade increases from southeast to northwest, from amphibolite to granulite facies conditions approaching the contact with the Mafic Complex. The estimated age of the Kinzigite Formation sedimentation is in the range of 480–700 Ma (model age, HUNZIKER and ZINGG, 1980).

Mantle slices (e.g. Balmuccia and Finero Complexes) occur in the north-western part of the Ivrea-Verbano Zone, near the Periadriatic Line. The ultramafics are mainly spinel peridotites and pyroxenites. Phl-Hbl peridotites prevail in the Finero Complex.

The Mafic Complex is composed of three main units (RIVALENTI et al., 1975; RIVALENTI et al., 1984): (i) the Layered Series with layered peridotites, pyroxenites, dunites, and anorthosites; (ii) the Main Gabbro; (iii) the Diorites, that occur close to the Kinzigite Formation. Prominent septa, 50–100 m thick, of granulite facies metapelites are interlayered between the Layered Series and the Main Gabbro (FERRARIO et al., 1982).

The Kinzigite Formation comprises amphibolite to granulite facies schists and gneisses (so-called kinzigites and stronalites, respectively) with interlayered metabasites of MORB affinity (SILLS and TARNEY, 1984), quartzites and thin metacarbonate horizons. Pegmatites are mainly concentrated towards the south-eastern margin of the Ivrea-Verbano Zone. QUICK et al. (1994), on the basis of structural data, demonstrated that the contact between Kinzigite Formation and Mafic Complex is magmatic and it is characterised (in places) by extensive partial melting of metapelites and metabasites of the Kinzigite Formation. In these areas, Opx-bearing rocks (Qtz + Kfs + Pl + Opx ± Grt ± Bt) occur and are interpreted as crystallised products of anatectic melts (SINIGOI et al., 1991).

In the Ivrea-Verbano Zone, the P-T estimates of regional metamorphism indicate a general increase from amphibolite to granulite facies conditions from S–E to N–W, although the available data scatter enormously: temperatures range from 500 to 950 °C for pressures between 5 and 11 kbar (SCHMID and WOOD, 1976; GARUTI et al., 1978/79; HUNZIKER and ZINGG, 1980; ZINGG, 1980; RIVALENTI et al., 1981; ZINGG, 1983; SILLS, 1984; GEBAUER et al., 1992; HENK et al., 1997). These heterogeneous data strongly depend on the retrograde evolution of the Ivrea-Verbano Zone. Actually, the reconstruction of a P-T-d path is very difficult due to the lack of structural information that could allow to relate deformation phase(s) to episodes of mineral growths.

2.1. MAFIC COMPLEX

Igneous textures and primary magmatic phases are locally preserved within the Mafic Complex, but subsolidus reequilibrations are frequently observed. The gabbroic rocks of the Mafic Complex exhibit granoblastic textures and medium to coarse grain-size. The subsolidus reequilibration occurred under static conditions and gave rise to the anhydrous granulite facies assemblage: $Pl_{(I)}$ + Cpx ± Opx ± Grt + Ilm ± Qtz ± Kfs (see CAPEDRI, 1971 for a detailed description of mineral assemblages). Subsequently, the rocks of the Mafic Complex developed hydrous associations retrograde with respect to the granulite facies conditions. This involves the growth of brown amphibole, biotite and $plagioclase_{(II)}$. Fine grained kelyphites and simplectites mark the destabilisation of Opx and garnet. Brown amphibole was subsequently overgrown by rims of green-hornblende. This green-amphibole coexists with green-brown biotite, oligoclase and titanite. This retrogression occurs within discrete extensional shear bands in the gabbros and is pervasive in the diorites.

P-T estimates of granulite facies conditions of the Mafic Complex point to temperatures of 850 ± 100 °C and pressures of 8–9 kbar (GARUTI et al., 1978/79; RIVALENTI et al., 1981; SILLS, 1984; GEBAUER et al., 1992; HENK et al., 1997). Higher pressures of up to 10–12 kbar are reported for the lower part of the Mafic Complex (Layered Series in MAZZUCCHELLI et al., 1992), high temperatures, around 1000–1200 °C, are considered to reflect the conditions of magmatic crystallization. In Val Sesia, near the Periadriatic Line, temperatures of 800 ± 50 °C and pressures around 9 kbar record the granulite facies conditions both on rocks from the Mafic Complex (gabbros) and Opx-rich charnockitic septa. The growth of brown amphibole is associated with an increase in temperature coupled with a significant decrease in pressure (850–900 °C / 7–7.5 kbar). The later rim of green amphibole records amphibolite facies conditions of 500–550 °C / 4–5 kbar (TUNESI and DIELLA, unpublished data).

2.2. KINZIGITE FORMATION

In the Kinzigite Formation, the metamorphism increases from SE to NW, from upper amphibolite facies, adjacent to the Serie dei Laghi, to granulite facies, near the contact with the Mafic Complex (PEYRONEL PAGLIANI and BORIANI, 1967; SCHMID, 1967). The metapelites of the Kinzigite Formation close to the contact with the Serie dei Laghi contain white micas and "fibrolitic" sillimanite associated with Pl + Qtz + Bt ± Grt. Westwards, the disappearance of muscovite in the presence of quartz yields the association of coarse-grained Sil + Bt + Grt + Qtz + Kfs + Pl. In Val d'Ossola, the Ms-Kfs isograd is roughly parallel to the compositional banding and strike but in the vicinity of Val Sesia it runs N–S, crosscutting the lithological banding (ZINGG, 1980).

In the metapelites, the modal proportion of the phases changes from SE to NW, mainly due to the growth of garnet at the expense of biotite due to the reaction: Bt + Sil + Qtz → Grt + Kfs + H_2O (SCHMID, 1967; SCHMID and WOOD, 1976). The rocks grade from high-T paragneisses (kinzigites) to leucocratic granulites (stronalites). Cordierite and andalusite are widespread to the south of the Val Sesia (ZINGG, 1980). In the northern regions cordierite and andalusite are less abundant, but not absent and sillimanite is the most stable Al_2SiO_5 polymorph. Staurolite and kyanite (for kyanite only three localities are indicated; BERTOLANI, 1959; CAPEDRI, 1971; BORIANI and SACCHI, 1973) are also locally found, but there is no consensus in the available literature on the timing of kyanite growth with respect to the main and widespread sillimanite- and garnet-bearing assemblage. The assemblage Ky + St + Grt (staurolite is enclosed in garnet, BURLINI, 1990; or completely surrounded by cordierite, ZINGG, 1980) could represent an early high-pressure event, as proposed by ZINGG (1983). These relictic assemblages are rare due to the later extensive high-temperature event.

SCHMID and WOOD (1976) estimated that the amphibolite to granulite facies metamorphism took place at temperatures of 700–820 °C and pressures of 9–11 kbar. In Val d'Ossola, P-T estimates are T = 940 ± 60 °C and P = 8.3 ± 0.5 kbar for the granulite facies conditions and T = 730 ± 50 °C and P = 5.5 ± 1 kbar for the upper amphibolite facies conditions (SCHMID et al., 1988). In Val d'Ossola, the boundary between the two facies is not transitional but, as recognised by SCHMID et al. (1988), is sharp and marking a gap in temperatures and pressures. This gap could correspond to the shear zones at the amphibolite-granulite boundary recognised by BRODIE and RUTTER (1987). In the Val Sesia, temperatures of 750–800 °C and pressures of 8 ± 0.5 kbar are reported for the granulite facies conditions (SILLS, 1984). In this area, the boundary between amphibolite and granulite facies conditions seems to be transitional (HENK et al., 1997); temperatures range from 750 ± 50 °C up to 616 ± 30 °C and pressures from 8 ± 2 kbar up to 4.3 ± 1 kbar. In areas further to the north and south of the Val Sesia, the metasediments indicate 750 ± 50 °C / 6 ± 1 kbar (SILLS, 1984).

Metabasites interbedded with paragneisses of the Kinzigite Formation show the same deformation and metamorphic history as the metapelites. In Val d'Ossola, amphibolite facies conditions are developed eastwards and the assemblage Pl + Hbl + Bt prevails in rocks with nematoblastic fabric. Towards the west, the fabric becomes equigranular and granoblastic, with the assemblage Pl + Cpx + Opx + Grt ± Hbl ± Qtz . On the basis of the first occurrence of Opx, ZINGG (1980) constrains the Opx isograd to trend more to the NW with respect to the Ms-Kfs isograd but nearly subparallel to it. A temperature of around 800 °C is estimated for the granulite facies conditions in the Val Sesia.

2.3. GEOCHRONOLOGY

The rocks of the Kinzigite Formation most probably experienced one or more regional metamorphic phase(s) prior to the emplacement of the Mafic Complex (Ky +St + Grt in kinzigites?). The age of the main metamorphic imprint in the Ivrea-Verbano Zone is the subject of continued debate, because different isotopic systems yield different ages and can be interpreted in various ways. So, Ordovician, Carboniferous or Permian ages are proposed for the peak of metamorphic conditions (see ZINGG et al., 1990; PIN, 1990; GEBAUER, 1993; SCHMID, 1993 for discussions).

The Mafic Complex intrusion influenced the evolution of the IVZ basement because extensive dehydration and melting occurred as a result of the high thermal regime. The age of these processes and the Mafic Complex emplacement, indirectly constrain the age of the high-temperature assemblages recognised in the IVZ. The U–Pb zircon age of 285 +7/–5 Ma from Diorites (PIN, 1986) suggests a Permian age for the emplacement of gabbros and diorites. A 274 ± 16 Ma age (interpreted as solidification age by BÜRGI and KLÖTZLI, 1990) for migmatites at the contact between Mafic Complex and Kinzigite Formation, indicates that partial melting was induced by magmatic underplating of the Mafic Complex at a deep crustal level in rocks that had already attained high temperatures. During cooling, the magmatic assemblages and textures of the mafic body reequilibrated under granulite facies conditions. VAVRA et al. (1996) interpreted zircon ages of 296 ± 12 Ma as indicating first melting due to dehydration under granulite facies conditions. VAVRA et al. (1996) constrain the climax of the regional metamorphism in the Ivrea-Verbano Zone to the time span between 296 and 273 Ma. This range of ages is also reported in HENK et al. (1977). Monazites (U–Pb) of metasedimentary rocks collected along a traverse across strike of the Ivrea-Verbano Zone, yield mainly concordant ages between 276 ± 2 Ma and 292 ± 2 Ma. Youngest ages are from rocks close to the Periadriatic Line and Mafic Complex, while oldest ages are recorded near the Pogallo Line. The authors interpreted these ages as due to the progressive cooling of the Kinzigite Formation after Mafic Complex emplacement. The complex history of crustal exhumation and cooling probably began at 300–280 Ma as also proposed by BRODIE et al. (1989) and was associated with high-temperature anhydrous shear zones (BRODIE and RUTTER, 1987; ZINGG et al., 1990).

In the Ivrea-Verbano Zone the ages of 230–200 Ma, appear to be associated with "magmatic" activity (alkaline-rich fluid circulations or melt infiltration?). Emplacement of syenite pegmatites (225 ± 13 Ma in STÄHLE et al., 1990), growth of zircons in the Finero ultramafic Complex (207 ± 5 Ma in VON QUADT et al., 1993), overgrowths of zircons in metapelites of the Kinzigite Formation (226 ± 5 Ma in VAVRA et al., 1996) are reported for this time span. These ages could correspond to a thermal event (see FERRARA and INNOCENTI, 1974) probably related to the onset of continental rifting leading to the opening of the Tethyan ocean (HANDY and ZINGG, 1991; ZINGG et al., 1990).

3. The Southern Alps to the east of the Ivrea-Verbano Zone

The basement of the Southern Alps to the east of the Ivrea-Verbano Zone (Fig. 1) comprises mainly metapelites and metapsammites with pre-Alpine amphibolite and/or greenschist facies assemblages. This metasedimentary sequence is interlayered with metabasites. Marbles and calc-silicate rocks locally occur. This portion of basement is characterised by the presence of large metagranitoid bodies with a composition generally ranging from tonalite to granite. They are particularly abundant in the western part of this basement but can be found with similar geochemical features as far east as the Adamello pluton. Plutonic bodies (intermediate to acidic in composition) of Early-Permian age also occur, but are small compared to the Mafic Complex of the Ivrea-Verbano Zone.

To the east of the Ivrea-Verbano Zone, the basement is commonly divided into the Serie dei Laghi, the Val Colla Zone and the Orobic Basement.

3.1. SERIE DEI LAGHI

The Serie dei Laghi (Fig. 1) is a large unit separated from the Ivrea-Verbano Zone by the Cossato–Mergozzo–Brissago Line (CMBL in Fig. 1) and locally by the Pogallo Line (PL). HODGES and FOUNTAIN (1984) report both lines as Pogallo Line. To the east and south, it is limited by the Val Colla and Cremosina fault system. The portion of the Southern Alpine basement occurring east of the Val Colla Line (VCL) is known as the Val Colla Zone. To the east of Lago Maggiore, the Serie dei Laghi is separated from the Alpine nappes by the Periadriatic Line.

The CMBL is an important subvertical tectonic contact, intersected at low angle by the Pogallo Line in the Val d'Ossola and Val Cannobina area. The CMBL is characterised by high temperature mylonites, migmatites and mafic to intermediate rocks (BORIANI et al., 1974a). These intrusives have an age of 285 ± 5 Ma (CUMMING et al., 1987) and seal the contact between the Serie dei Laghi and the Ivrea-Verbano Zone (BORIANI et al., 1990a). The CMBL is interpreted as transcurrent fault with a strong vertical component (BORIANI et al., 1990a). The age and significance of the Pogallo Line is still highly debated: late-Hercynian transcurrent fault (BORIANI et al., 1990a) or Late-Triassic to Early- to Middle Jurassic low-angle normal fault (HODGES and FOUNTAIN, 1984; HANDY, 1987). The Val Colla and Cremosina system is considered to be of Late Carboniferous-Permian age, reactivated in Alpine times (BORIANI et al., 1974b).

According to BORIANI et al. (1990b), the main structure of the Serie dei Laghi is a large synform with fold axis steeply dipping to the SW and subvertical axial plane. A later vortex tectonics

(Schlingenbau, BÄCHLIN, 1937) deformed the main foliation and the compositional banding.

The Serie dei Laghi consists of metasedimentary rocks and Ordovician metagranitoids (orthogneisses; BORIANI et al., 1982/83), intruded by Early Permian mafic to intermediate rocks and granites; it represents an intermediate continental crust of Paleozoic age (BORIANI et al., 1990b). The Permian granites (the so-called Graniti dei Laghi) occur as several intrusions between Lago Maggiore and Val Sesia (westernmost area). Their intrusion age is around 275 Ma (whole rock and mineral ages, BORIANI et al., 1992 and references therein) and thus they are slightly younger than the mafic rocks ("appinite suite"). The granites produced a small contact aureole with static recrystallization in the metapelitic country rocks and growth of biotite, andalusite, cordierite ± spinel ± corundum (GALLITELLI, 1943; BORIANI et al., 1988). A minimum temperature of 720 °C and a depth of 4–5 km for the emplacement of the Montorfano pluton (lower Val d'Ossola) can be inferred, whereas a lower temperature and depth is proposed for the Baveno body.

Two subunits are recognised in the Serie dei Laghi (Fig. 1): a prevailing metapelitic unit, the Scisti dei Laghi and a prevailing metapsammitic one, the Strona Ceneri Zone (for a correlation of names used in literature, refer to ZINGG, 1983, Tab. 1). The metapelitic sequence mainly occurs in the southern part of the Serie dei Laghi, from Lago d'Orta to Lago Maggiore. Possibly, they represent the deepest pelitic portion of the whole sedimentary sequence; their sedimentation age is unknown, but surely pre-Ordovician, because they are intruded by Ordovician granitoids. The metapelites contain also minor metapsammites and amphibolites. Locally, in metabasites, relics of high pressure (eclogitic?) assemblages are present: garnet, rutile, zoisite, quartz, symplectites around Na-Cpx (BORGHI, 1989). BORGHI (1989) considered this metamorphic event to be pre-Ordovician in age, because it is not recognised in the orthogneisses. The main metamorphic event developed under amphibolite facies conditions in all the Serie dei Laghi. The metapelites contain Qtz + $Pl_{(20\% An)}$ + WM + Bt + Grt + St + Ky ± Sil; the metabasites Hbl + Pl + Di + Ep + Ilm. Garnet, kyanite and staurolite are porphyroblasts that grew syn- to post-kinematically with respect to the main foliation. The association of Sil + Qtz + Ilm replaces biotite under static conditions and is interpreted by BORGHI (1989) to represent the thermal peak following the pressure peak evidenced by the occurrence of kyanite. A subsequent retrogression to greenschist facies conditions is locally observed to give sericite, albite-oligoclase, ripidolite, $garnet_{(II)}$, spinel in metapelites and actinolitic-hornblende, albite-oligoclase, chlorite, clinozoisite, spinel in metabasites.

To the north, the metapelites are in contact with the metapsammitic portion through a continuous horizon of metabasites (GIOBBI ORIGONI et al., 1982/83), that has a thickness of about 500 m in the westernmost part and consists of amphibolites interlayered with schists, paragneisses and quartzites. Also lenses of metagabbro, garnet-amphibolite, pyroxenite and peridotite are present to the west of Lago d'Orta and to the north of Lugano (GIOBBI ORIGONI et al., 1997). This horizon was defined as the "Strona Ceneri Border Zone" by GIOBBI ORIGONI et al. (1997). The banded amphibolites of the southern part of the horizon often contain K-feldspar megacrysts up to 10 cm in length. BORIANI et al. (1990b) interpreted the sequence as basaltic tuffites interlayered with siliciclastic products. The microstructures and mineralogical assemblages indicate a polymetamorphic history (GIOBBI ORIGONI et al., 1997; ZURBRIGGEN et al., 1997) for these rocks. They may represent eclogites that were transformed under amphibolite facies conditions: Na-clinopyroxene, rutile and hornblende inclusions are locally recognised within garnet only to the NE of Lago Maggiore. Metagabbros contain zoned plagioclase and pale green amphibole in a coarse-grained flaser fabric. Mineralogy and geochemistry of the mafic and ultramafic rocks suggest that these rocks derived from an ophiolite belt dismembered to form slivers then embedded in the sedimentary protolith of the "Strona Ceneri Border Zone".

The metapsammitic sequence comprises medium to coarse-grained gneisses (i.e. Cenerigneisses) and fine-grained massive gneisses (Gneiss Minuti). The Cenerigneisses show variable fabric, "enclaves" of quartz, mica-rich rocks, mafic rocks, zoned Ca-silicate nodules and no sedimentary layering. In contrast, the Gneiss Minuti have relics of sedimentary structures, such as grain size gradation and compositional layering. The mineralogical association is: Qtz + Pl (polygonal aggregates) + Ms + Bt + Kfs (locally in porphyroclasts up to 5 cm in length). Fine-grained gneisses (Gneiss Minuti) do not generally contain K-feldspar. Kyanite, garnet and sillimanite locally occur in the mica-rich aggregates. This assemblage is related to the main amphibolite facies metamorphic phase.

The chemical composition of the Cenerigneisses is very similar to that of the Gneiss Minuti. The origin and evolution of the coarse-grained gneisses (Cenerigneisses) is up to now highly debated. BORIANI et al. (1990b with references) and

BORIANI et al. (1997) interpret the Cenerigneisses to be metasandstones to metacomglomerates that were deposited as coarse-grained turbidites (mass flow). These sediments were later infiltrated by granitic residua and then metamorphosed. On the other hand, ZURBRIGGEN et al. (1997) consider the Cenerigneisses to be granitoids derived from dehydration melting of a metasedimentary protolith (e.g. the Gneiss Minuti). According to BÄCHLIN (1937), the Gneiss Minuti could represent the highest structural portion and the finest-grained sediments of the metasedimentary sequence. The banding in the Gneiss Minuti is crosscut by many pre-metamorphic aplitic and pegmatitic dykes, probably associated with the Ordovician magmatic event. They contain Ca-silicate nodules and Al-silicate nodules which are interpreted as the regional metamorphic products of original chiastolite porphyroblasts (BIGIOGGERO and BORIANI, 1975). The chiastolite may be the product of a contact metamorphism related to the intrusion of aplites and pegmatites into a non-metamorphic sedimentary sequence. These sediments later underwent a regional post-Ordovician metamorphism (BORIANI et al., 1990b). In contrast, according to ZURBRIGGEN et al. (1997) Al-silicate nodules pre- to syn-date the main S_2 schistosity (considered Ordovician in age and developed under amphibolite facies conditions) and chiastolite grew statically after D_2 deformation in the Al-silicate nodules.

Thermobarometric data were evaluated for pyroxenites from the "Strona Ceneri Border Zone", metapsammites and metapelites. Thermobarometry on pyroxenites (GIOBBI ORIGONI et al., 1997) yield temperatures > 800 °C and pressures around 12 kbar, suggesting a lower crustal environment under upper amphibolite-granulite facies conditions which possibly reequilibrated the original HP assemblage. ZURBRIGGEN et al. (1997) report temperatures between 690–750 °C and pressures between 9–11 kbar for the symplectite formation, but pressures greater than 15–16 kbar for the eclogitic assemblage Na–Cpx + Grt + Rt + Hbl. The main metamorphic overprint under amphibolite facies conditions occurred at a temperature of about 600 °C and pressure of 6–8 kbar (GIOBBI ORIGONI et al., 1997; ZURBRIGGEN at al., 1997). The age of the HP event must predate the intrusion of Ordovician granitoids, because the garnet amphibolites are often found as xenoliths in the orthogneisses. Thermobarometry on the Cenerigneisses yield temperatures between 550–600 °C and pressures of about 8 kbar (ZURBRIGGEN et al., 1997). For mafic enclaves of the Cenerigneisses the estimated temperature ranges from 540 to 600 °C, but the pressures are not well constrained (BORIANI et al., 1997). P-T conditions of 570–610 °C, 7–9 kbar are obtained by FRANZ et al. (1996), HENK et al. (1997) and ZURBRIGGEN et al. (1997) on a "Grt-St mica-schist" from the Strona Ceneri Zone. All these data are consistent and represent the metamorphic conditions for the main amphibolite facies event in the Serie dei Laghi. Slightly higher temperatures (647–660 °C) and lower pressures (6.5–7 kbar) are reported by BORGHI (1989) for the thermal peak of the main metamorphism in the metapelites of the Scisti dei Laghi.

3.1.1. Geochronology

The HP (eclogitic) event is not constrained by radiometric data, but it is surely older than Late-Ordovician magmatic rocks, based on geological and structural evidence.

Data pertaining to the age of the main metamorphic event were mainly obtained with the metapsammitic rocks (Strona Ceneri Zone) and the interpretation was then extended to the whole Serie dei Laghi. Early Paleozoic ages were obtained from paragneiss zircons (430–500 Ma: PIDGEON et al., 1970; KÖPPEL and GRÜNENFELDER, 1971; 456 Ma: RAGETTLI, 1993), monazites (450 Ma: KÖPPEL and GRÜNENFELDER, 1971; 440–450 Ma: KÖPPEL and GRÜNENFELDER, 1978–79; 452 Ma: RAGETTLI, 1993), from staurolite in micaschists, (385 Ma, minimum age: ROMER and FRANZ, 1998), and from a whole rock Rb–Sr isochron (473 ± 23 Ma: HUNZIKER and ZINGG, 1980). The cited authors consider the ages around 450 Ma to be the age of the main metamorphism under high temperature conditions, responsible for the melting that lead to the Ordovician magmatism (450–466 Ma). An age of 479 ± 24 Ma (U–Pb on zircon, lower intercept) on Cenerigneisses is instead interpreted as "the age of crystallisation just following anatexis", since this rock type is considered plutonic by ZURBRIGGEN at al. (1997).

BORIANI and VILLA (1997) consider the Early Paleozoic ages to be the consequence of the granitoids intrusion: their emplacement produced fluid circulation which induced Pb loss of the detrital paragneiss zircons. According to the authors, the ages around 450 Ma record an Ordovician diagenesis and fluid circulation rather than the main metamorphism.

Another group of age points to "Variscan" or younger ages. These are mostly mineral ages (200–300 Ma: MCDOWELL, 1970; HUNZIKER, 1974; KÖPPEL, 1974; about 320 Ma: BORIANI et al., 1982/83; 340 Ma: BORIANI and VILLA, 1997;

321 Ma: ZURBRIGGEN, 1996). The age of around 340 Ma is considered by BORIANI and VILLA (1997) to date the thermal peak of the main Variscan amphibolite facies metamorphism. Similar ages (220–250 Ma) and interpretations are reported by many authors (BOCCHIO et al., 1981; MOTTANA et al., 1985; DAL PIAZ and LOMBARDO, 1985; SASSI and SPIESS, 1993) in the entire Southern Alpine domain east of the Serie dei Laghi. Younger ages, around 290–300 Ma, possibly represent the age of the greenschist facies retrogression, connected to the "Schlingen" tectonics. ZURBRIGGEN et al. (1997, 1998) consider the Carboniferous ages to record an amphibolite facies metamorphism connected with the "Schlingen" tectonics.

3.1.2. Geological considerations

There is general agreement that the Serie dei Laghi represents a pre-Ordovician accretionary prism. The entire sequence was intruded by Ordovician plutonic bodies.

According to BORIANI and VILLA (1997), the Serie dei Laghi contains remnants showing relics of HP metamorphism pre-Ordovician in age (lenses of garnet-amphibolites embedded in orthogneisses). A diagenetic phase occurred during Ordovician time. A Carboniferous ensialic convergence caused the main metamorphic event: a first phase under amphibolite facies conditions (around 340 Ma), a second phase under greenschist facies conditions (around 300 Ma). The uplift of the Serie dei Laghi began between the two phases and ended before Upper Westphalian (basement rocks pebbles in basal conglomerate).

According to ZURBRIGGEN et al. (1997), the HP metamorphism, the main (amphibolite facies) tectonometamorphic phase and the granitoid intrusion are possibly parts of a single Ordovician orogenic event; alternatively, the HP metamorphism may be either Cadomian or Early Ordovician, the main metamorphism and the granitoid intrusions are Ordovician. High-temperature conditions would be preserved until Variscan time, when the main metamorphism was overprinted by a second amphibolite facies metamorphism under lower pressure conditions.

If we consider the age of emplacement of two micas- and hornblende-bearing orthogneisses (450–466 Ma), their chemical features similar to post-collisional magmatism and their deformational history similar to that of the country rocks (BORIANI et al., 1995), it is much more plausible that they suffered a post-Ordovician metamorphic event. Moreover, also ZURBRIGGEN et al. (1997) point out that the kinematics of the main phase (Ordovician) is "obscured by a strong D_3 overprint" again under amphibolite facies conditions and Carboniferous in age. Other important constraints are the studies on zircon Pb-loss due to fluid circulation (LEE, 1993), which allow to reinterpret the zircon ages around 450 Ma as an event producing great amount of fluids (diagenesis?). The Variscan event could not be recorded by U/Pb zircon system, because it involved lower fluid pressures than the Ordovician event. Also the $^{39}Ar/^{40}Ar$ determinations (BORIANI and VILLA, 1997) on green hornblende from amphibolite samples collected east of Lago Maggiore, where the greenschist retrogression is absent, yield only Variscan ages (around 340 Ma).

3.2. VAL COLLA ZONE

The Val Colla basement (Fig. 1) occupies an area east of the Val Colla Line (VCL). It is separated from Alpine nappes to the north by the Periadriatic Line and from Mesozoic cover rocks to the south by the Grona Line (GrL). The latter is interpreted by BERTOTTI and VOORDE (1994 with references) to be a Late Triassic to Early Jurassic normal fault that was steepened during south-directed Alpine thrusting tectonics. The Val Colla basement is mainly composed of metapelites, minor metapsammites and metabasite lenses. Peraluminous leucocratic gneisses prevail in its southern part.

The main rock types are micaschists with the following mineral composition: Qtz + $Pl_{(20–30\%\ An)}$ + Ms + Bt + Grt ± Ky ± St. Plagioclase is often poikiloblastic (as in the Orobic Basement) and garnet is locally included in staurolite. The metabasites are composed of hornblende, $plagioclase_{(30–50\%\ An)}$ ± biotite ± garnet. These assemblages indicate a metamorphic event under amphibolite facies conditions connected to the main phase of deformation. The staurolite growth testifies to a thermal peak that was syn- to post-kinematic with respect to the regional foliation. The lithological association is very similar to that observed to the west in the Scisti dei Laghi. A second metamorphic phase under greenschist facies conditions overprints the first association and develops chlorite, white mica and albite. The age and PT conditions of metamorphism are not well constrained, but it is likely that the rocks in this region record a metamorphic evolution similar to that exhibited in other parts of the Southern Alps. Towards the Val Colla Line, a strong retrogression affected the rocks: the phyllonitic products have a thickness of about 3 km and grade into the normal micaschists. Locally, the rocks seem to be true phyllites, rich in graphite. These rocks have been interpreted as the youngest portion of the basement sequence (Carboniferous in age) occurring along the Val Colla Line (REINHARD, 1964; BORIANI and SACCHI, 1973). Even if the age of this diaphthoretic phase is unknown, it can be considered pre-Triassic (FUMASOLI, 1974) or pre-Carboniferous, according to REINHARD (1964).

In the eastern part of the Val Colla Zone, a greenschist facies mylonitic zone (Musso Line-ML) separates the metapelites of the Val Colla basement from metapsammitic rocks of the Domaso-Cortafo Series (DCS in Fig. 1; FUMASOLI, 1974). In the Domaso-Cortafo Series, D_1 fabrics are marked by Grt + Bt + Qtz ± St ± Ky + Ms + Pl and S_2 is associated with Qtz + Ab + $Ms_{(II)}$ + Chl (DI PAOLA et al., 1997). EL THALAWI (1965) suggests that the Musso Line may represent the easternmost continuation of the Val Colla Line. Unfortunately, there is no exposure in the northern area, due to the south-directed Alpine brittle thrusting. FUMASOLI (1974) considered the Musso Line to be a fault within basement rocks with very similar composition. The Musso Line does not affect the Norian cover rocks (Dolomia Principale) and so it must predate the Norian.

3.3. THE OROBIC BASEMENT

The Orobic Alps encompass the area south of the Periadriatic Line between the Lago di Como and the Adamello massif. Metamorphic rocks (Fig. 1) occur mainly in the northern part and in some tectonic windows to the south. The basement rocks override the Permo-Mesozoic volcano-sedimentary cover along the Orobic Line. The metamorphic basement is made up mainly of pelitic to psammitic metasediments, orthogneisses, and minor marbles, quartzites and calc-silicates. Rarely, lenses of amphibolite with MORB affinity (BOCCHIO and DE CAPITANI, 1998) occur in the metasediments. Small plutons of Early Permian age occur in basement rocks of Val Biandino (VB) and Val Torgola – Val Navazze. The VB pluton (DE CAPITANI et al., 1988) is composed of several elongate bodies of qtz-diorites and tonalites that strike E–W. Dykes of granitic composition occur close to the metapelitic country rocks. A contact aureole is recognised over a width of 200–300 m with the occurrence of Sil → Crd → And moving away from the pluton.

From west to east, the basement of the Orobic Alps is divided into three lithological units: the "Gneiss di Morbegno", the "Filladi di Ambria" and the "Scisti di Edolo". The "Gneiss di Morbegno" are more arenaceous and have poikiloblastic plagioclase up to several centimetres in length. The other two units are more pelitic in composition. Palynological investigations of GANSSER and PANTIC (1988) yield an Ordovician-Silurian age span as the time during which the argillaceous to fine sandy marine sediments (protholiths of the Scisti di Edolo) were deposited, probably in a passive continental margin.

Over the past decade, detailed structural mapping in different regions of the Orobic Alps have lead to the recognition of different tectonic units that preserve distinct metamorphic assemblages and deformational phases which are not coeval (CASSINIS et al., 1986; MILANO et al., 1988; SILETTO, 1990; SILETTO et al., 1990; DIELLA et al., 1992; BERTOTTI et al., 1993; SILETTO et al., 1993; ALBINI et al., 1994; MARONI et al., 1995; CADEL et al., 1996; GOSSO et al., 1997). In the central and western areas, the amphibolite facies assemblage is well preserved. It is contemporaneous with the first phase of deformation, associated with a well developed axial plane foliation (S_1). In the metapelites, the D_1 fabric is associated with the assemblage $Grt_{(I)}$ + $Bt_{(I)}$ + Ms + Pl + Qtz + St + Ky + Ilm + Rt. The orthogneisses contain Pl + Kfs + Bt + Ms + Qtz + Ilm ± Hbl ± Grt, whereas the metabasites have Pl + Hbl ± Cum ± Bt ± Grt ± Qtz + Ilm assemblages. Chloritoid was recently found south-west of Edolo, in S_1 microlithons of metapelites where the assemblage quartz, Ca-plagioclase, garnet, rutile is preserved (ALBINI et al., 1994). According to MARONI et al. (1995) and SPALLA and GOSSO (1997), this association predates the S_2 greenschist foliation.

In the Orobic basement, the physical conditions of the amphibolite facies metamorphism are well constrained by thermobarometric studies (DIELLA et al., 1992; SILETTO et al., 1993; MOTTANA et al., 1994; GOSSO et al., 1997). The temperatures are in the range of 550–630 °C with pressures of 7–9 kbar. Higher pressures (8–11 kbar; GOSSO et al., 1997) are obtained in rocks of the Monte Muggio Zone (south-western region). The D_1 phase of deformation and the associated metamorphism is attributed to the Variscan event: 350–330 Ma determined with K/Ar and Rb/Sr methods on white micas, biotites and hornblendes (BOCCHIO et al., 1981; MOTTANA et al., 1985; WIEDENBECK, 1986). A similar age (around 340 Ma) is proposed by some authors for the D_1 main phase of deformation and metamorphism in the Serie dei Laghi (see previous section).

D_2 deformation occurred under greenschist facies conditions, with the mineral assemblage:

Ms + green Bt + Chl + Ab + Ep + Cal + Qtz ± Mrg in metapelites (DIELLA et al., 1992; GOSSO et al., 1997) and with Ab + Chl + WM in orthogneisses (MARONI et al., 1995). The S_2 foliation is more pervasive in the easternmost part of the Orobic Basement, where S_1 foliation occurs as relics within S_2 microlithons. D_2 conditions derived from mineral equilibria point to T < 500 °C and P < 4 kbar. The age of the greenschist facies metamorphism is not as well constrained as that of the amphibolite facies event, but pebbles of basement with greenschist retrogression occur in conglomerates of lower Permian age (Collio Formation). So the age of exhumation was probably older than 290 Ma (probably ~ 300 Ma, in MOTTANA et al., 1985). In the areas where palynomorphs are preserved, only a greenschist assemblage is recognised (SPALLA and GOSSO, 1997).

In the Orobic Alps near Lago di Como, high-temperature/low-pressure conditions post-dating the main amphibolite event have been recognised (EL TAHLAWI, 1965; BOCCHIO et al., 1980; DIELLA et al., 1992). In the Dervio Olgiasca Zone (DOZ in Fig. 1), a widespread occurrence of sillimanite is observed. The locally developed S_2 foliation, is marked by sillimanite and red-brown $biotite_{(II)}$. Sillimanite and $biotite_{(II)}$ aggregates also replace pseudomorphically the old $Grt_{(I)}$. Field relationships suggest that high temperature conditions were reached during an extensional tectonic phase (DIELLA et al., 1992; SILETTO et al., 1993; SANDERS et al., 1996). In metapelites of the Dervio Olgiasca Zone the assemblage is given by Sil + $Bt_{(II)}$ + $Grt_{(II)}$ + Plg ± Kfs. Clinopyroxene and red-brown amphibole are locally observed in the metabasite lenses (BOCCHIO and DE CAPITANI, 1998). Andalusite porphyroblasts have been observed on both shores of Lago di Como (EL TAHLAWI, 1965; BOCCHIO et al., 1980; DIELLA et al., 1992). Andalusite crystals up to 3–4 cm in length enclose all the minerals of the previous amphibolite facies assemblage. The physical conditions of this metamorphic phase, determined with geothermobarometry, point to temperatures of 650–750 °C and pressures of 4–5.5 kbar. For this high-temperature/low-pressure event, an age of around 220–240 Ma is suggested by the mineral ages (BOCCHIO et al., 1981; SANDERS et al., 1996 also for discussion of geochronological data).

The southernmost occurrence of metamorphic rocks is the Massiccio delle Tre Valli Bresciane (MTVB in Fig. 1; GIOBBI ORIGONI and GREGNANIN, 1983). A well developed S_2 foliation is recognised in this region. The relictic foliation S_1 is rarely preserved between spaced microlithons of S_2 foliation. The first recognisable assemblage is given by Qtz + Ms + Plg + Grt + Chl + opaques. S_2 is marked by white micas and chlorite, although chloritoid, albite and epidote also occur in layers with an appropriate composition. Newly formed garnet grew later than S_2 and is associated with biotite that partially replaces chlorite.

3.4. METAGRANITOIDS (ORTHOGNEISSES)

The existence of metagranitoids in the Southern Alps east of the Ivrea-Verbano Zone is the peculiar feature of this part of basement and their occurrence is reported on the metamorphic map. In the central and eastern part of the Serie dei Laghi (both in the metapsammitic Strona Ceneri and in the metapelitic Scisti dei Laghi), the metagranitoids are very abundant as lenses of up to 1 km in thickness. The original shape and size of these plutonic bodies can only be inferred, because they suffered strong deformation during regional metamorphism which also affected the country rocks. The metagranitoids are mainly granodioritic in composition. Some bodies are locally dioritic to leucogranitic in composition and show a calc-alkaline affinity and mainly meta-aluminous character (BORIANI et al., 1995 with references; CAIRONI, 1994). Following ZURBRIGGEN et al. (1997), three types of Ordovician magmatic rock could be distinguished, one of which, the Ceneri granitoids, has a metasedimentary heritage and a peraluminous character (as a whole the Ordovician magmatism, see figure 8 in ZURBRIGGEN et al., 1997). The mineralogical association is: Qtz + Pl (oligoclase; andesine in the diorites) + Kfs + Bt ± Hbl ± Ms. KÖPPEL and GRÜNENFELDER (1971), HUNZIKER and ZINGG (1980), BORIANI et al. (1982/83) obtained ages of 450 Ma (U–Pb) or 466 ± 5 Ma (Rb–Sr) with initial isotopic ratio .7087 ± 2. This points to an Ordovician emplacement age. According to ZURBRIGGEN et al. (1997) the zircon ages (479 ± 24 Ma) record Ordovician anatexis and related high-grade metamorphism in the entire Serie dei Laghi. Rb–Sr muscovite ages of 311–325 Ma represent the age of the metamorphic overprint (BORIANI et al., 1995).

In the Orobic Basement, metagranitoids form lenses or small bodies. Unfortunately, there are no radiometric determinations on these rocks. On the basis of structural analyses (SILETTO, 1990), geochemical data (SILETTO et al., 1993; COLOMBO et al., 1994) and zircon typology (COLOMBO et al., 1997), the metagranitoids are considered to be pre-Variscan in age, possibly Ordovician, as in the Serie dei Laghi orthogneisses.

Leucocratic gneisses (Gneiss Chiari del Corno Stella or Gneiss Chiari; LIBORIO and MOTTANA, 1971) occur near the contact between basement and volcano-sedimentary cover from Val Sesia to the Adamello massif. This rock type has inequigranular microstructure, peraluminous character and extremely low Fe, Mg, Ca content (BORIANI and COLOMBO, 1979). They present the assemblage: Ab + Qtz + Kfs + Ms ± Grt. The geochemical features point to decompressional melting under vapour-absent conditions (COLOMBO et al., 1997). The origin of the Gneiss Chiari is still debated: volcanic products or epiplutonic leucogranites. The emplacement age of the Gneiss Chiari is only constrained by structural data: these rocks are affected by the same phases of deformation as the other basement rocks, so a pre-Variscan age is the most plausible.

4. Concluding remarks

The two main units of the Southern Alpine basement experienced the main phase of regional metamorphism in different times: mainly during the Permian in the Ivrea-Verbano Zone, mainly during the Variscan (320–350 Ma) in the unit to the east of the Ivrea-Verbano Zone. Although some data and interpretations point to an Ordovician age for the main metamorphism in the Serie dei Laghi (but no evidence or data exist in all the other parts of the Southern Alps), all the authors agree that an amphibolite facies metamorphism ($T = 600 \pm 50$ °C and $P = 6$–9 kbar) occurred during the Variscan in the central-western part of the Southern Alpine basement. Close to the Adamello massif, where palynomorphs are preserved, only a greenschist facies metamorphism is recognised. To the east of the Adamello massif, it is still possible to recognise a stratigraphic sequence consisting of metapsammites and metapelites with interlayered acidic (Ordovician) and basic metavolcanics (e.g. Agordo Basement; POLI and ZANFERRARI, 1992). In the Scisti di Edolo and in the Agordo Basement, acritarch assemblages of Late-Cambrian age have been found (SASSI et al., 1984). Since the palynomorphs date the time of sedimentation, a Variscan age of the metamorphism is probable. The high-pressure relics, preserved only in the northern part of the Serie dei Laghi, testify to a pre-amphibolite facies event ($P > 15$ kbar; $T = 700 \pm 50$ °C).

After the climax of the Variscan event, almost all of the basement rocks record the exhumation history of the Variscan chain and retrograde metamorphic assemblages developed under greenschist facies conditions. This retrogression is older than 290 Ma. Locally, (e.g. in the Dervio-Olgiasca Zone) the decompression was associated with a significant increase of temperatures testified by the widespread occurrence of sillimanite and pegmatites. Rocks with sillimanite, andalusite and cordierite are found in the Serie dei Laghi adjacent to the CMB Line (BORIANI and BURLINI, 1995), associated with pegmatites and Permian mafic to intermediate rocks. It is very probable that they suffered an evolution similar to the DOZ series. This thermal event is constrained by the age of pegmatite emplacement that is coeval with thc growth of sillimanite (SILETTO et al., 1993). According to SANDERS et al. (1996), it probably started around 240 Ma and could be related to rifting of the upper crust.

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