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SPECIAL ISSUE 2: A showcase of the Italian research in metamorphic petrology

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Does the basement of western southern Alps display a tilted section through the continental crust? A review and discussion

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ABSTRACT. — One of the most intriguing geo-petrological problems of Central Alps is the meaning of the presence side by side in the southalpine basement of a lower crustal unit, the Ivrea-Verbano Zone and an upper crustal unit, the Serie dei Laghi separated by a ductile shear zone, the Cossato-Mergozzo-Brissago (CMB) Line. This situation has been interpreted as an «exposed continental section». In this paper a great part of the data produced in the last thirty years are examined and discussed critically. However the authors are well aware that their work is unfortunately not exhaustive especially for what concerns the Ivrea-Verbano Zone on which an enormous amount of papers has been produced. The idea of a tilted section of the lower Paleozoic crust is criticized in favor of a model of a trans-tensional emplacement of the Ivrea Verbano Zone.

RIASSUNTO. — Uno Uno degli aspetti geo-petrologici più problematici delle Alpi Centrali è il significato della presenza, nel basamento sudalpino, di una unità con caratteri di crosta inferiore, la Zona Ivrea-Verbano accanto ad una unità di crosta superiore, la Serie dei Laghi, separate da una zona di shear duttile, la linea Cossato-Mergozzo-Brissago (CMB). Questa situazione è stata interpretata come una «sezione di crosta continentale esposta». In questo lavoro sono esaminati e discussi, in modo critico, gran parte dei dati prodotti negli ultimi trent'anni. Gli autori sono tuttavia coscienti che il loro lavoro non può essere completamente esaustivo, specialmente per quel che riguarda la Zona Ivrea-Verbano sulla quale esiste una vastissima letteratura. L'idea che la Zona Ivrea Verbano rappresenti una sezione di crosta inferiore Paleozoica ruotata, è qui discussa criticamente e viene prospettato un modello di messa in posto in un ambiente transtensionale.

KEY WORDS: *Lower crust; granulites, strike-slip faults, pull-apart basins*

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GEOLOGICAL FRAMEWORK OF THE CENTRAL ALPS

The Alps are a mountain belt extended from the Ligurian Sea to the Vienna basin over a length of about 1000 km. Their evolution is indeed very complex and controversial: the description that follows is necessarily very schematic. The Alps show a crustal structure with double vergence. They include two nappe belts that propagated in opposite directions: A belt with European vergence, or Alpine Belt sensu stricto, consisting of a sequence of tectonic systems thrusted towards the European foreland (on the average towards NW), and a southern tectonic system with African vergence, known with the name Southern Alps. In the W-Central Alps the boundary between these two belts, the Periadriatic Lineament (here called Canavese Line), runs across the lower Val d'Ossola in SW – NE direction. From Locarno, at the northern end of Lago Maggiore, the boundary swings to an E-W strike and takes the name of Iorio-Tonale Line.

The Europe-vergent belt includes, from top to bottom, and from the inner to the outer part of the belt: a) The Austroalpine system; b) The upper, intermediate and lower systems of the Penninic Zone, with associated thin ophiolitic units of «oceanic» origin; c) The Helvetic system; d) The prism of the external molasse (an Oligocene-Neogene foredeep basin partly translated under the front sector of the nappe belt); e) The thin detachment nappes of the French-Swiss Jura and the Meso-European foreland underthrusting beneath the external sector of the belt.

The Africa-verging belt – the Southern Alps – have been considered for a long time the autochthonous background of the Alpine Belt. Its basically allochthonous nature, as well as its structure, with south-verging basement and cover nappes, has only been recently demonstrated.

The prodromes of the formation of the Alpine orogenic belt already occurred in Permian times, when, during a phase dominated by important transcurrent movements, a series of basins filled with volcanics and red beds, appeared in the part of Pangea that later should become the Alpine belt. The break-up of Pangea started in the Triassic and eventually resulted in the formation of an ocean, the Tethys, at the time of the opening of the North Atlantic. The pull-apart basins, filled with volcanics originated by the post-Hercynian wrench faulting, were segments in which a thinned continental crust presumably underwent mafic underplating and extensive melting.

The W-central basement of the Southern Alps – the Massiccio dei Laghi – is part of the Hercynian belt. It includes one of the most studied part of the continental crust: the Ivrea-Verbano Zone. The reason is that this unit shows most of the characters that are considered typical of a thinned lower continental crust. The contact with the adjoining upper crustal Serie dei Laghi is considered, by many authors, an exposed tilted upper/lower crust transition. But not all the authors share this view: this has originated a very interesting discussion. This paper is a contribution to this discussion from the standpoint of two authors that, in collaboration with many colleagues and students, have been studying the Serie dei Laghi and its contact with the Ivrea-Verbano Zone for more than thirty years.

THE TWO UNITS OF MASSICCIO DEI LAGHI: A LITHOSTRATIGRAPHIC APPROACH

As stated above, the basement of the Southern Alps of the Lago Maggiore district (NW Italy) is considered by many authors one of the most interesting «exposed continental sections» of the world.

This basement includes the Ivrea-Verbano Zone (IVZ), an upper-amphibolite to granulite facies sequence with a large mafic body (BORIANI and RIVALENTI, 1984), and the Serie dei Laghi (SdL), a lower-amphibolite facies unit rich of younger and older granites (BORIANI and SACCHI, 1973; BORIANI *et al.*, 1990_b) (Fig. 1).

Recently a new lithostratigraphic map of Serie dei Laghi has been compiled by the authors of this paper. In that map (in publication) the various units are distinguished on the basis of their lithology, or association of rock types, both metasedimentary and metaigneous, and on the basis of the relationships with the adjoining units. The map permits to construct a model of the tectonic environment of sedimentation, igneous activity and metamorphic evolution.

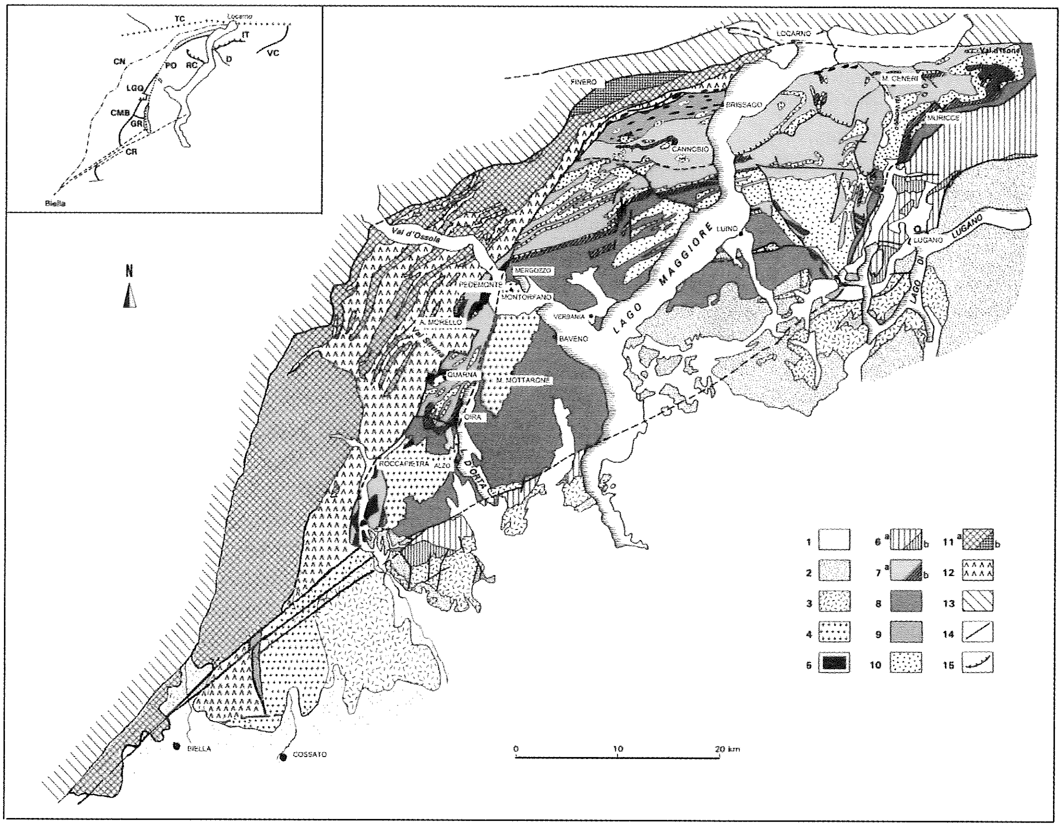

Fig. 1 – Geological sketch-map of Massiccio dei Laghi (modified after BORIANI *et al.*, 1990a).
1 - Quaternary. 2 - Sedimentary Mesozoic-Cainozoic cover. 3 - Permian volcanic rocks. 4 - Permian granites («Graniti dei Laghi»): 5 - Permian mafic and acidic stocks and dykes («Appinites»).
VAL COLLA ZONE: 6 - a) Schists, phyllonites, epidote- amphibolites; b) «Gneiss Chiari».
SERIE DEI LAGHI: 7a - Strona Ceneri Zone (paragneisses, including Cenerigneisses and Gneiss minuti). Between V. Ossola and V. Sesia these rocks are migmatitic near the CMB Line; 7b - Strona Ceneri Border Zone (mostly banded amphibolites with retrogressed eclogites and minor ultramafites - LAG); 8 - Scisti dei Laghi (micaschists, paragneisses); 9 - Serie dei Laghi rocks with low-P, high-T Permian overprint along the CMB Line in Val Cannobina; 10 - Ordovician metagranitoids.
IVREA VERBANO ZONE: 11 - a) Basic rocks, in both granulite and amphibolite facies; b) Ultramafites. 12 - Kinzigites and stronalite (pelitic and semipelitic, high-grade metasedimentary rocks, with minor marble and metabasite intercalations).
13 - ALPINE DOMAIN
14 - FAULTS. In the inset: CN = Canavese; TC = Tonale-Centovalli; CMB = Cossato - Mergozzo -Brissago; GR = Grottaccio; PO = Pogallo-Lago d'Orta; LGQ = Val Lessa, Germagno, and Quarna faults; CR = Cremosina; D = Val Dumentina; VC = Val Colla; IT = Indemini-Monte Tamaro overthrust.
15 – OVERTHRUSTS

THE IVREA-VERBANO ZONE

The Ivrea-Verbano Zone (IVZ) consists of high-T amphibolite and granulite facies with steep isograde surfaces.

The Kinzigite Formation, a volcano-sedimentary sequence with lenses of ultramafites, was intruded by a large mafic body (Mafic Complex) during the Early-Permian time (VOSHAGE *et al.*, 1990). It comprises metapelites (the so–called kinzigites and stronalites), quartzite and thin metacarbonate horizons, with interlayered metabasites of MORB affinity (SILLS and TARNEY, 1984). The metamorphic grade increases from SE to NW, from upper amphibolite facies (white mica and «fibrolitic» Sil, in kinzigites), adjacent to the Serie dei Laghi, to granulite facies (Sil and Kfs, in stronalites), near the northwestern boundary of the unit (PEYRONEL PAGLIANI and BORIANI, 1967; SCHMID, 1967). According to SCHNETGER (1994) the transition from kinzigite to granulite (stronalite) entailed the formation of 20-40% granitic melt.

The ultramafite lenses (e.g. Balmuccia and Finero Complexes) mostly occur in the north-western part of the Ivrea-Verbano Zone, near the Canavese Line: the ultramafites are mainly Spl lherzolites (Lensch, 1968). The presence of these ultramafites in the granulites near the mafic intrusion induced many authors to consider IVZ as an exhumed crust-mantle transition (Menhert, 1975; Fountain, 1976; Zingg, 1983). QUICK *et al.* (1995) demonstrated that the mantle peridotites in the southern Ivrea-Verbano Zone were lenses tectonically interfingered with metasedimentary rocks prior to the intrusion of the mafic complex.

The Mafic Complex, that is thought to have been intruded during the late Paleozoic, is up to 10 km thick. It is mostly exposed between Ivrea and Val Mastallone. Recent data (QUICK *et al.*, 1992, 1994) indicate that this complex is pervasively deformed under hypersolidus conditions and concentrically foliated. The presence of analogous features in ophiolitic gabbros suggests that emplacement involved large-scale flow of crystal mush in an extensional tectonic environment.

The mafic body is composed of three main units (RIVALENTI *et al.*, 1975; RIVALENTI *et al.*, 1984, BORIANI and RIVALENTI, 1984): (1) the Layered Series, that consist of layered peridotites, pyroxenites, dunites, anorthosites; (2) the Main Gabbro; (3) the Diorites, that occur close to the Kinzigite Formation. The gabbroic rocks of the Mafic Complex exhibit a granulite facies assemblage. P-T estimates of granulite conditions point to temperatures of 850 ± 100°C and pressures of 8-9 kbars (GARUTI *et al.*, 1978/79; RIVALENTI *et al.*, 1981; SILLS and TARNEY J., 1984; HENK *et al.*, 1997). Higher pressures of up to 10-12 kbars 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 crystallisation. The contact between Mafic Complex and Kinzigite Formation is magmatic (QUICK *et al.*, 1994). The T – P estimates for granulite facies conditions point to 750-940°C and P = 8 kbars (SILLS 1984; SCHMID *et al.*, 1988), whereas those for the amphibolite to granulite facies conditions point to T between 616-820°C and P between 4-11 kbars (SCHMID and WOOD, 1976; SILLS and TARNEY J., 1984; SCHMID *et al.*, 1988; HENK *et al.*, 1997). DEMARCHI *et al.* (1998) published thermobarometric estimates giving a continuous increase in equilibration pressure from 5.6 kbars along the eastern intrusive contact of the complex to 8.6 Kbar near the western limit of the complex (although they recognise the large uncertainties inherent in the geo-barometric calculations relative to the narrow pressure range recorded). The observed pressure gradient ranging from 0.32 to 0.38 kb/km is indistinguishable from a normal, vertical pressure gradient in the lower crust. BARBOZA and BERGANTZ (2000) published pressure estimates on the kinzigites from the eastern intrusive contact that fall in the same range as those measured by DEMARCHI *et al.* (1998), but they attributed these pressure conditions to the overprint of the contact metamorphism of the upper part of the mafic body on the kinzigites in a decompression episodes that occurred after the regional metamorphic thermal peak. The heat supplied by the mafic intrusion induced resetting of the mineral assemblages and, locally, extensive partial melting (20-30%) in the kinzigites. BARBOZA and BERGANTZ (2000) cast doubts on the common belief that the high-grade metamorphism of the IVZ was caused by the intrusion of the main mafic body (HENK *et al.*, 1997).

THE SERIE DEI LAGHI

Whilst for the Ivrea Verbano the terminology is widely accepted, some discrepancies still exist for «Serie dei Laghi».

NOVARESE (1929) called «Formazione dei Laghi», or «Serie dei Laghi» (SdL), the association of micaschists and biotite rich-gneisses that is found east of the Ivrea-Verbano Zone. The gneisses correspond the «Gneis Strona Orientali» of ARTINI and MELZI (1900). They were also found to correspond the «Ceneri Zone» of REINHARD (1953, 1964) by SCHMID (1968) who therefore used the name «Strona-Ceneri Zone» for the whole unit.

For a correlation of names used in literature, see ZINGG (1983, Table 1).

In the most recent works the Serie dei Laghi (SdL) has been divided into four units:

A meta-arenaceous formation called Strona Ceneri Zone (SCZ);

An association of banded amphibolites, with lenses of ultramafites, metagabbros and garnet-bearing amphibolites (retrogressed eclogites) and intercalation of paragneisses, called Strona-Ceneri Border Zone (SCBZ) (GIOBBI ORIGONI *et al.*, 1997);

A meta-pelitic formation called Scisti dei Laghi (SL);

The Ortogneisses (OG), large lens -shaped bodies of metagranite-metagranodiorite, accompanied by meta-pegmatite, meta-aplite and augen gneisses (PEZZOTTA & PINARELLI, 1994), mainly localised within or close to the SCBZ.

The only remnants of the Permian volcano-sedimentary cover of the SdL occur at Arosio in Sottoceneri (REINHARD, 1964). These deposits lie horizontally over the Strona Ceneri rocks.

THE STRONA CENERI ZONE

This is an amphibolite facies metapsammitic sequence which comprises fine-grained massive gneisses (Gneiss Minuti) as well as medium to coarse-grained gneisses (i.e. Cenerigneisses).

Gneiss Minuti

The Gneiss Minuti are finely layered amphibolite facies meta-sandstones, with abundant Ca-silicate lenses.

Their mineralogical composition is: Qtz, Pl and Bt ± Ms ± Grt, arranged in a granoblastic texture; For this reason in the Swiss literature they are called «Hornfelsgneise». Near the Ordovician intrusions the Gneiss Minuti contain thin metaplites and metapegmatites. In the more Al-rich layers of Gneiss Minuti near the metapegmatites are present many flattened ovoid nodules, rich in micas, Grt and Ky and/or Sil. These nodules have been interpreted as original chiastolite porphyroblasts (BÄCHLIN, 1937, BIGIOGGERO and BORIANI, 1975) formed as a result of a contact metamorphism. We interpret the Gneiss Minuti protolith as a deposit from a turbidite current.

Cenerigneiss

The Cenerigneiss is a unit consisting of a very peculiar rock type. Its mineral composition is: Qtz, Pl, Bt, Ms ± Grt ± Ky and variable amounts of Kfs. These minerals are arranged in a typical glomeroblastic texture. The Cenerigneiss does not show relics of sedimentary banding. It contains pebbles of quartzite and diorite, and Al-rich lumps (with Ms, Grt ± Ky), and decimetre scale zoned Ca-silicate nodules. Most of them are spheroid and show a gradual zoning characterised by the presence, from the core to the rim, of Grt, Py, Hbl and Bt (BORIANI and CLERICI RISARI, 1970). Others are just fragments of a single part of the zoned nodules. These Ca-silicate nodules can be interpreted as the metamorphic product of dolomite concretions, typical of many arenitic deposits.

Near the granitoid lenses the Cenerigneisses acquire an augen texture due to the appearance of large Kfs porphyroclasts, often surrounded by myrmekites. Kfs megacrysts show synneusis textures and parallel inclusions of zoned plagioclase. These features suggest crystallisation from a melt.

The Cenerigneisses protolith is interpreted as sandstones to conglomerates produced by a mass-flow turbidite, deposited in an accretionary prism (BORIANI *et al.*, 1997). The leucogranitic augen gneisses could be the product of «melt infiltration and infiltration metasomatism» that occurred before the Variscan orogenic metamorphism (PINARELLI *et al.*, 2004). These rocks have also been interpreted as granitoids derived from more or less in situ melting of a sedimentary protolith (BORIANI *et al.*, 1977; ZURBRIGGEN *et al.*, 1997).

STRONA CENERI BORDER ZONE

The Strona Ceneri Border Zone (SCBZ) forms a continuous horizon interposed between the Strona Ceneri Zone and the Scisti dei Laghi. It varies from less than one hundred to several hundred meters in thickness. It mainly consists of banded amphibolites, associated to minor paragneisses with lenses of ultramafites, metagabbros and garnet-bearing amphibolites (retrogressed eclogites).

Banded amphibolites

The SCBZ banded amphibolites consist of cm-scale alternating dark (fine-grained amphibolites) and leucocratic («leptynites») layers. The positive eNd_i and low Sr_i of the SdL banded amphibolites with their leucocratic inlayers (the «leptynites») point to a common mantle origin (GIOBBI MANCINI *et al.*, 2003). This unit is indeed very similar to the Leptyno-Amphibolitic Group (LAG) of the French Massif Central (PIN and VIELZEUF, 1988).

Near the contact with the Ordovician granitoids the banded amphibolites grade into Bt-Hbl augen gneisses, with Kfs megacrysts up to 10 cm in length. Recently they are interpreted as due to an infiltration metasomatism induced by the Ordovician magmatic residua well before the Hercynian metamorphism (PINARELLI *et al.*, 2004).

Ultramafites

Lenses of peridotite associated to metagabbro and garnet-bearing amphibolite are present almost everywhere along the horizon, but they are particularly abundant in the surroundings of Omegna (Oira and Alpe Morello)and north of Lugano (Muricce in Val d'Isone).

The Alpe Morello body consists of a partly serpentinised dunite-harzburgite with websterite veins (MARCHESI *et al.*, 1992) associated with amphibolite with Grt relicts (BORIANI and PEYRONEL PAGLIANI, 1968) as well as banded amphibolite. The Alpe Morello body lies along the Cossato-Brissago-Mergozzo Line, which separates the Ivrea Verbano Zone from the Serie dei Laghi. It has usually been attributed to the Ivrea Verbano Zone, but our field work has shown that this attribution must be revised. The lens of Muricce consists of a Sp peridotite accompanied by metagabbro, garnet bearing amphibolites and banded amphibolites (GIOBBI MANCINI *et al.*, 2003).

ORTHOGNEISSES

Large lenses of metagranitoids with metapegmatite and meta-aplite (PEZZOTTA, 1993, PEZZOTTA and PINARELLI, 1994; BORIANI *et al*, 1995) are mainly localized within or close to the SCBZ. The metagranitoids are the metamorphic products of Ordovician granites and granodiorites, that were intruded across the SCBZ in both the Strona Ceneri Zone and Scisti dei Laghi. These metagranitoid bodies display a composition ranging from tonalite to granite. They suffered the same regional metamorphism, which also affected their country rocks. The metagranitoids show a calcalkaline affinity and mainly meta-aluminous character (Boriani *et al.*, 1995 with references; Caironi, 1994). The radiometric age determinations around 450-460 Ma (Köppel and Grünenfelder, 1971; Boriani *et al.*, 1982/83) point to an Ordovician emplacement age. Mineral ages of 311-325 Ma record the regional metamorphism (Boriani *et al.*, 1995).

Scisti dei Laghi

The Scisti dei Laghi cover a large area from Lago d'Orta to Lago Maggiore, near Verbania and, on the eastern shore of the lake, near Luino, were they are cut by the Val Colla-Cremosina fault. This unit corresponds to the «Giumello gneise» in the Swiss literature (Reinhard, 1964). The Scisti dei Laghi consist of alternating micaschist and paragneisses, strongly foliated, with isoclinal folds. The micaschists show typical Qtz rods. Their mineralogical composition is Qtz, Ms, Bt, Pl ± Grt ± Ky ± St.

The contact between Ivrea Verbano and Serie dei Laghi

The contact between Ivrea-Verbano Zone and Serie dei Laghi occurs through an important subvertical tectonic lineament (Boriani *et al.*, 1990_a): the Cossato-Mergozzo-Brissago Line (CMB or CMBL in the literature), a lineament characterised by the simultaneous occurrence of three distinctive features: high-T mylonites, basic-to acidic dikes and stocks (the «Appinite Suite») and migmatites. The line is dissected by contemporaneous orthogonal faults (Val Lessa fault in the lower Val Strona), and later lower-T discontinuities, among which the most important is the Pogallo Line (PL). The PL is characterised by amphibolite to greenschist facies mylonites. Because of the presence side by side along the PL of the two units from the lower (IVZ) and from the upper (SdL) continental crust, Fountain (1976) proposed to consider this situation as complete cross section through the crust, and the fault between them as a tilted low angle normal fault (see also Hodges and Fountain, 1984, Handy 1987). The idea of tilting was based on the assumption that the two units were coherent parts of the same crust and shared the same regional metamorphism (Caledonian, according to Hunziker and Zingg, 1980; Caledonian and Variscan, according to Zingg *et al.*, 1990). Handy (1986; 1987) attributed a Late-Triassic to Early Jurassic age to the activity of the Pogallo Line because he found greenschist facies mylonites in it, and the greenschist facies conditions were assigned, on the basis of the purported cooling history of the area, to those ages (Zingg, 1983). In Handy's opinion, the tilting of the Pogallo Line and of the whole cross section of the 60-85° necessary to reach the present setting, occurred in the Early-Middle Jurassic and completed during the Alpine orogeny. These ideas also appear in later papers by Zingg *et al.*, (1990), S. Schmid (1993) and Mulch *et al.* (2002). In this last paper, of which Handy is co-author, the role of the CMBL as the main tectonic contact between the Ivrea-Verbano Zone and the Serie dei Laghi (Strona-Ceneri Zone in the Swiss literature) is recognised, but the Mesozoic age of the Pogallo Line and the tilting are reaffirmed. The idea of a rotation of the entire crustal section as large as 90° is also supported by Demarchi *et al.* (1998), Barboza and Bergantz (2000), Peressini *et al.* (2003).

Different views were expressed by Boriani *et al.* (1990_a). The SdL had already cooled down to the greenschist facies conditions before the emplacement of the Early Permian granites which show evidence of having been rotated of not more than 20° after their solidification. BORIANI and co-workers consider this fault an oblique strike-slip fault of Early Permian age.

THE INTRUSIVE ROCKS CONNECTED WITH THE TECTONIC CONTACT

Along the contact, the SdL, and to some extent also the IVZ, are intruded by Late-Hercynian magmatic rocks. They are unmetamorphosed and generally only slightly deformed (BORIANI *et al.* 1988_a, GIOBBI ORIGONI *et al.*, 1988). They form two main groups: 1) Small bodies of mafic- to- acidic rocks (the «Appinite Suite»), which occur along the CMBL; 2) Large crosscutting granitic plutons.

THE APPINITE SUITE

A predominantly mafic swarm of small stocks and dikes is intruded in a belt along the CMBL. Between Valsesia and Val d'Ossola these rocks mostly form stocks of gabbrodioritic to granitic composition which, in some cases (Quarna, Alzo-Roccapietra) are strictly connected with the large granitic plutons occurring more to the south. In the IVZ we find mafic dikes as well as small granitic stocks, although they are less abundant than in the SdL. Two small granitic stocks are exposed in Val d'Ossola (CALDIROLI, 1996): one on the eastern slope near the Cemetery of Mergozzo (Granite of San Rocco), the other on the western slope near Gravellona Toce (Granite of Pedemonte). The Appinites are not present along the Pogallo Line; they reappear in Val Cannobina as generally fine-grained mafic to acidic dikes with chilled margins. No chilled margins are present in some coarse grained stocks mostly occurring on the watershed between Val Cannobina and Lago Maggiore. Pseudo-brecciated structures are often present. Fragments of mafic rocks are cemented by a «granitic» matrix . The mafic rocks are slightly foliated. This character has been interpreted by ZURBRIGGEN (1996), MULCH (1999) and MULCH *et al.* (2002) as indicative of a synmylonitic intrusion of the appinites, while the «granitic» matrix is considered as due to a back-veining from the partially melted country rock but no geochemical or isotopic data are given in support of this idea. The dikes are mostly concordant with the mylonitic foliation but it is not rare to find crosscutting dikes sub-parallel to the Pogallo fault. The pattern of the dikes suggests that they were intruded essentially after the mylonitization along CMB, in a pull-apart tectonic environment probably related to the sinistral strike-slip movement of the Pogallo Line. According to MULCH *et al.* (2002), instead, the Pogallo Line post-dates the intrusion of the Appinites.

The determination of the radiometric age of intrusion of the Appinites was not an easy task. PINARELLI *et al.*, (1988) could not obtain a Rb/Sr isochron because of the scatter caused by assimilation of country rocks. Rb/Sr biotite ages vary between 251 and 170 Ma. An U-Pb age of 285 ± 5 was obtained by KÖPPEL and GRÜNENFELDER (1978-79) on a monazite from a dyke near Mergozzo. The Ar/Ar data of BORIANI and VILLA (1997) on hornblendes from the appinites do not permit an age determination. However, since the appinite intrusion sealed the CMBL, an indirect estimation of their age of intrusion can be obtained by the Ar/Ar age of 271 ± 1 Ma of a hornblende from an amphibolite from Alpe Morello along the CMB (BORIANI and VILLA, 1997) and from a Rb-Sr muscovite age of 275 + 8 Ma on a kinzigite from M. Zuccaro near Alpe Morello (PINARELLI *et al.*, 1988). This age is confirmed by the U-Pb age determinations (upper intercept on discordant zircons) on the appinites (275-285 Ma, MULCH *et al.*, 2002).

GRANITES

The Permian granites, the so-called Graniti dei Laghi, occur in the metamorphic rocks of both Scisti dei Laghi and Strona Ceneri, though mainly in the SL, where they produced narrow contact aureoles (biotite, andalusite, cordierite ± spinel ± corundum. GALLITELLI, 1943; BORIANI *et al.*, 1988_a), which overprint the non-pervasive greenschist facies Hercynian retrograde phase. The Graniti dei Laghi form a batholith elongated NE-SW, and composed of many plutons (the Valsessera – Biellese, Alzo - Roccapietra, Quarna, Mottarone – Baveno, Montorfano) that occur between the zone of Biella and the western shore of Lago Maggiore.

The geological and petrographic details of each pluton may be found in BORIANI *et al.* (1988_a), and CAIRONI (1985).

The Mottarone - Baveno pluton contains the pink granite «Granito Rosa di Baveno», which constitutes a sort of layer, dipping 15° degrees E, in the upper part of the pluton. It contains plenty of miarolithic cavities which indicate a shallow depth of emplacement.

Two Rb-Sr whole rock isochrons of about 277 Ma, as well as biotite ages of about 280 Ma, point to an intrusion age of around 280 Ma. The presence of younger biotite ages (down to 170 Ma) indicate that the isotopic systems of these minerals have been opened again more recently, particularly near the CMB line (PINARELLI *et al.*, 1988).

THE SOURCE OF THE PERMIAN MAGMA

VANNUCCI *et al.* (1989) and BORIANI *et al.* (1992) performed a thorough geochemical investigation on the origin of the magma of granites and appinites. Their Pb, Sr and Nd systematics was studied by PINARELLI *et al* (1993), BORIANI *et al.* (1995) and PINARELLI *et al.* (2002). New data on the geochemistry of the granitic differentiates of the appinites were provided by CALDIROLI (1996). Their REE pattern is completely different from that of the main granites of Baveno and Montorfano (Fig.2a). It does not show Eu anomaly like the appinites and appears depleted in HREE (Fig. 2b,c). BORIANI *et al.* (1992) envisaged an origin of appinites and granites from a mafic magma similar to that of the Ivrea body. This did not necessarily imply that the Ivrea-Verbano Zone was actually beneath Serie dei Laghi in the Early Permian. The mafic magma evolved through fractional crystallization, assimilation of lower crust, mixing with anatectic melts and tapping of the deep magma

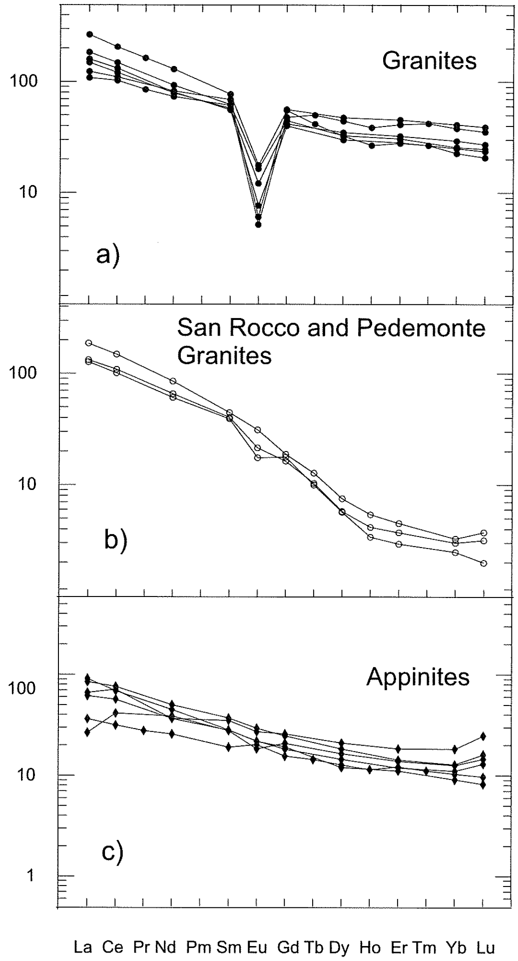

Fig. 2 – Chondrite-normalized REE patterns of granites and Appinites. The patterns of the San Rocco and Pedemonte granites (2b) are very different from those of the graniti dei Laghi (Baveno and Montorfano, 2a). Their formation was clearly dominated by the fractionation of hornblende. In general they appear very akin to Appinites (2c). Normalization after SUN and MC DONOUGH, 1995. Data of granites and Appinites from BORIANI *et al.*, 2003; data of San Rocco and Pedemonte granites from CALDIROLI, 1996.

chamber at different stages. The solid/liquid fractionation processes operated in a deep parent magma chamber, with plagioclase and the accessories playing different roles in the most mafic part of the series and the felsic part. In a more recent model of PINARELLI *et al.* (2002), based on Pb, Nd and Sr isotope distribution, the primary magma of appinites and granites had the composition of the most mafic gabbro-noritic appinite. This magma derived from an enriched mantle source, contaminated during an early Hercynian subduction. The primary magma underwent an AFC process that lead to the formation of the different kinds of appinites and of their felsic differentiates. Later on the mafic magma further evolved via AFC, producing the large granitic plutons. As a whole, the highly variable (0.704-0.710) initial Sr isotope ratios of the Permian intrusives support a genesis through variable degrees of crustal assimilation by a mantle derived melt.

This process is well portrayed in Fig. 3 (εNd_i vs. $^{87}Sr/^{86}Sr_i$) where the appinites and the granites (Pinarelli *et al.*, 2002) plot in an area which includes the representative points of the IVZ gabbro and diorite (Voshage *et al.*, 1990).

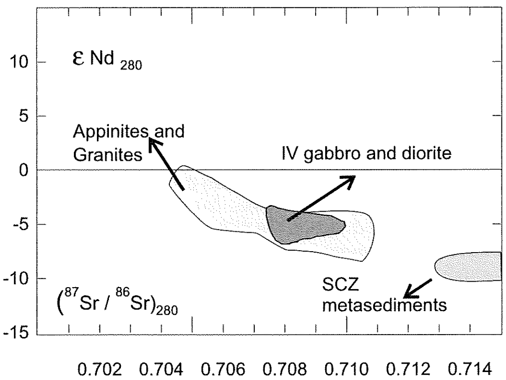

Fig. 3 – εNd_{280} vs. $(^{87}Sr/^{86}Sr)_{280}$ of Permian Granites, Appinites, SCZ metasediments (Pinarelli *et al.*, 2002) and IV gabbro and diorite (Voshage *et al.*, 1990). It is very likely that the granites did not derive from the IVZ magma but from a magma similar to the most primitive appinite. This magma evolved through an AFC process with assimilation of metasediments similar to those of SCZ.

The most primitive appinites derive from a mantle source. The primary magma may have evolved through an AFC process with assimilation of crustal material similar to the SdL metasediments.

METAMORPHIC EVOLUTION

The age of the main metamorphic imprint in the Ivrea-Verbano Zone has been the subject of continued debate: Ordovician, Carboniferous or Permian ages are proposed for the peak of metamorphic conditions (see BORIANI *et al*, 1985; ZINGG *et al.*, 1990; PIN, 1990; GEBAUER, 1993; SCHMID S., 1993; BORIANI and VILLA, 1997 for discussion). The climax of the regional metamorphism appears to be in the time span between 273-296 Ma (PIN, 1986; BÜRGI and KLÖTZLI, 1990; VAVRA *et al.*, 1996; HENK *et al.*, 1997; BORIANI and VILLA, 1997). The complex history of crustal exhumation and cooling probably began since 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). Now most of the authors agree that the IVZ rocks had already experienced the Hercynian regional metamorphism and that the high T parageneses of the upper amphibolite and granulite facies were formed because of the heat supplied by the intrusion of the mafic body in the early Permian. According to HENK *et al.* (1997) the early Permian thermal event completely res*et al*l the radiometric clocks as well as all the geo-termobarometers. Therefore it is not possible to reconstruct the earlier evolution.

The age of the main metamorphic event in the Serie dei Laghi has also been debated: Early Paleozoic (around 450 Ma) or Hercynian (320-340 Ma). Early Paleozoic ages were considered to be the age of the main metamorphism under high temperature conditions (responsible for the melting that lead to the Ordovician magmatism) by PIDGEON *et al.* (1970), KÖPPEL and GRÜNENFELDER, (1971), RAGETTLI (1993), KÖPPEL and

GRÜNENFELDER (1978-79), HUNZIKER and ZINGG (1980). The main metamorphism under amphibolite facies conditions occurred at a temperature between 540-610°C and pressure of 6-9 kbar (FRANZ *et al.*, 1996; GIOBBI ORIGONI *et al.*, 1997; ZURBRIGGEN at al., 1997; BORIANI *et al.*, 1997; HENK *et al.*, 1997). BORIANI and VILLA (1997) obtained Hercynian ages, in agreement with similar data (320-350 Ma) and interpretations reported by many authors in the entire Southern Alpine domain East of the Serie dei Laghi. An older high pressure event is recorded by the retrogressed eclogites of the SCBZ (GIOBBI ORIGONI *et al.*, 1997).

Younger ages (<300 Ma; MCDOWELL, 1970; HUNZIKER, 1974; KÖPPEL, 1974.) possibly record the greenschist facies retrogression connected with the uplift and erosion of the Hercynian belt.

Eventually IVZ and SdL shared the metamorphic evolution starting from the early Permian (HENK *et al.*, 1997).

THE LOW-P OVERPRINT AND THE ORIGIN OF THE MIGMATITES ALONG THE CMBL

In the zone of occurrence of the Appinites, the host rocks show a low pressure amphibolite facies overprint (widespread occurrence of andalusite: BORIANI *et al.*, 1977). This overprint is particularly developed between Val d'Ossola and Valsesia where it produced extensive postkinematic partial melting (described as dehydration melting by BURLINI and CAIRONI (1988). The rocks are migmatitic in a belt 1-3 km wide near CMBL. A connection between Appinite intrusion along the CMBL and a low P overprint plus partial melting was proposed by BURLINI and CAIRONI (1988) and MULCH *et al.* (2000). It seems possible that the appinitic intrusion contributed to the thermal disturbance, but probably most of the necessary heat was supplied to the «cold» SdL by the «hot» IVZ through the CMB fault plane.

STRUCTURE

In the IVZ, SCHMID (1967) described syn- to post- metamorphic synforms and antiforms in Val d'Ossola. The northernmost antiform is refolded by an alpine fold (Proman antiform, SCHMID *et al.*, 1987). BERTOLANI (1969) described the Ivrea Verbano Zone as dominated by a huge antiform with a SSE trending axis. The folds occurring in the mafic body are described by QUICK *et al.* (1992,1994), and DE MARCHI *et al.* (1998) as synmagmatic. The emplacement of the mafic body (SNOKE *et al.*, 1999) was accompanied by the development of a shear zone in the kinzigites. A piecemeal emplacement of the mafic body in an extensional environment involved the formation above the roof of the pluton, of a stretching fault. This is represented by a thick shear zone running NNE, parallel to the eastern contact of the Ivrea body, except at the northern margin of the pluton where the intrusive contact bends westward to form an antiform. This antiform is interpreted by QUICK *et al.* (1994) and by RUTTER *et al.* (1993) as synmagmatic. The shear zone may have the same age and sense-of-shear (oblique sinistral) of the Forno-Anzola shear zone described by BRODIE and RUTTER (1987) and BRODIE *et al.* (1989) in Val Strona and Val d'Ossola.

The problem is: the metamorphic isograd surfaces in the IVZ are subvertical, while presumably they were originally horizontal. Is their present attitude really due to tilting, as asserted by most of the researchers who have been studying the IVZ?

The Serie dei Laghi (BORIANI *et al.*, 1990_b), is affected by large folds with variable axial plunges, the largest of which has its hinge in Val d'Isone in Ticino (Switzerland). Its core is formed by Gneiss Minuti. It can be interpreted as a syncline whose axial plane can be traced towards SW for about 50 kilometres. The main foliation lies in the axial plane of this fold (F1). F2 folds («Schlingenbau», BÄCHLIN, 1937) appear near the contact with the Ivrea Verbano (BORGHI, 1989; BORIANI and BURLINI, 1995). They show steep axes and a weak axial plane crenulation cleavage. W of Cannobio, these folds become tighter near the IVZ, where they grade into a thick zone characterised by strong boudinage of the more competent intercalations. This zone in turn grades into a subvertical belt of mylonites belonging to the CMBL. «Schlingenbau» and mylonites seem to be connected to the late Hercynian wrench faulting movements with an important vertical component at the contact between SdL and IVZ. A problematic occurrence at Nivetta (Val Cannobina) is described by ZURBRIGGEN *et al.* (1998). In a magnificent outcrop in the riverbed, are exposed leucotonalitic veins folded with the Gneiss Minuti. Other veins cut across the folds. The early Permian.U-Pb zircon age of these veins provides an upper limit to the age of the «Schlingenbau» tectonics.

A GEOCHEMICAL MODEL AND HEAT FLOW CALCULATIONS

A petrographic, petrophysical and geochemical composition modelling of Massiccio dei Laghi was proposed by BORIANI *et al.* (2003). Since the present setting of the foliation and of the lithological boundaries is almost vertical, the authors considered the geological maps of this region as approximately a cross-sectional view of a volume of continental crust. Using a procedure based on the one described by TOUGH (1988), the volume fraction occupied by every rock type was calculated.

The Ivrea-Verbano Zone (Lower Crust) consists of 2.38% ultramafic rocks, 57,14% mafic rocks, 40,48% of leucocratic granulite, kinzigite and marble. Serie dei Laghi (Upper Crust) consists of 36,21% of micaschist and paragneiss (Scisti dei Laghi), 37,93% paragneiss with minor amphibolite (Strona Ceneri), 12.93% Orthogneiss and 12.93% acidic and intermediate Permian intrusive rocks.

BORIANI *et al.* (2003) calculated the average chemical composition of the single lithologic units, using the data, for Ivrea Verbano from: HARTMANN and WEDEPOHL (1993); MAZZUCCHELLI and SIENA (1986); MAZZUCCHELLI *et al.* (1992); LU *et al.* (1997); SINIGOI *et al.* (1994); BURLINI (personal communication, 2000); SCHNETGER (1988, 1994), and for Serie dei Laghi from: BORIANI *et al.* (1992); PEZZOTTA (1993); PEZZOTTA and PINARELLI (1994); BORIANI *et al.* (1995); GIOBBI ORIGONI *et al.* (1997); GIOBBI MANCINI *et al.* (2003).

All these data enabled the authors to calculate the rate of radiogenic heat production (m W m^{-3}) according to the model proposed by PHILPOTTS (1990). The results are presented in Fig. 4. The Serie dei Laghi presents a radiogenic heat production comparable with that of the Upper Continental Crust, whilst the heat production of the Ivrea Verbano Zone is almost four times higher than that of the Lower Continental Crust (TAYLOR and MCLENNAN, 1985).

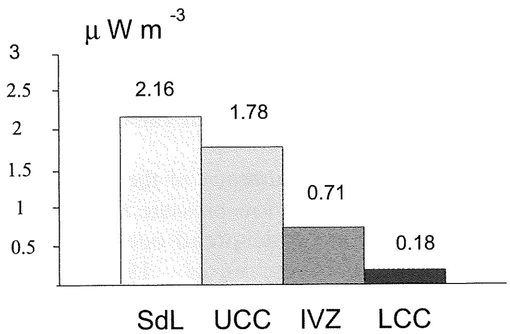

Fig. 4 – The rate of radiogenic heat production (according to the formula of PHILPOTTS (1990) of Serie dei Laghi (SdL) is compatible with that of the average Upper Continental Crust (UCC). That of the Ivrea Verbano Zone (IVZ) is almost four times higher than that of the average Lower Continental Crust (LCC) (TAYLOR and MC LENNAN, 1985).

CONCLUSIONS

In conclusion our field, chemical and isotopic data, as well as a careful examination of the vast literature, cast serious doubts that the paired Serie dei Laghi – Ivrea-Verbano

Zone may really represent Upper and Lower Continental Crust separated by a now vertical low angle normal fault, i.e. a coherent section of the pre-Alpine continental crust.

The two units display very different characters and evolution.

1. The parametamorphic rocks of SdL and IVZ have contrasting characters. The only SdL unit comparable to the IVZ is the SCBZ (presence of metabasalts and ultramafites). SILLS and TARNEY (1984) pointed out that the IVZ metabasalts have MORB chemistry. GIOBBI MANCINI *et al.* (2003) attributed the SCBZ metabasalts to a back arc environment. The presence of retrogressed eclogites («spotted amphibolites», BORIANI, 1965; GIOBBI ORIGONI *et al*, 1997) in both units supports the idea that both IVZ and SCBZ were formed in a convergent environment.

2. The IVZ does not contain the Ordovician granitoids. This means that the two units were not close to one another in the Ordovician.

3. The metamorphic evolution is different. The pre-early Permian evolution of the IVZ cannot be reconstructed because of the pervasive early Permian overprint. The evolution becomes common only after the early Permian. No important relative movements occurred after that age. The two units were exposed in their present setting by the uplift associated with the Cretaceous-Tertiary Alpine orogeny.

4. According to the available geochemical data, the SdL displays the features of an upper crust, but IVZ does not have the composition of a true lower crust. Its LILE content (Fig.5) and its estimated radiogenic heat production (Fig.4) are too high for a model lower crust.

The main arguments against tilting are the following:

1. The origin of the appinitic and granitic magma seems to be independent from the Ivrea mafic magma (PINARELLI *et al.*, 2002).

2. The appinitic dikes show evidence of having been intruded in vertical discontinuities in a transtensional environment.

3. The granite of Baveno shows evidence of having been rotated eastward of not more than 15-20 degrees after its emplacement.

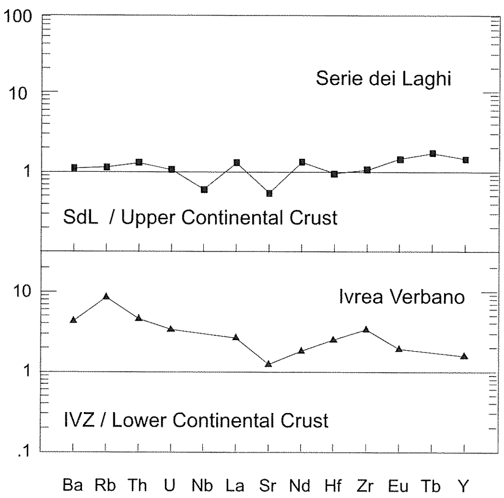

Fig. 5 – a) The incompatible elements of Serie dei Laghi (SdL) do not deviate sensibly from those of the average Upper Continental Crust (UCC), to which they are normalized. b) Those of the Ivrea-Verbano Zone (IVZ) are definitely too high compared to the average Lower Continental Crust (LCC). Data for the Continental Crust from TAYLOR and MC LENNAN (1985).

4. The Permian volcano-sedimentary deposits lie almost horizontally over the SdL (Arosio).

In our opinion all these features can only be explained with an early Permian emplacement of the IVZ near the SdL through the CMBL, an oblique sinistral wrench fault, in a transtensional environment. The fault can be viewed as a boundary of a pull-apart basin similar to many others that characterised in the Permian the Hercynian belt, which was dominated by continent scale wrench faulting (MATTE, 1991).

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