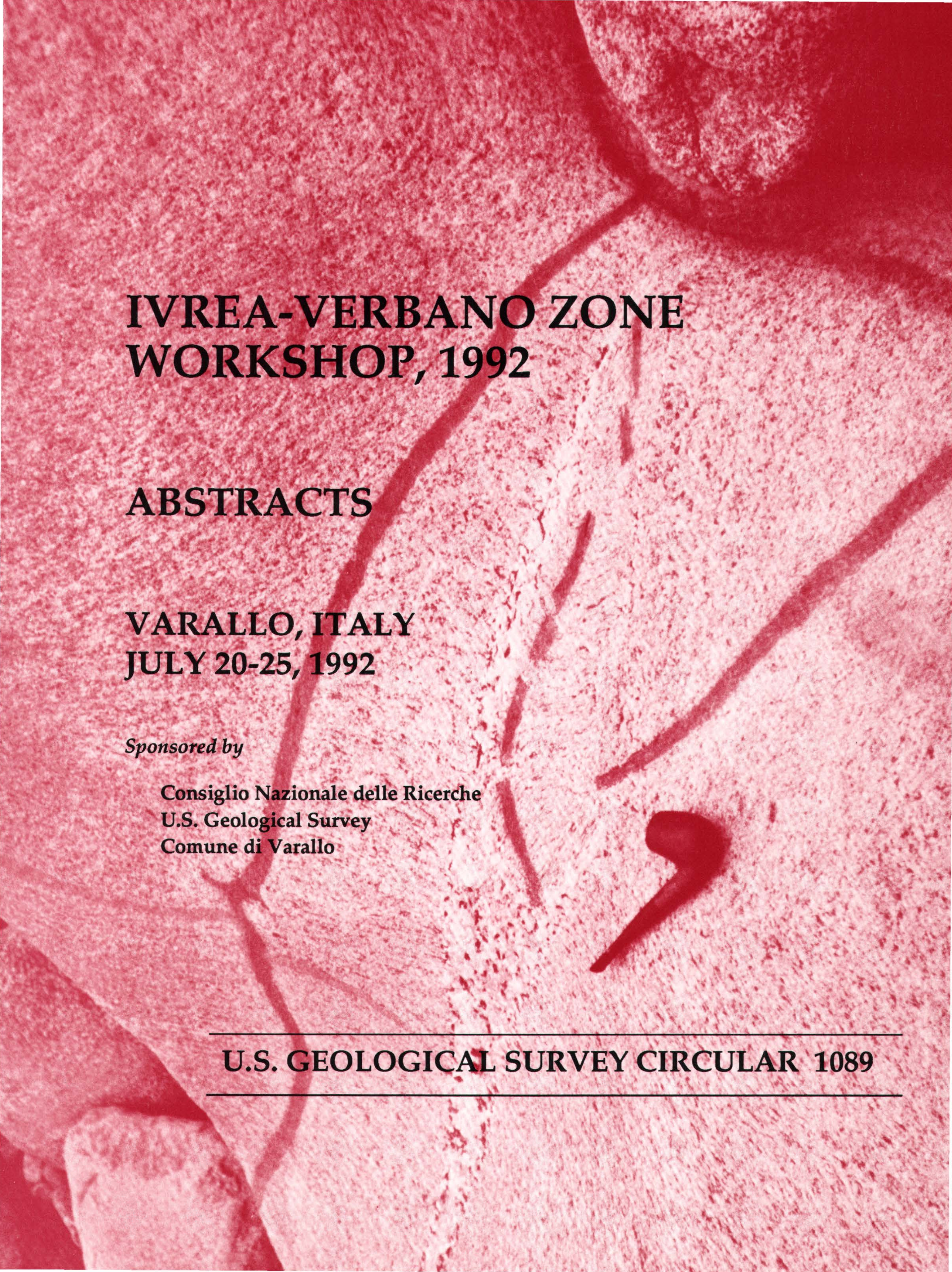

IVREA-VERBANO ZONE WORKSHOP, 1992

ABSTRACTS

VARALLO, ITALY
JULY 20-25, 1992

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Comune di Varallo

U.S. GEOLOGICAL SURVEY CIRCULAR 1089

Cover--Intrusive relationships in the Sessera Valley, Ivrea-Verbano Zone. Photograph by Silvano Sinigoi.

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James E. Quick, U. S. Geological Survey, Denver, CO
Silvano Sinigoi, Università di Trieste, Italia

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U.S. DEPARTMENT OF THE INTERIOR
MANUEL LUJAN, JR., Secretary

U.S. GEOLOGICAL SURVEY
Dallas L. Peck, Director

UNITED STATES GOVERNMENT PRINTING OFFICE: 1992

Free on application to the
Book and Open-File Report Sales
U.S. Geological Survey
Federal Center, Box 25425
Denver, CO 80225

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IVREA-VERBANO ZONE WORKSHOP, 1992

James E. Quick and Silvano Sinigoi, *Editors*

INTRODUCTION

Our understanding of the continental crust-mantle transition is based primarily on indirect observation. Geophysical data provide constraints on large structures and regional variations, and xenolith populations and magma compositions provide insight into the local chemistry and petrology of this vast region. However, there are few exposed terranes where this transition may be studied directly.

The Ivrea-Verbano Zone (IVZ), northern Italy (fig. 1), is one of the best exposed and most accessible lower crustal terranes in the world. It is characterized by pronounced Bouguer gravity and magnetic anomalies, and seismic and potential-field data suggest that it dips steeply to the southeast and merges with the lower crust beneath the Po basin (for example, Lanza, 1982; Wagner, 1984; Kissling, 1984; Nicholas and others, 1990). Rocks of the IVZ crop out in a northeast-trending, tectonically bounded sliver that is more than 100 km long and as much as 15 km wide. To the northwest, they are separated from pre-Triassic basement, ophiolitic rocks, and high-pressure metamorphic rocks of the central Alps by the Canavese segment of the Insubric Line (Gansser, 1968; Schmid and others, 1987). To the southeast, they are separated from amphibolite-facies gneiss and late Paleozoic granites of the Strona-Ceneri Zone by the Cossato-Mergozzo-Brissago and Pogallo Lines (Boriani and Sacchi, 1973; Zingg, 1983; Handy, 1987). Although the precise relationship between the Strona-Ceneri and Ivrea-Verbano Zones remains to be unequivocally demonstrated, several investigators (for example, Mehnert, 1975; Fountain, 1976) have proposed that the Ivrea-Verbano and Strona-Ceneri Zones collectively represent an exposed cross section of continental crust.

The IVZ displays a possible continental crust-mantle transition that is cited as one of the best exposed examples of magmatic underplating in the world. Three principal lithologic components are recognized: (1) mantle peridotite (Shervais, 1979; Sinigoi and others, 1980; Rivalenti and others, 1981) (2) the Mafic Complex (Rivalenti and others, 1975, 1981, 1984), which consists of predominantly gabbro and lesser amounts of dioritic and felsic rocks; and (3) amphibolite- to granulite-facies paragneiss grouped as the Kinzigite Formation (Schmid and Wood, 1976; Zingg, 1983). Some investigators have concluded that the Mafic Complex was magmatically underplated beneath continental crust (for example, Rivalenti and others, 1981, 1984; Fountain, 1989; Voshage and others, 1990). According to this view, the lower continental crust is represented by the Kinzigite Formation, and mantle peridotites near the western margin of the IVZ preserve contacts that may be deformed relics of the intrusion floor. Geobarometry and mineral assemblages suggest that underplating, followed by isobaric cooling, occurred beneath a relatively thin (<25 km) crust (Sills, 1984; Bohlen and Mezger, 1989). This event, best dated by zircon and monazite ages, is thought to have occurred between 290 and 250 Ma (Voshage and others, 1990). Final rotation of the zone into a subvertical orientation and emplacement into the upper crust resulted from Alpine transpression and lithospheric wedging (Nicolas and others, 1990; Zingg and others, 1990).

The potential of the IVZ as a natural laboratory has provoked considerable scientific interest in recent years. More than 350 publications have addressed the IVZ since 1950, and work in progress includes new field mapping and geochronologic, geochemical and petrologic, and geophysical investigations. The following abstracts present results of some of the most recent investigations on the Ivrea-Verbano and adjacent Strona-Ceneri Zones. The structure and evolution of the underplated Mafic Complex are addressed by Brodie and others, Quick and others, Meyer and others, and Sinigoi and others, and Evans and Burlini report on structure between the Pogollo and Cannobina Valleys in the northern IVZ. Boriani and others consider the relationship between and possible pre-Alpine tilting of the Ivrea-Verbano Strona-Ceneri zones in light of geologic, geochemical, and radiometric-age data. Ferrario and others and Hofmann and others discuss chemical and isotopic evidence for crustal contamination and metasomatism of IVZ peridotites and the Mafic Complex. New isotopic age data are reported by Gebauer and others, Ragettli and others, and von Quadt and others. Experimentally determined seismic velocities for Ivrea-Verbano rocks are discussed by Barruol and Kern, Burlini, and Fountain and others. Zappone reports seismic velocity calculations and structural aspects of the Balmuccia peridotite and, with colleague, describes efforts to geophysically probe the deep geometry of the Ivrea-Verbano Zone. Barker and others, Piccardo and others, Snoke and Fountain, and Thornber describe geologic and petrochemical characteristics of selected convergent and extensional terranes to provide a basis for comparison with the IVZ.

ACKNOWLEDGMENTS

We gratefully acknowledge the skill and effort of Marsha Simpkins (USGS/Denver), who provided invaluable assistance in the preparation of this volume. Reviews were supplied by Carl Thornber and John Pallister.

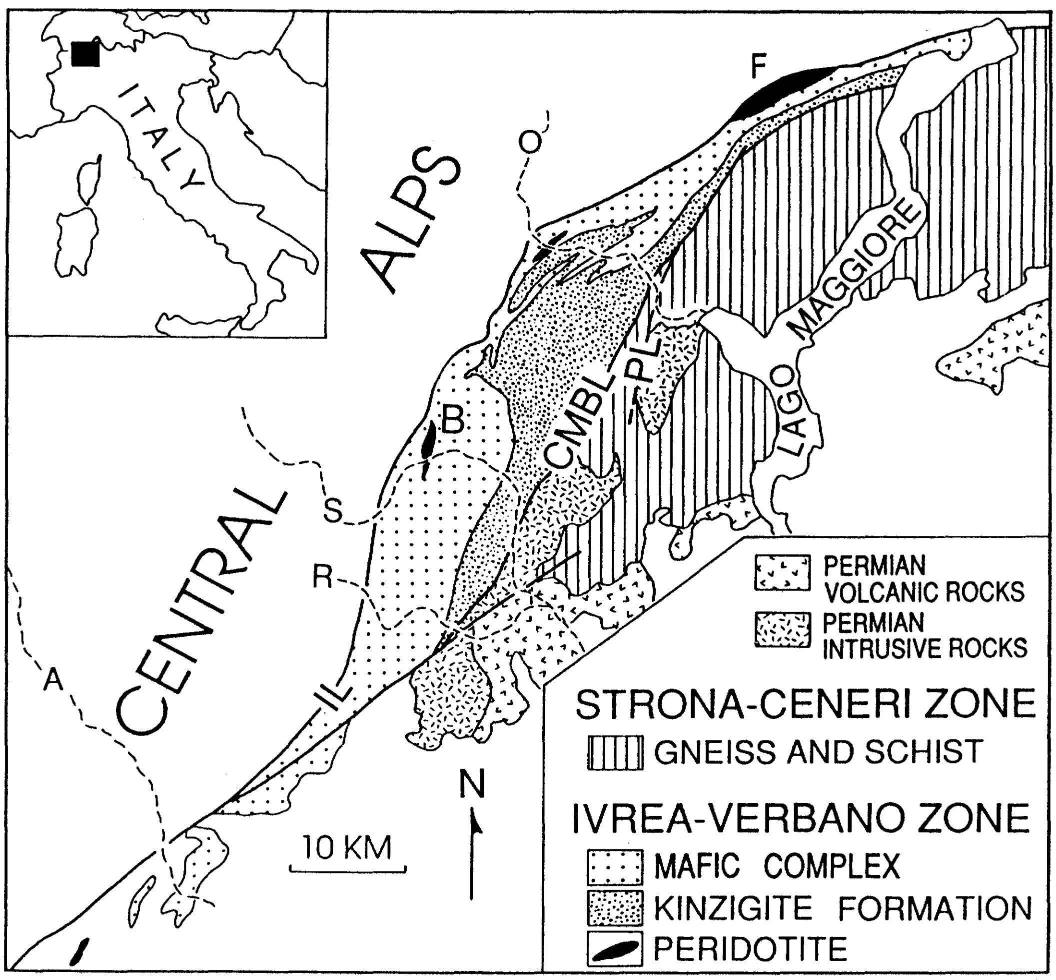


Figure 1. Geology of southern Alps in vicinity of Ivrea-Verbano Zone based on Zingg (1983). IL, Insubric Line; CMBL, Cossate-Mergozzo-Brissago Line; PL, Poggallo Line; B, Balmuccia peridotite; F, Finero peridotite; A, Aosta Valley; R, Sessera Valley; S, Sesia Valley; O, Ossola Valley.

ABSTRACTS

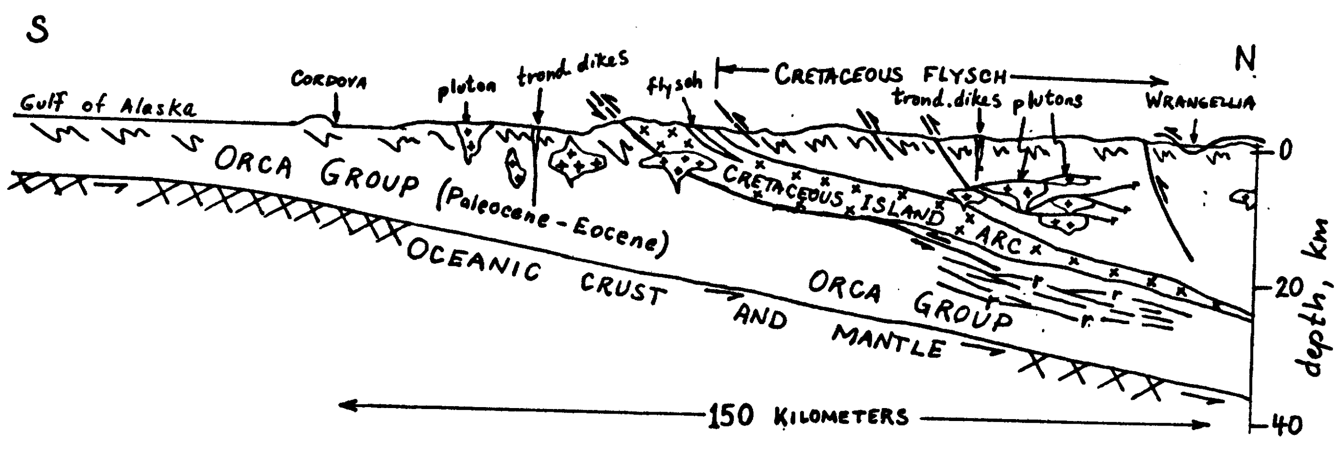
THE ACCRETIONARY PRISM AND MAGMATISM OF THE GULF OF ALASKA

Fred Barker, *U. S. Geological Survey, Denver, CO,* G.L. Farmer, *University of Colorado, Boulder, CO,* George Plafker, *U. S. Geological Survey, Menlo Park, CA,* R. A. Ayuso, *U. S. Geological Survey, Reston, VA*

Accretionary prisms are important in generation of continental crust: (1) they are emplaced from surface to Moho, so any mantle-derived magma intrudes them; and (2) they are fertile in granitic melt--especially those prisms rich in graywacke--and all their sediments are easily assimilated by gabbroic liquid. Prisms are found in the Archean (for example, Quetico Belt) and are abundant in the Proterozoic and younger eras.

The Gulf of Alaska contains a large (100-200 X 2,100 km), composite prism of Cretaceous to Eocene rocks emplaced about 65-50 Ma. This prism was formed by (1) accretion of the Wrangellia-Alexander composite terrane to southeastern Alaska and British Columbia about 110-100 Ma, with crustal overthickening; (2) growth of an Andean arc in this collage; (3) uplift of this arc of 20-30 km and outflow of turbidites onto the north-moving Kula plate(s); (4) magmatism of arc and MORB-seamount-transform types into the Kula-with-turbidite crust; and (5) offscraping against the continental margin with continued basaltic magmatism. The Cretaceous part of the prism consists of graywacke, pelite, basalt, and an island-arc fragment. The Paleocene to Eocene part--the Orca Group--consists of quartzofeldspathic graywacke, 15-20% basalt, and minor pelagic sediment.

Granitic rocks formed at 63-53 Ma in the western Gulf of Alaska, and at 53-50 Ma in the eastern Gulf. The Orca Group rocks, near Cordova, eastern Gulf, contain scattered plutons of granodiorite of 5-150 km^2 area. Rare coeval gabbro plutons and trondhjemite dikes also occur. Three granodiorite plutons studied here show SiO_2=66.3-71.3%, Na_2O=2.8-3.6%, K_2O=1.8-3.0%, ε_{Nd}=+2.1 to -3.3, $^{87}Sr/^{86}Sr$=0.7051-0.7067, $^{206}Pb/^{204}Pb$=19.04-19.20, $^{207}Pb/^{204}Pb$=15.60-15.66, and $^{208}Pb/^{204}Pb$=38.59-38.85. One pluton generally shows slightly lower K_2O, higher Al_2O_3, higher ε_{Nd}, and lower $^{87}Sr/^{86}Sr$ ratios. All three plutons, however, have similar, well-defined minor and trace-element abundances characterized by relative enrichment in light rare earth elements and depletion in high field strength elements.



Schematic present-day section through accretionary prism at Cordova. Overall control by seismic methods, but note that clear signals were received only from that part of the Orca Group where reflectors (=r) are shown. Present-day surface about 4-7 km below that at 50 Ma.

The granodiorite plutons and flysch of the Orca Group show overlapping elemental and isotopic compositions. The only clearly defined chemical differences between the flysch and the plutons are weak negative Eu anomalies in the plutons and slightly lower Ca and higher Na contents in the flysch. The Nd and Sr isotopic compositions of two plutons completely overlap those of the flysch. The third pluton, however, shows discretely higher ε_{Nd} and slightly lower $^{87}Sr/^{86}Sr$ values than those of the flysch. Pb isotopic compositions of the flysch and this pluton also overlap, but Pb of the other two plutons is slightly less radiogenic.

Our chemical data, modeling, and comparison with melting experiments (Conrad and others 1988) of graywacke indicate that the granodiorite originated by large fractions (65-90%) of melting of the Orca Group graywacke and argillite. Plagioclase, pyroxene(s), and biotite(?) were residual to melting at about 850°-950°C and at low H_2O activities. The trondhjemitic dikes have elemental and isotopic compositions (for example, ε_{Nd}=+7.9, Sr_i=0.7036) appropriate to origin from a basaltic protolith.

These granodiorite plutons were generated where the prism was 15-20 km thick and while the prism was still being deformed. They are wholly flysch derived, do not contain a gabbroic component, yet were coeval with gabbro and trondhjemite. This magmatism is best explained by (1) introduction of basaltic liquid from the Kula plate during subduction; (2) pooling of basaltic liquid in lower regions of the prism; (3) growth of melting-precipitating cells in flysch over convecting, crystallizing lenses of gabbroic magma (as in Huppert and Sparks, 1988); and (4) requiring lenses of layered gabbro 1-3 km thick and thinner layers of flysch-melt residua.

P AND S WAVE VELOCITIES AND SHEAR WAVE SPLITTING OF ROCKS FROM LOWER CRUST/UPPER MANTLE TRANSITION (IVREA ZONE): NEW EXPERIMENTAL AND CALCULATED DATA.

G. Barruol, *Laboratoiré de Tectonophysique, France*, and H. Kern, *Institut der Universetät Kiel, Germany*

To better constrain lower crustal seismic properties and particularly the relationships between anisotropy, S wave splitting, and kinematics, the seismic properties of rocks from the Ivrea lower crust and upper mantle (metagabbros, pyriclasites, amphibolites, pyroxenites) have been determined. P and S wave seismic velocities have been obtained either by direct velocity measurements (performed in laboratory on cubic samples at pressure as great as 600 MPa and temperature as great as 600°C), and(or) by calculations based on the modal composition of the rock, the lattice preferred orientations (LPOs), and single crystal stiffness coefficients. The 21 elastic constants characterizing each sample allow calculation of the complete three-dimensional seismic properties (Vp, Vs1, Vs2, Vs1-Vs2 or seismic birefringence and the polarization planes of the shear waves). The two complementary techniques have been applied to a number of samples, and quantitative comparisons have been made between measured and calculated properties.

The measured P and S wave velocities (6.0-7.5 km/s and 3.6-4.2 km/s) are typical of lower crust. The P wave anisotropy is in the range 0-10% and is mainly controlled by the number of mineral phases. Seismic birefringence is in the range 0.0-0.6 km/s, but typical values are in the range 0.0-0.2 km/s. In many cases, the birefringence is clearly related to inherent fabric elements (foliation, lineation).

Mafic rocks such as anorthosite or pyroxene-bearing gabbro exhibit low P wave anisotropies (<5%) and complex seismic properties particularly for the S waves; that is, shear wave birefringence is low (0.1 km/s) and without clear relationships between the fast shear wave polarization plane orientations and the fabric.

In contrast, the seismic properties of felsic rocks such as biotite-bearing gneiss or of mafic rocks such as amphibolite display strong birefringence (0.3 km/s) and high V_p anisotropy (10%) and exhibit clear relationships to the structure. Biotite and amphibole preferred orientations clearly dominate seismic anisotropy, particularly in shear wave splitting. There is a strong correlation between the orientation of the foliation and the amplitude of the delay time. Maximum delay time is often observed for waves propagating parallel to the foliation. The fast shear wave is furthermore polarized parallel to the foliation plane. The lineation seems to be invisible by shear wave splitting measurements.

The seismic anisotropy of the exposed lithologic sequence in the Ivrea Zone affects the P wave reflectivity in a very complex manner. Compared to the isotropic case, anisotropy enhances the reflection coefficient for 60 percent of possible lithological interfaces. For 40 percent of lithologic contacts, anisotropy has a destructive effect on the P wave reflectivity.

RELATIONSHIPS BETWEEN THE GRANITES OF SERIE DEI LAGHI AND THE IVREA MAFIC MAGMA: GEOLOGICAL, GEOCHEMICAL, AND ISOTOPIC EVIDENCE

Attilio Boriani, *Università di Milano, Italia,* Laura Pinarelli, *Istituto di Geocronologia e Geochimica Isotopica del CNR, Italia,* Luigi Burlini, *Università di Milano, Italia,* Evelina Giobbi Origoni, *Università di Milano, Italia*

A possible genetic link between the Ivrea-Verbano (IV) mafic magma and the Lower Permian granites of Serie dei Laghi (SdL) arises from the recent demonstration that the mafic IV body is also of Lower Permian age (Voshage and others, 1990). Much of new geochemical and isotopic data (Boriani and others, 1992, Pinarelli and others, in press) speak in favour of such a common origin. The Lower Permian geological setting of IV and SdL that is now possible to reconstruct enables us to describe a scenario in which the origin and evolution of magmas can reasonably be envisaged.

Two different Lower Paleozoic accretionary terranes, the IV and SdL (the latter with Ordovician acidic intrusives), were involved in the Hercynian orogeny. IV played the role of lower crust after the Hercynian thickening. At the end of the orogeny, large-scale strike-slip faulting, with remarkable vertical component, favours local thinning of the crust and intrusion of mafic magma. Induced crustal melting and granulitization were accompanied by complex interaction between mantle- and crust-derived melts.

Early (around 280 Ma) tapping of hydrous mafic-intermediate magma produced the Appinite suite, a dyke swarm that was emplaced along the tectonic contact between IV and SdL, the CMB Line, but not along the Pogallo Line. Because the Appinites were not affected by the Pogallo deformation, this tectonic line must be coeval with their emplacement.

More evolved, viscous, acidic magmas rose slowly in the crust and were emplaced at about 275 Ma in SdL at shallow depth or gave rise to a volcanic belt. Intrusion and extrusion were again guided by Lower Permian tectonic lineaments.

This possible evolution conflicts with that proposed by many authors in the last years because it implies that IV and SdL are two segments of respectively lower and upper crust merely juxtaposed by the late-Hercynian tectonics. Therefore, the section through IV and SdL is not a tilted crustal section; this in turn implies that below SdL there are rocks similar to those of the IV. This scenario is far from satisfactory in many respects. Much research is still to be done in order to understand this fascinating geological mystery.

HORNBLENDE ^{40}AR/^{39}AR AGE TRAVERSES OF VAL CANNOBINA AND VAL STRONA D'OMEGNA AMPHIBOLITES

Attilio Boriani, *Università di Milano, Italia,* and Igor M. Villa, *Istituto di Geocronologia CNR and Isotopengeologie, Switzerland*

We report a dozen $^{40}Ar/^{39}Ar$ dating experiments on hornblends from the upper amphibolite facies rocks of the northernmost tip of the Ivrea Zone and from the lower amphibolite facies metabasites of the Strona-Ceneri Boundary Zone.

The first observation of the Ar data is the ubiquitous presence of excess Ar (Ar_{XS}). All samples have saddle-shaped age spectra. K/Ar ages from total gas release are always greater than saddle minima or plateaus. Few or no indications of alpine overprint are seen, but Ar_{XS} in the early gas release might be masking small losses.

The release of Ca-derived isotopes indicates a protracted interaction with fluids and formation of rather complex microstructures.

The age pattern, despite the difficulties of unambiguously correcting for Ar_{XS}, gives Triassic ages (three samples between 196 and 226 Ma from Cursola, higher epidotization correlating with higher rejuvenation) close to the Insubric Line (IL), gradually reaching 308 Ma in Falmenta, older than the appinites' Pb/Sr ages by Pinarelli and others (1988).

Comparison with lower-temperature chronometers is unsatisfactory. Zingg (1983, fig. 1) implies that biotite cooling ages show no trend with distance from the IL. On the contrary, Bürgi and Klötzli (1990) state that their biotite ages become older away from the IL, but the presence of chlorite and a rather irregular pattern somewhat limit the usefulness of their K/Ar biotite ages, whereas their three muscovite ages are uniform from east to west.

Following Zingg's figure 1, it can be observed that the change from a marked west-east trend to no trend is constrained to have taken place between the youngest hornblende cooling ages and the uniform biotite ages, that is between uppermost Triassic and middle Jurassic. In other words, there already existed a Schrägstellung in pre-Alpine times during the Jurassic.

THE STRUCTURAL GEOMETRY OF A LOWER CRUSTAL SECTION: IVREA-VERBANO ZONE, SOUTHERN ALPS

K. H. Brodie, E. H. Rutter, and P. Evans, *University of Manchester, United Kingdom*

The Ivrea-Verbano zone is believed to represent an upended cross section through the lower continental crust as it existed at the end of the Hercynian orogeny in the Southern Alps. We have carried out structurally oriented geological mapping in the central and northern parts of the Ivrea-Verbano zone, a region some 40 km along strike.

The geology of the southern half of the zone is dominated by a large mafic-ultramafic complex (the Mafic Formation), which contacts a strongly banded metasedimentary and metabasic sequence to the north. We have paid particular attention to (1) the structural relationships between the rocks of the mafic formation and their envelope of high-grade metasedimentary and metabasic rocks, (2) the geometrical configuration throughout the Ivrea-Verbano zone of high-temperature shear zones, which accommodate post-Hercynian crustal extension, and (3) the geometry of late (Alpine?) faulting, the effects of which have been removed in order to produce a restoration of the structure as it existed during the late Hercynian extensional phase.

The intrusion of large volumes of basic magma (about 50 percent of the outcrop area) to form the rocks of the Mafic Formation appears to be coeval with the onset of extension. The main basic body has a laccolithic form, originally about 10 km thick. Overfolding developed at the northern margin of the laccolith and is interpreted in terms of the gravitational collapse of the hot, immediately subsolidus body, incorporating its envelope of hot metasediments into a large, originally recumbent fold. A geometrical association with a high-temperature low-angle fault zone suggests that faulting was localized by the several kilometers of uplift associated with the laccolithic intrusion. The Ivrea-Verbano zone may therefore demonstrate at least one particular geometry of lower crustal magmatic underplating, which may aid interpretation of present-day deep seismic profiles. It also demonstrates the geometry of a network of conjugate, high-temperature, low-angle shear zones in a well layered lower crustal section.

ELASTIC PROPERTIES OF THE IVREA-VERBANO ZONE AND SERIE DEI LAGHI METAPELITES

Luigi Burlini, *Università di Milano, Italia*

Metapelite is the dominant rock type of the whole Massiccio dei Laghi (that is Ivrea-Verbano Zone and Serie dei Laghi). The metamorphic condition of the Serie dei Laghi (SdL) metapelites falls in the staurolite-kyanite subzone, whereas that of the Ivrea-Verbano Zone (IVZ) ranges from the staurolite-sillimanite subzone up to the granulite facies with inferred partial melting. The fabric of metapelites from the two adjacent zones is significantly different. These differences cause variations in the seismic properties: the SdL metapelites are typically transversely isotropic for the compressional wave propagation whereas the IVZ metapelites show an orthorhombic anistropy. The slowest compressional wave velocity, measured in laboratory up to 600 MPa confining pressure and room temperature, is normal to the foliation, whereas the fastest is parallel to the lineation (when present). The average V_p of IVZ metapelites is about 6.75 km/s, with a maximum of 8.35 km/s; the average V_p of SdL metapelites is 6.48 km/s, with a maximum of 7.58 km/s. The slowest shear wave velocity is again normal to the foliation, whereas the fastest propagation occurs in two directions, i.e, at 45° to the lineation within the foliation plane (VS1) and in a plane normal to the lineation and at 45° between the foliation plane and the normal to the foliation (VS2). Because foliation and lineation are almost constant along the IVZ, a strong seismic anisotropy is to be expected in the intermediate to lower crust, with a maximum V_p parallel to the dominant foliation and minimum normal to it. The total anisotropy (as much as 28 percent) means that if the foliation within the continental crust is mainly horizontal, the compressional waves travelling vertically in a thick layer of metapelites will be as much as 28 percent slower than those travelling horizontally. In such a case near-vertical-reflection and wide-angle-reflection correlation will be difficult.

Within the foliation plane the anisotropy is as much as 15 percent, which indicates that a compressional wave travelling horizontally and parallel to the lineation (the stretching direction) will be much faster than the wave travelling horizontally in the direction normal to the lineation.

The comparison between samples collected at different distances from a post-metamorphic gabbrodioritic stock shows that the total anisotropy decreases from 20 percent to 2 percent approaching the stock. This decrease may indicate that if a great amount of mafic magma is intruded in the lower crust, as in the IVZ, under static conditions, the total anisotropy of host rocks will be drastically reduced by annealing and static recrystallization.

DEFORMATION WITHIN THE IVREA-VERBANO ZONE BETWEEN VALLE POGALLO AND VALLE CANNOBINA (N. ITALY)

Paul Evans, *University of Manchester, United Kingdom* and Luigi Burlini, *Università di Milano, Italia*

The Ivrea-Verbano Zone (IVZ) of northern Italy is a slice of lower crustal granulite- to amphibolite-facies metapelites, and metabasic and ultrabasic rocks that have been rotated into a vertical orientation. It has a northeast-southwest orientation, and it is bounded to the northwest by the Insubric Line and to the southeast by the Pogallo Line (POG) and the Cossato-Mergozzo-Bissago (CMB) Line. At the northwest end of the IVZ, between Valle Pogallo and Valle Cannobina, the zone is relatively thin, having a maximum thickness ranging from 3 to 4.5 km. A traverse from southeast to northwest passes from predominantly metapelite schists (kinzigites) with marble lense, into predominantly hornblende-plagioclase-garnet metabasic rocks, containing peridotite bodies (for example, the Finero peridotite).

Mapping of this part of the IVZ has shown the presence of high-temperature mylonites (at least amphibolite facies) in the hornblende-plagioclase metabasic rocks, as much as 40-100m thick southeast of the contact with the Finero peridotite. The mylonites show an intense grain-size reduction. The mylonitic foliation is at a low angle to the metamorphic banding, and the lineation plunges 20°-40° northeast. These zones have a dextral movement sense and extend the metamorphic banding. Outside of the mylonites less intense recrystallization results in the formation of a lineation which also plunges towards the NE.

Within the metapelites the shear zones are more diffuse, with some grain size reduction. At La Piota a shear zone is some hundreds of metres thick and contains shear bands with both dextral and sinistral kinematics, although are dextral. The mylonites at La Piota trend 040° and dip 70°-85° northwest. To the northeast of La Piota the mylonites appear to form several separate movement horizons. The most southern of these is the CMB, which juxtaposes the Serie dei Laghi metapelites, eclogitic amphibolites, and orthogneisses within the kinzigites. The deformation is generally diffuse, with limited grain-size reduction and dextral shear bands. However, this horizon contains a mylonite a few metres thick, with intense grain-size reduction and dextral kinematics. The other shear zones within the kinzigites north of the CMB are of amphibolite to greenschist facies. These are also diffuse zones within which are thin mylonites, and they contain both dextral and sinistral mylonites. East of Torrente Cannobino both the metamorphic banding and the mylonitic foliation trend 070° and dip steeply northwest. The shear-band lineation plunges northest about 40°. Between the most southerly and the most northerly of the metapelite mylonites are many granodioritic dykes, from a few tens of centimetres to 150 m thick. Most of these are intruded parallel to the mylonitic foliation but are not deformed by the mylonitization. The thickness and frequency of the dykes diminishes towards the southeast, disappearing completely between Gurro and La Piota, where the CMB and POG meet.

Tight to isoclinal folds are common within the kinzigites with wavelengths of a few centimetres to 10 metres. Open to isoclinal folds also occur within the metabasic rocks, although they are not so common. These folds can be broadly divided into three groups. The oldest folds have axial planar fabric, defined by the metamorphic banding. The second are the most common and folds the metamorphic banding. Thirdly, there are late folds that fold greenschist-facies fabrics. The first two groups plunge at 20°-35° northwest. The overall "Z" asymmetry of these folds when viewed toward the northwest suggests a major antiform toward the southeast.

Associated with the Insurbric Line is a large greenschist-facies thrust that dips at a shallow angle toward the northwest. A stretching lineation and chlorite-rich shear bands suggest a dextral extensional movement sense. This extensional movement results in the reappearance of kinzigites next to the Insubric Line. Within the thrust slice is a greenschist-facies synform, although it may be tightening an earlier fold. This fold has a low angle of plunge toward the northwest. The Insubric Line mylonites in contact with the IVZ show this same dextral extensional movement.

MINERAL, TRACE, AND RARE EARTH ELEMENT SIGNATURE: RECORD OF A METASOMATIC EVENT IN THE FINERO ULTRAMAFIC COMPLEX

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The mafic-ultramafic complex of Finero is in the northeastern part of the Ivrea-Verbano Zone, which is made up of a volcano-sedimentary sequence metamorphosed under amphibolite- to granulite-facies conditions. The complex shows ellipsoidal shape with a northeast-southwest trending long axis. A phlogopite-rich peridotite (PP) core is rimmed by three outer units: layered internal zone, amphibole peridotite (AP), and external gabbro. Other peridotite complexes (for example, Balmuccia, Baldissero) are found in the Ivrea-Verbano Zone close to the Insubric lineament and are considered, as is the Finero complex, to be fragments of subcontinental mantle uplifted into high crustal levels.

If compared with the Balmuccia and Baldissero bodies, the peculiar feature of the Finero complex is the widespread occurrence of hydrate phases (for example, phlogopite and pargasitic amphibole) and the unusual presence of zircon, apatite, chromite, base-metal sulfides (BMS), and platinum group minerals (PGM) in the AP and PP.

Textural relationships, mineral chemistry, and trace-REE patterns show that these minerals were formed in two main structural settings: marginal zones in the PP and shear zones in the AP. The former is characterized by the presence of chromite, Cr-diopside, olivine, zircon, and minor phases such as BMS and PGM that are concentrated in patches, layers, and seams. The shear zones are similar to those found by Brodie and others (1989) in the metapelitic sequence (kinzigitic serie) that represents the host rocks of the Finero complex. The shear zones are characterized by a low-temperature stage developed in a brittle regime superimposed over a high temperature stage linked to a ductile regime. Cr-spinel, ilmenite, pentlandite, zircon, apatite, phlogopite, pargasite, and BMS were formed during the high-temperature event. The low-temperature event is characterized by serpentine, chlorite, talc, awaruite, native Cu, valleriite, heazlewoodite, djerfisherite, pyrite, marcasite, bravoite, violarite, mackinawite, and Cu sulfides formed in a hydrothermal regime.

Minerals such as zircon, apatite, phlogopite, and pargasite constrain the REE pattern. The rock-chondrite spidergrams show enriched REE profiles unusual for normal subcontinental peridotites. The peridotites of Finero display pronounced LREE (La_N/Yb_N ~ 5.00), TiO_2, K_2O, and Zr enrichment consistent with alkali-rich fluid metasomatism. The alkaline fluid addition interacted by local diffusion along the marginal zone of the PP and by penetrative circulation along the extensional shears in the AP.

The metasomatic event took place in a time span ranging from 200 to 230 Ma (v. Quadt and others, this volume) when the ascending mantle slab experienced partial melting. This event can be related to an extensional dynamic phase and relative crustal thinning. During this event, local and irregular input of high-temperature K-alkaline fluids formed minerals such as zircon, apatite, phlogopite, pargasite, and concentrated PGE-bearing chromite. The low-temperature assemblage has to be related to hydrothermal phenomena during alpine compressional tectonics.

COMPRESSIONAL WAVE VELOCITIES OF LOWER CRUSTAL MYLONITES FROM THE IVREA-VERBANO ZONE, NORTHERN ITALY

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One popular theory, among many, to explain the pronounced seismic reflectivity of the continental lower crust is that reflections may be caused by a contrast of seismic properties between deep crustal mylonites and their undeformed adjacent protolith. To explore this hypothesis we measured compressional wave velocities (V_p) at high confining pressures of high-grade mylonites and bounding protoliths collected from high-temperature shear zones exposed in Valle d'Ossola in the Ivrea-Verbano Zone. Oriented samples were collected from mylonites developed in metapelites (stronalites), an upper amphibolite-facies metabasic rock (Anzola metagabbro), and mafic garnet granulites (pyriclasites). Measurements were made on three orthogonal cores for each sample, and the cores were cut parallel to the major fabric elements (for example, lineation, foliation). The maximum confining pressure for each run was 600 MPa.

The upper amphibolite-facies metabasic protolith collected at the quarry at Anzola is an equigranular rock with a granoblastic texture and is composed of calcic amphibole, plagioclase, minor oxides, and minor clinopyroxene (Brodie and others, 1989). The mylonitized equivalent is a fine-grained mylonite with porphyroblasts of amphibole. Brodie and others (1989) recognized that the formation of orthopyroxene by the breakdown of amphibole and plagioclase in this zone indicated that deformation occurred during prograde metamorphism into the granulite facies. The mean V_p of the protolith is high (7.5 km/s) and the sample is modestly anisotropic. In contrast, mean velocity of the mylonite is lower (7 km/s) and its anisotropy is reduced.

A similar pattern was observed for the mafic garnet granulites (pyriclasites). Samples of these rocks were collected along Rio del Ponte above Premosello where a nearly complete 20-m-thick fabric transition from relatively undeformed to ultramylonitic pyriclasite is exposed (Brodie and others, 1991). A garnet-clinopyroxene-orthopyroxene-plagioclase granofels is progressively deformed from rocks that exhibit weak protomylonitic textures to mylonites and ultramylonites that contain recrystallized orthopyroxene and plagioclase in the shear zone; plagioclase and orthopyroxene increase at the expense of garnet and clinopyroxene. Protomylonitic rocks are characterized by high average V_p (7.5 km/s), low anisotropy, and densities of about 3100 kg/m^3. Average V_p decreases to about 7 km/s, density decreases to about 2900 kg/m3, and anisotropy is very low in the ultramylonite sample. These results could, in part, be explained by randomization of the fabric due to high strain, but the occurrence of small pseudotachylite veinlets and somewhat higher quartz content, as betrayed by the lower density, suggest that compositional changes in the shear zone may be responsible for the dramatic change in properties.

Granulite-facies metapelites (stronalites) from the Ivrea Zone are typified by high velocities and high seismic anisotropy (Fountain, 1976; Burke and Fountain, 1990). In marked contrast, mylonitic stronalites are characterized by relatively low average velocities (6.8 to 6.9 km/s) and low anisotropy. These samples also contain minor amounts of pseudotachylite.

These results suggest that deep crustal shear zones may have lower compressional wave velocities than surrounding undeformed rocks. The reduced velocities are not a consequence of anisotropic effects as commonly thought because anisotropy is diminished in the mylonites. Instead, there are compositional changes that cause velocity and density decreases in the zones. In the case of the stronalites and pyriclasites, these compositional changes may be partly caused by the introduction of pseudotachylite into the mylonites. The pseudotachylite could be due to later reactivation of these shear zones under upper crustal conditions. But, if pseudotachylite can form under deep crustal conditions (Hobbs and others, 1986), the physical property changes associated with these shear zones may also occur in lower crust that shared the same type of strain history as the Ivrea Zone.

EVOLUTION OF GABBRODIORITIC ROCKS OF THE BALMUCCIA PERIDOTITE AND OF THE LOWER LAYERED GROUP IN THE IVREA ZONE

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U-Pb dating (SHRIMP) of magmatic zircons from a meta-gabbrodiorite dike within the Balmuccia peridotite yields an Oligocene age (31.1 +/- 1.5 Ma). Similarly, a meta-gabbrodiorite within the Lower Layered Group (LLG), adjacent to the Balmuccia peridotite, yields an age of 26.0 +/- 0.8 Ma. Based on petrological data and microstructural observations, both rocks must have been emplaced into, and equilibrated within, deep crustal levels, at ambient conditions of > 700°C and > 700 MPa. Sm-Nd whole-rock data of these two rocks plot on the 600 Ma isochron of Pin and Sills (1986) established for similar rocks of the LLG. This isochron must thus be reinterpreted as an inherited mantle mixing line possibly resulting from Panafrican mantle melting. The initial ε_{Nd} values of +7.7 and +11.1, as well as the geochemical data, suggest a heterogeneous depleted mantle source for the two gabbroic rocks, possibly created by east-southeast subduction of Mesozoic oceanic crust (Valais trough?). Such a model is in line with south-directed Oligocene subduction of similar oceanic crust of the Valais trough inferred for the Lepontine Alps (Gebauer and others, 1992).

The remanent magnetization direction (after thermal and alternating magnetic field demagnetization) of the meta-gabbrodiorite within the LLG plunges northeast (236/-38). This is more than 40° apart from the direction of the magnetic field of "stable Europe" during the Oligocene or from all known remanent magnetization directions of Ivrea rocks (Heller and Schmid, 1974; Schmid and others, 1989). The reason for this deviation is not yet known.

A Panafrican magmatic event at 670+/-36 Ma, probably related to mantle melting as well as a Permian high-temperature event (265+4/-5 Ma), interpreted to be the result of underplating during successive Permo-Triassic rifting episodes, was detected in zircons of a meta-pyroxenite layer from the LLG.

CONTRASTING STYLES OF CRUSTAL CONTAMINATION IN IVREA MAGMA CHAMBERS AND PERIDOTITES

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The peridotites and mafic complexes of the Ivrea Zone provide nearly ideal geological settings for "in situ" (or at least in-outcrop) studies of crust-mantle interaction. Our previous isotope and chemical work (Voshage and others, 1990) has shown that the lower crustal magma chamber of the Sesia Valley has been extensively contaminated by in situ assimilation of crustal material. The earliest magma injections have $\varepsilon_{Nd}(270)$ values very similar to those of the underlying peridotite. They could, therefore, have been directly derived from the peridotite. This similarity is hidden in subsequent magma injections because they were progressively contaminated by an irregular AFC-like process, until a thermal balance between magmatic heat input and anatexis of crustal material was reached. This balance means that each successive injection of magma into the chamber caused an approximately proportional amount of crust to be melted and mixed into the chamber. Consequently, the hybrid magma maintained an approximately uniform isotopic composition of Nd and Sr. At the same time, the chemistry of the magma changed to become progressively enriched in incompatible elements and silica, roughly as predicted by the magma chamber model of O'Hara and Mathews (1981).

New data for the underlying Balmuccia peridotite and the Baldissero peridotite show that both bodies are isotopically much more uniform than, for example, the Ronda Peridotite. Most of the more extreme heterogeneities found in the Ivrea peridotites are derived from pyroxenite dikes. Incompatible trace elements in these bodies show progressive depletion of LREE and extreme depletion in Th, U, and Nb. There is relatively little evidence for metasomatic or crust-derived enrichment of trace elements in these bodies.

The situation in Finero is the reverse of that of Balmuccia. All the gabbros have rather uniform, positive ε_{Nd} values with no sign of crustal contamination. A series of six cumulate amphibole peridotites within the mafic body yields an apparent isochron of 449 +/-52 Ma, the significance of which is uncertain. We are currently attempting to extract zircons from the gabbros for an independent age determination. Three internal Sm-Nd isochrons (gar-amph, gar-cpx-plag) yield ages of 215 to 227 Ma, which probably represent the age of cooling through a ~600°C isotherm. In contrast, the mantle peridotite at Finero is strongly contaminated by metasomatism probably derived from (subducted?) continental crust. $^{147}Sm/^{144}Nd$ ratios range from 0.10 to 0.14, much like typical continental crust, and $\varepsilon_{Nd}(270)$ values range from -3 to -4, only slightly higher than typical Hercynian continental crust. Nearly ubiquitous phlogopite and amphibole provide additional evidence for extensive metasomatism of the otherwise highly refractory dunitic to harzburgitic peridotite. The isotope contrast between mantle peridotite and mafic intrusion precludes any direct genetic connection between the two units, and their contact must be tectonic.

A comparison between the Baldissero, Balmuccia, and Finero peridotites shows a general, inverse relationship between the major-element and mineralogical fertility and the degree of metasomatic contamination, with Baldissero having nearly pyrolitic, that is primitive major-element composition, combined with severe depletion of incompatible trace elements, and Finero being the most refractory peridotite, combined with the most pronounced metasomatic enrichment of incompatible elements.

GEOLOGY AND GEOCHEMISTRY OF THE IVREA MAFIC COMPLEX ON THE SOUTH OF SESIA VALLEY: PRELIMINARY DATA ON THE VALMALA SECTION

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A small peridotite lens crops out in Comba di Valmala, south of the Sesia Valley, and is roughly along the strike with the Balmuccia peridotite body. The Valmala peridotite is composed of protogranular to tabular lherzolite and harzburgite and is characterized by the presence of Cr-diopside and Al-augite dikes. Bulk-rock major-element composition and preliminary Sr isotopic ratios are indistinguishable from those of the Balmuccia peridotite. On the basis of these considerations, the Valmala peridotite is interpreted to be a mantle tectonite similar to, although smaller than, the Balmuccia body.

On the east of the Valmala peridotite, the stratigraphic sequence of the Mafic Complex is similar to that of the Sesia Valley, although the thicknesses of the various units are different. As in the Basal Zone in the Sesia Valley and near the Premosello peridotite in Val d'Ossola, a pegmatoidal clinopyroxenite occurs close to the mantle peridotite. At higher levels in the section, cumulus pyroxenites with minor peridotites, possibly corresponding to the Intermediate Zone in Sesia Valley, are interlayered with gabbros and metasedimentary septa. Charnockites and quartz-bearing leuconorites are closely associated with the metasedimentary septa. In this sequence, Sr isotope initial ratios are highly variable as in the corresponding stratigraphic units in Sesia Valley (Voshage and others, 1990). Sr isotopic compositions are positively correlated with SiO_2 (fig. 1), indicating large ranges in the ratios of mantle and crustal components of the hybrid igneous rocks. In general, an increase in the value of $(^{87}Sr/^{86}Sr)_{270}$ in gabbroic rocks is observed approaching charnokites and(or) metasedimentary septa. This observation suggests that the contamination of the mafic magma occurred in situ. Gabbros east of the Sella Boera fault are geochemically and petrographically akin to those in the Upper Zone of the Sesia Valley. It is still uncertain if this sudden variation is related to the offset of the fault or to the last appearance of metasedimentary septa.

West of the Valmala peridotite, the sequence consists mainly of garnet- and(or) amphibole-bearing gabbros, and metasedimentary-charnockitic septum borders the western side of the mantle peridotite. Gabbroic rocks show a decrease in $(^{87}Sr/^{86}Sr)_{270}$ values away from the septa. All gabbros on the western side, with only one exception, are characterized by high $(^{87}Sr/^{86}Sr)_{270}$ values, suggesting that crustal contamination affected also this part of the Mafic Complex. Nevertheless, their trace-element contents are distinct from those of the gabbros on the east of the peridotite. This fact suggests that they may not be tectonically repeated but may represent a deeper part of the intrusion. If so, the Valmala and Balmuccia peridotites do not represent the base of the mafic intrusion but, more likely, are fragments of mantle material mingled with deep crustal rocks prior to the intrusive event. Fieldwork is in progress with the aim of resolving this problem.

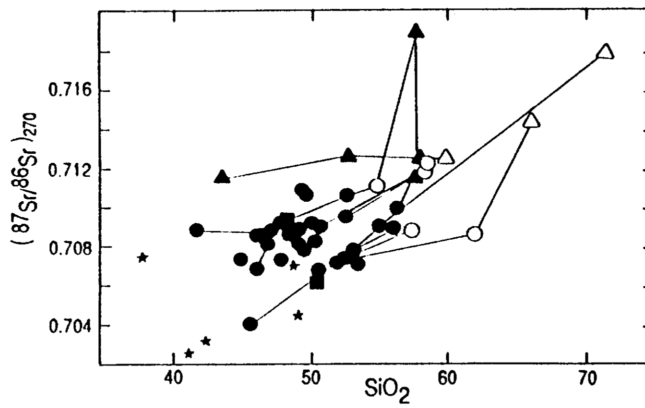

Figure 1. Plot of SiO_2 versus Sr isotopic composition at 270 Ma. Stars=Ultramafic rocks. Filled circles=gabbros. Open circles=quartz-bearing nonites. Open triangles=charnockites. Filled triangles=restitic metasediments and granatites. Solid lines connect samples that were collected at short distance from each other across metasediment-charnokite-gabbro transitions.

EVOLUTION OF MANTLE PERIDOTITES DURING PASSIVE CONTINENTAL RIFTING: EXAMPLES FROM ANCIENT AND PRESENT SITUATIONS

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Riccardo Vannucci, *Università di Pavia, Italy*

This work aims to revise petrological and geochemical knowledge of the tectonic, metamorphic, and magmatic processes that characterize the evolution of the lithosphere-asthenosphere system during passive rifting and the inception of an oceanic basin.

The pre-oceanic rifts and the early stages of opening, connected to passive extension of the lithosphere, expose at the sea floor large masses of upper mantle rocks.

Most of these mantle peridotites show relatively fertile compositions, incompatible with refractory residua after mid-oceanic-type partial melting. They preserve chemical, isotopic, and geochronologic signatures related to the accretion to the lithosphere of deeper asthenospheric material.

Age constraints, in particular, show that the evolution of the accreted material was older than, or coeval with, the main tectono-metamorphic and magmatic events recorded by the associated continental crust. Peridotite bodies from the Alpine-Apennine system show Proterozoic to Variscan ages, whereas mantle ultramafics from the Northern Red Sea (that is, Zabargad peridotites and Arabian mantle xenoliths) have Proterozoic to late-Precambrian ages. The latter are consistent with the Pan-African events recorded in the Arabian-Nubian Shield.

After emplacement within the lithosphere and complete equilibration under spinel-facies conditions at intermediate geothermal gradients (that is, pressure in the range 10-22Kb and temperature not exceeding 1000-1100^{0}C), the new lithospheric mantle underwent various metasomatic processes. Both Alpine-Apennine and Red Sea bodies show a widespread modal metasomatism, characterized by the growth of kaersutite-Ti-rich pargasite amphiboles in equilibrium with the spinal-bearing assemblage. Trace-element compositions of coexisting clinopyroxenes and Ti-rich amphiboles indicate that Ti-pargasite crystallized during the upward migration of low-density H_2O-rich fluids equilibrated with deeper (garnet-bearing) mantle levels. These data are consistent with experimental results on aqueous fluid compositions in equilibrium with upper mantle rocks at different pressures. This process, well recorded by other sub-continental lithospheric mantle rocks (that is, Eastern Pyrenean massifs), could be related to degassing of deeper levels during the initial stages of extension.

Lherzolitic rocks of sub-continental lithospheric origin underwent large structural-textural and paragenetic changes from the beginning of extension (passive rifting), which probably started during the Triassic in the Ligure-Piemontese system and during the Oligocene in the Northern Red Sea system. These changes denote a progressive exhumation from the lower lithosphere along nonadiabatic decompressional trajectories, at almost subsolidus conditions. The exhumation led to emplacement at shallow levels.

The above trajectories are significantly different from those assumed for upwelling asthenospheric mantle beneath active rifts, as, for instance, mid-oceanic ridges. They could, however, be compatible with uplift along lithospheric shear zones during whole lithosphere extension.

The pressure-temperature trajectories of the sub-continental lithospheric lherzolites from Zabargad (Northern Red Sea) and the External Ligurides (EL) (Northern Apennines) are consistent with a subsolidus evolution as footwalls of lithospheric shear zones, where progressive thermal relaxation can be caused by the juxtaposition with a progressively cooler hanging wall.

The late evolutionary stages of the pre-oceanic rift mechanisms were characterized by basaltic dyke intrusions, probably related to the inception of partial melting by decompression on the underlying asthenosphere, which began to rise following the passive extension of the overlying lithosphere.

In the Jurassic Ligure-Piemontese Basin, asthenosphere-derived mantle rocks were first depleted by partial melting during the inception of rifting and then emplaced at the sea-floor. Their geochemical character is typical of melting residua from MORB sources and ages consistent with the rifting stages.

The primary melts of the MORB-type basalts of the Internal (that is, more oceanic) Liguride Units (IL) of the Jurassic Basin appear to have been generated by fractional melting processes in an asthenospheric MORB source, closely similar to the parental asthenospheric mantle of the IL oceanic depleted peridotites. The early basaltic melts (for example, the parental liquids for some of the EL basalts) appear to derive from lower partial melting degrees with respect to the parent melts for the IL basalts.

The data presented and discussed in this paper can be useful to identify the petrogenetic processes typical of pre-oceanic rifting and passive lithospheric extension, as contrasted with those dominated by active asthenospheric upwelling (active rifts).

DYNAMIC EVOLUTION OF THE IVREA-VERBANO ZONE MAFIC COMPLEX: PART I: GEOLOGIC CONSTRAINTS

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The Ivrea-Verbano Zone (IVZ) of northern Italy is one of the few exposed lower-crustal sections in which the effects of magmatic underplating may be studied directly. The steeply dipping section of the IVZ is composed of mantle peridotite; an igneous complex as much as 10 km thick, referred to as the Mafic Complex, and amphibolite- to granulite-facies paragneiss grouped as the Kinzigite Formation. Most investigators now agree that the Mafic Complex was magmatically underplated beneath continental crust represented by the Kinzigite Formation. We present new data, which indicate that the Mafic Complex is concentrically foliated and layered and that it contains evidence of widespread deformation under hypersolidus conditions.

New measurements of foliation and layering orientations reveal an "onion-like" gross structure in the

Mafic Complex (fig. 1). South of the Sesia River, foliation, layering, and metasedimentary septa define a northwardly concave, arcuate structural grain. In terms of the inferred primary orientation of the complex, attitudes steepen gradually up section and locally overturn near the overlying Kinzigite Formation. North of the Sesia River, an opposing, southwardly concave structural grain is defined by foliation, layering, and the contact between the Mafic Complex and the Kinzigite Formation. South of the Sesia Valley, the Mafic Complex has been profoundly affected by high-temperature deformation. Rocks are foliated and lineated, and isoclinal folds and boudinage are evident. Many dikes and layers are disrupted by small-scale normal faults. *Most of this high-temperature deformation appears to have occurred under hypersolidus conditions.* Locally, undeformed, poikilitic hornblende has grown across the foliation, suggesting that several percent of interstitial melt was present during and after penetrative deformation. Many of the small-scale normal faults are healed by undeformed veins crystallized from late-stage melts, and late-stage melt has crystallized as patches of undeformed leucogabbro that crosscut foliation and fill pressure shadows at the ends of boudins. This deformation is not uniform throughout the Mafic Complex. Primary igneous textures are more commonly preserved near the roof of the complex, and foliation is weak to absent in a zone a few kilometres in diameter centered about the Sesia Valley and corresponding to the relatively undeformed diorite and Main Gabbro of Rivalenti and others (1981).

Features similar to the IVZ "onion" and the synmagmatic deformation in the mafic complex are also characteristic of ophiolitic gabbros (Nicolas, 1989). In the latter case, these are symptomatic of high-temperature ductile deformation in an extensional environment. On the basis of an analogy with ophiolitic gabbros, we interpret the IVZ "onion" to be a primary igneous feature, and suggest that the "onion" and the synmagmatic deformation in the IVZ could be interpreted as additional evidence that underplating occurred beneath rifting, albeit continental, crust.

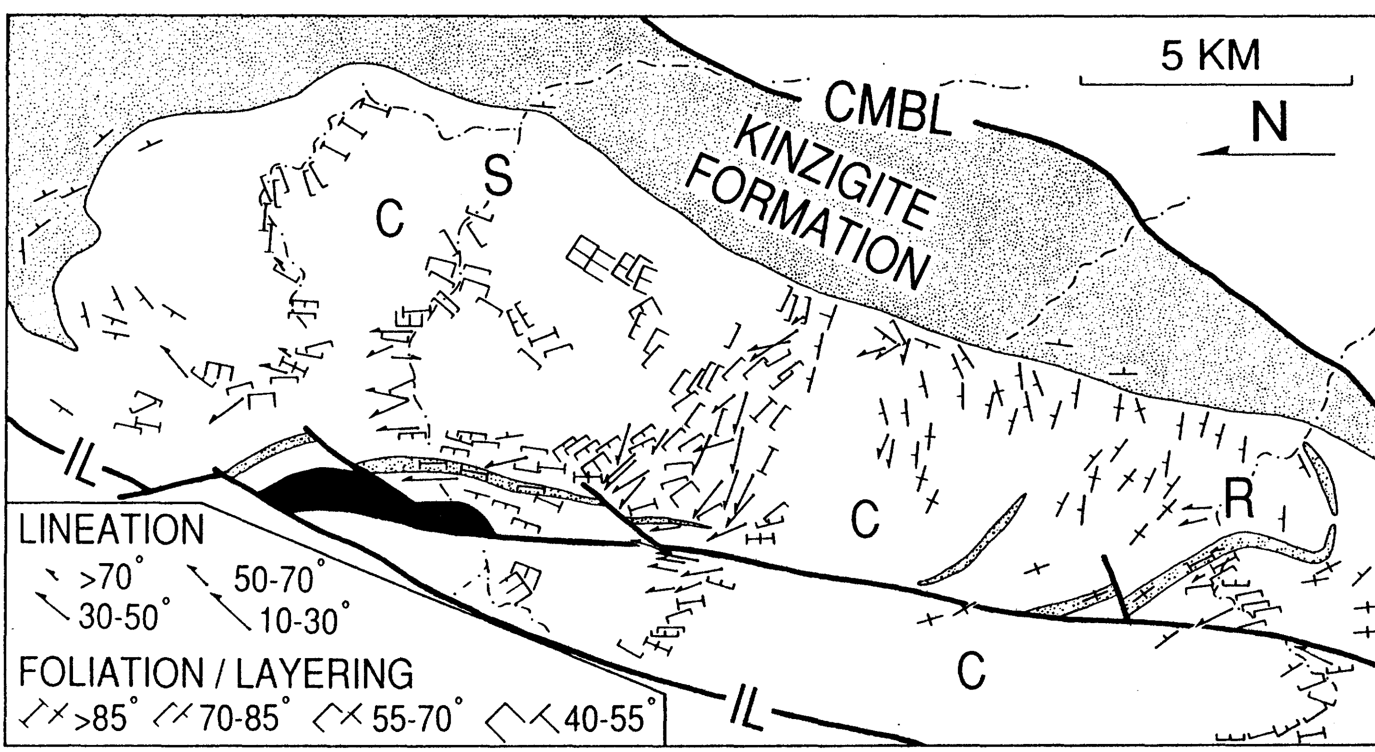

Figure 1. Structure of the southern Mafic Complex (C). Balmuccia peridotite, black; Insubric Line, IL; Cossta-Mergozzo-Brissago Line, CMBL; Sesia River, S; Sessera River, R.

LARGE-SCALE DEFORMATION AND EVOLUTION OF THE UNDERPLATED IGNEOUS COMPLEX OF THE IVREA-VERBANO ZONE

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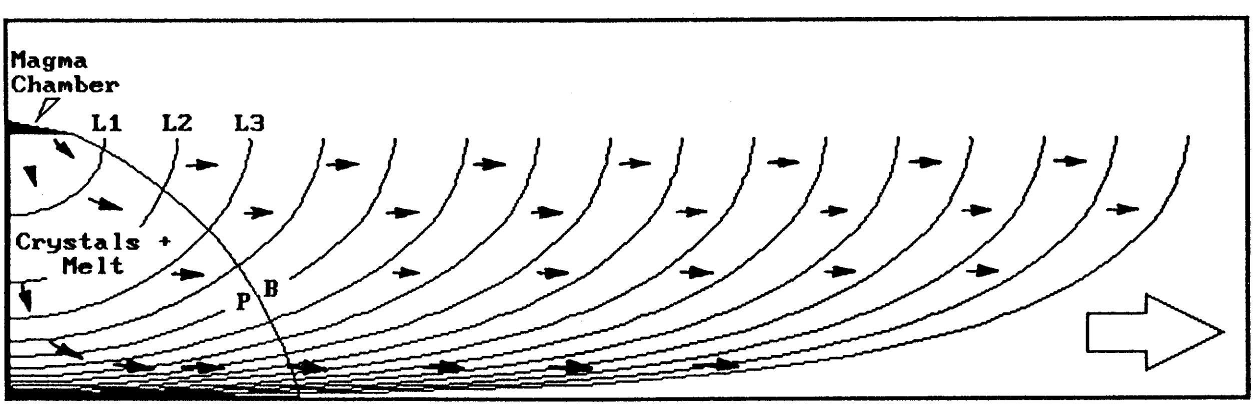
The Ivrea-Verbano Zone (IVZ) exposes a slice through a concentrically foliated and layered, synmagmatically deformed igneous complex (Quick and others, 1992). In terms of the presumed primary orientation of the igneous complex, the foliation, layering, and metasedimentary septa south of the Sesia River steepen gradually up section and locally overturn near the top of the complex. Isoclinal folds, boudinage, and high-temperature normal faults appear to have developed while the complex was still partially molten.

Analogous features are described in ophiolite gabbros. Upward steepening layering and foliation occur in the Bay of Islands and Samail ophiolites (for example, Casey and Karson, 1982; Smewing, 1981). Nicolas and others (1988) suggested that the regionally consistent foliation and lineation in ophiolitic gabbro are products of pervasive, viscous, synmagmatic flow. As a result of this flow, gabbro layers are locally isoclinally folded, and layers and foliation are cut in many places by small, high-temperature normal faults similar in scale and appearance to those in the IVZ.

Only two types of models address both the regionally consistent, high-temperature deformation and the upwardly concave layering and foliation in ophiolitic gabbros. Subsiding-floor models (for example, Dewey and Kidd, 1977) envision a small, thin magma chamber resting on a thick zone of crystal mush beneath spreading centers. During spreading, synmagmatic deformation and rotation of layering and foliation occur as the crystal mush subsides, moving downward and outward from the magma chamber. Nicolas and others (1988) proposed another model in which layers crystallize on the roof and hanging walls of a large, thick magma chamber with initial orientations dipping away from the spreading axis; synmagmatic deformation is induced by large amounts of mantle underflow. These models are difficult to test in ophiolites, which have no unequivocal indicators of spreading direction or initial layer orientation. In the IVZ, however, metasedimentary septa must have been incorporated from the root as the intrusion migrated upward. Also the concentric structure of the complex preserves the "spreading center," and the maximum magma chamber dimensions are indicated by the size of the Main Gabbro--the last intrusion into the complex (Sinigoi and others, this volume).

To demonstrate how underplating during extension could produce the gross structure of the Mafic Complex south of the Sesia River, we present results of a model that approximates the effects of deformation due to extension of a broad lens of crystal cumulates. The actual geometry utilized in the calculation is for the right side of a symmetric oceanic spreading center proposed



by Sinton and Detrick (1992). This is clearly only a first-order approximation for the IVZ Mafic Complex, but we suggest that the left side of figure 1, which would represent the spreading axis in an oceanic spreading center, could be thought of as corresponding approximately to the Sesia Valley, which passes through the core of the Mafic Complex. In the model, cumulates, consisting of crystals and interstitial melt, are overlain by a small magma chamber (<2 km wide). Flow is induced in the partially molten cumulates by a pull on the right boundary, and resistance to flow along the base and left boundary of the model is assumed to be negligible. Addition to the cumulates from the magma chamber balances removal along the right boundary, and the flow is calculated assuming a temperature- and strain-rate-dependent visco-plastic rheology consistent with the observed mechanical behavior of many mixtures of solid particles and fluid.

Figure 1 illustrates results of this calculation. Cumulates move downward and outward from the small magma chamber, and layers are stretched and rotated into upwardly concave shapes. The similarity of layering orientations produced by this model observed in the Mafic Complex south of the Sesia Valley suggests that the gross structure of the complex may indeed be consistent with underplating during extension. In contrast to ophiolites, however, the geometry of the Mafic Complex north of the Sesia River suggests that subcontinental extension in this instance was asymmetric. We suggest that the addition of cumulates by underplating was compensated in part by symmetric rifting and that the Mafic Complex may be thought of as filling a giant "tension gash" near the base of the crust.

U-PB ZIRCON AND MONAZITE AGES FROM THE IVREA ZONE AND THE ADJOINING SERIE DEI LAGHI

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To obtain more detailed knowledge about the metamorphic history of the Ivrea zone and the adjacent Serie dei Laghi (Strona-Ceneri) U-Pb ages on zircons and monazites have been determined (Köppel, 1974). Samples were collected along a profile crossing the Cossato-Mergozzo-Brissago (CMB) fault which separates the above tectonic units (Boriani and others, 1981). The observed decrease of the monazite ages from about 450 Ma to 300 Ma was also confirmed by lower intercept ages on discordant zircons (Köppel, 1974). In this study we present U-Pb zircon and monazite results from additional samples collected along, as well as across, the CMB-fault and discuss them together with the previously obtained age data.

Monazites from rocks of the Strona-Ceneri zone northeast of the Valle d'Ossola either show only minor lead loss and yield U-Pb ages of 460 Ma to 440 Ma (Val Grande: Alpe Ruspesso, Ponte Casletto) or they are strongly discordant indicating intercept ages of 440 Ma and 270 Ma, respectively (Valle Cannobina, Lago d'Orta). Zircon data of metasediments (Ceneri gneiss) from Ponte Casletto are discordant. They form a linear array showing considerable scatter. However, two size fractions yield overlapping concordant data points of 458 Ma.

A late- to post-metamorphic diorite crops out between the CMB-fault and the Pogallo-line near Mergozzo and Candoglia. Monazite data partly show a weak lead loss and point to an intrusion age of 300-305 Ma. Monazites from a paragneiss immediately adjoining yield slightly older ages. Zircon data points from the diorite scatter due to the combined effects of post-intrusive lead loss and presence of inherited lead components.

Zircon data from the Mte. Orfano granite reflect the presence of premagmatic zircon components as well as post-intrusive lead loss, which was mainly observed in uranium-rich size fractions. U-Pb monazite data plot on the concordia curve or slightly below it, indicating minor lead loss. An estimated age of 280 Ma is considered to be a minimum age.

Among the samples from the Scisti dei Laghi was one taken from the immediate contact to the Mte. Orfano granite. The monazites separated yielded nearly concordant U-Pb ages of about 310 Ma. Slightly older monazite ages were determined on samples more distant from the contact. All the monazite data points from the Scisti dei Laghi lie above the discordia intersecting at 440 Ma and 270 Ma, respectively, which are defined by some of the monazites from the Strona-Ceneri zone. We therefore conclude that the main metamorphic overprint of the Scisti dei Laghi took place during the Hercynian. Contrastingly, monazite formation ages and lower intercept ages of zircons from the Strona-Ceneri zone indicate for this unit a high-grade metamorphic event of Caledonian age.

Monazites of kinzingitic gneisses from Candoglia show ages of about 280 Ma, and a concordant monazite fraction from a stronalite near Anzola yields an age of 271 Ma. These results thus indicate that northwest of the CMB fault, high -grade metamorphic conditions prevailed during the Permian.

DYNAMIC EVOLUTION OF THE IVREA-VERBANO ZONE MAFIC COMPLEX: PART II, GEOCHEMICAL CONSTRAINTS

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Recent investigations have shown that the underplated Mafic Complex of the Ivrea-Verbano Zone (IVZ) consists mainly of hybrid rocks formed by mixing of mantle melt(s) with a significant amount of crustal component(s) (Voshage and others, 1990). The thickest part of the complex, which crops out in the southern part of IVZ, is concentrically layered and foliated as a result of hypersolidus deformation of crystal mush in an extensional tectonic environment (Quick, and others, 1992).

Gabbroic rocks collected along the Sesia Valley section show significant geochemical variations that correlate with height in the Mafic Complex. A large variation in isotopic compositions shown by the Basal and Intermediate Zones is followed by a relative homogeneity in the Upper Zone, Main Gabbro, and "Diorites" (Voshage and others, 1990). Nevertheless, from the Upper Zone to the roof, a U-shaped profile is defined by isotopic compositions of strontium and oxygen (fig. 1). Similar patterns are defined by Ba and Zr absolute concentrations. These profiles, accompanied by field evidence, suggest that the Main Gabbro crystallized from the last magma pulses injected into the core of the magma chamber and that these last melts were slightly less contaminated than the previous batches.

Isotopically uncontaminated gabbros from the Basal and Intermediate Zones are depleted in incompatible elements and LREE. Hybrid gabbros show LREE enrichment accompanied by high Ba but low K and Rb concentrations. Therefore, the contaminating melts may have been produced by a garnet- and feldspar-rich crustal source, which has been previously depleted in K and Rb with respect to Ba. Metasedimentary septa enclosed in the lower part of the Mafic Complex and the associated charnockites have the appropriate compositions to represent examples of the contaminating crustal source and anatectic melt, respectively. In contrast, leucosomes in the roof migmatites have high K and Rb and comparatively low Ba abundances and, therefore, cannot represent a suitable contaminant. Similar K- and Rb-rich compositions are shown by the Permian granites of the Strona-Ceneri Zone. On this basis, it is suggested that the incompatible elements composition of hybrid rocks is strongly affected by the degree of depletion of the crustal source. It may be noteworthy that rocks of the Mafic Complex have chemical compositions close to estimates for the deep crust, whereas the roof rocks, as well as the coeval granites of the Strona-Ceneri zone, show compositions appropriate for the middle and upper crust.

Considering the geochemical constraints collectively and the structural and field evidence, we suggest that the Mafic Complex was contaminated in situ by the enclosed, and previously depleted, deep crustal rocks, and that the intrusion occurred along a deep detachment fault, possibly close to the mantle-crust transition. Displacement of the fault concomitant with continuous magma injection, crystallization, and deformation brought an allocthonous roof of amphibolite-facies rocks into contact with the still partially molten Mafic Complex. Heat provided by the Mafic Complex on the roof rocks, accompanied by similar, although smaller, mafic intrusions at higher crustal levels induced melting of fertile middle to upper crust and consequent production of large volumes of granitic hybrid melts.

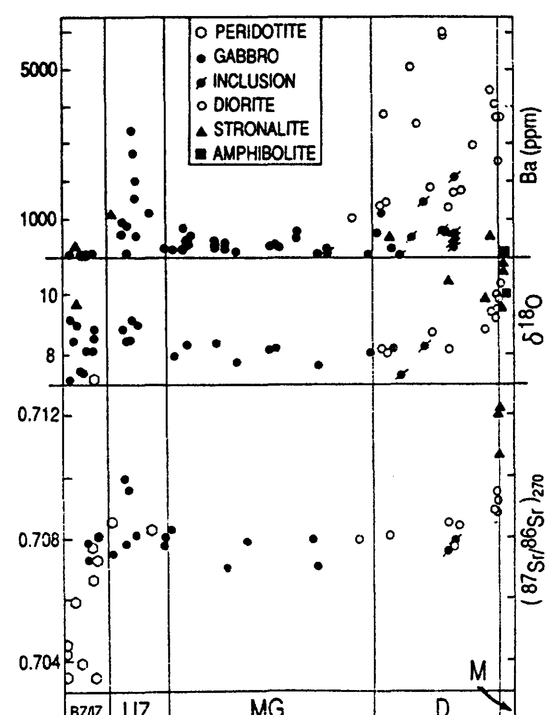

Figure 1. BZ, Basal Zone; IZ, Intermediate Zone; UZ, Upper Zone; MG, Main Gabbro; D, Diorite.

A left-lateral sense of shear is suggested by the megascopic shape of the mafic body and is consistent with the sense of shear of widespread mylonites of Permo-Triassic age in the area. Lubrication by underplated magma and consequent detachment along a large listric fault may have resulted in Permo-Triassic crustal thinning as an event precursory to the opening of the Tethyan ocean.

THE IVREA-VERBANO ZONE, NORTHERN ITALY, AS A LOWER CRUSTAL ANALOG TO THE DEEP CRUST OF THE CENOZOIC BASIN AND RANGE PROVINCE, WESTERN U. S. CORDILLERA: PERSPECTIVE AND PROBLEMS

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The lower crust of the Late Cenozoic Basin and Range Province (BRP), western U.S. Cordillera, has been cited by several authors (for example, Shervais, 1979; Fountain, 1989, Brodie and others, 1991) as a possible actualistic analog to the inferred late Paleozoic tectonothermal regime of the Ivrea-Verbano Zone (IVZ), northern Italy. Several distinctive aspects of BRP evolution are commonly cited in support of this model: steep geothermal gradients; inferred underplating by mafic magmas based on petrologic, geochemical, and geophysical studies; and widespread low-angle, normal-sense, plastic-to-brittle shear zones. The BRP is a broad zone (about 800 km wide in the northern BRP) of normal faulting and active seismicity, high heat flow, widespread Cenozoic volcanism, thinned crust and lithosphere, but high elevation and is considered a classic example of continental extension. The Holocene BRP is part of a protracted history of extension that began at least in the mid-Tertiary and perhaps even earlier. Although the present extensional regime lies essentially behind an active transform fault (San Andreas fault system), the earlier extensional history occurred during back-arc and intra-arc rifting.

Although principally upper crustal rocks are exposed at the surface in the BRP, in highly extended areas, middle crustal rocks form domiform footwall below low-angle, normal-sense faults (that is, Cordilleran metamorphic core complexes). These high-grade, metamorphic footwalls were exhumed during Tertiary crustal extension and uplift associated with deeply penetrating normal-fault systems. The Ruby-East Humboldt metamorphic core complex, northeastern Nevada, provides an exceptionally deep "window" into northern BRP crust, and seismic reflection data provide additional constraints on the character of the lower crust in this area. A cross section for the exposed rocks of the Ruby-East Humboldt core complex includes (shallow to deep) (1) upper crustal synextensional Tertiary volcanic and sedimentary rocks above subjacent Paleozoic to early Mesozoic cover rocks; (2) a transitional zone of greenschist- to amphibolite-facies metamorphic rocks intruded by Mesozoic granitic rocks; and (3) a mylonitic to migmatitic upper amphibolite-facies zone including abundant Tertiary granitic rocks (orthogneisses), synextensional plastic deformation, and high-temperature synextensional metamorphism (sillimanite-grade). Tertiary synextensional magmatism, deformation, and metamorphism apparently increase with structural depth. Normal-incident seismic reflection data indicate a reflective middle and lower crust perhaps related to extensional flow, whereas wide-angle seismic reflection data suggest significant increases in velocity with depth, probably related to extensional granulite-facies metamorphism and magmatic underplating (Valasek and others, 1989).

On a superficial level, most, if not all, of the above general characteristics can be found in the IVZ and the structurally higher parts of the Southern Alps. However, before a BRP analog can be explored in more depth, certain key questions must be addressed in regard to the IVZ.

1. In the eastern BRP, supracrustal rocks were deposited on an older Precambrian crystalline basement. What is the basement for the supracrustal rocks that compose part of the IVZ?
2. In the BRP, low angle, normal-sense, plastic-to-brittle fault systems are widely developed and well exposed. Were the conjugate extensional shear zones, now well documented in the IVZ (Brodie and Rutter, 1987), truly developed at a low-angle and subsequently rotated to their present subvertical orientations?
3. Synextensional, Tertiary (about 40 to 29 Ma) quartz dioritic to granitic orthogneisses are widespread in the migmatitic footwall of the Ruby-East Humboldt core complex and broadly coeval volcanic rocks also compose part of the Tertiary cover rocks. Can consistent age and geochemical relationships be demonstrated between possible synextensional magmatic rocks of the IVZ and structurally higher levels (for example, Strona-Ceneri zone and the late Paleozoic volcanic rocks of the Southern Alps)?
4. Granulite-facies metamorphism has been inferred by several authors (for example, Sandiford and Powell, 1986) for the deep crust of the BRP based on the high "reduced" heat flow for many parts of the region. Wide-angle seismic reflection data also suggest granulite-

facies compositions and velocities in the lower crust of the BRP. This inferred deep crustal metamorphism would be synextensional and presumably related to magmatic underplating. What is the age of metamorphism in the wallrocks of the mafic complex in the IVZ? Are multiple metamorphic events preserved in these rocks? Is the granulite-facies metamorphism in the IVZ related to the emplacement of the mafic complex?

5. The BRP developed across a complex regional geologic framework that involved widespread Mesozoic shortening, magmatism, and metamorphism prior to Cenozoic crustal extension. Can a regional geologic framework be devised that places the magmatism, metamorphism, and inferred extension of the IVZ within a specific tectonic sequence as well as a plate-tectonic setting?

The BRP is an unusually superb area in which crustal extension and associated magmatism and metamorphism can be studied at contrasting structural levels. This extensional history was widespread and long lived, but subsequently has not been overprinted by a contractile deformation. Therefore, the lower crust of the BRP provides a provocative present-day geological-geophysical analog for the commonly inferred late Paleozoic tectonothermal evolution of the IVZ. However, the detailed documentation of truly analogous relationships shared by both regions await ongoing and future studies.

LITHOSPHERIC-MANTLE MAGMATISM ASSOCIATED WITH RIFTING OF CONTINENTAL TERRANES: A CASE STUDY OF ULTRAMAFIC INCLUSIONS AND MAFIC ALKALINE MAGMAS FROM HARRAT HUTAYMAH, SAUDI ARABIA

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Mafic and ultramafic components of the Ivrea-Verbano Zone (IVZ) have been interpreted by numerous investigators as products of rift-related upper-mantle/deep-crustal magmatism (for example, Shervais, 1979; Fountain, 1989 and Quick and others, 1992). Petrologic, geochemical, and isotopic systematics of continental-rift-related magmas and entrained xenoliths of mantle and deep-crustal rocks document the genetic link between mantle-magmatism and regional crustal extension. Detailed studies of such occurrences provide information which is relevant to evaluating rift-related characteristics of IVZ subcrustal evolution.

Harrat Hutaymah is an isolated, diatreme-dominated, and xenolith-rich Tertiary/Quaternary volcanic field made up of basaltic magmas erupted through the continental lithosphere on the east flank of the Red Sea rift. To the extent that magmatic underplating in the IVZ is related to nascent rifting, Harrat Hutaymah may provide a Tertiary/Quaternary analog. Thorough investigation of an extensive suite of Hutaymah volcanics and ultramafic inclusions provides a basis for establishing general petrographic and chemical criteria for identifying rift-related heterogeneities among upper-mantle and deep-crustal rock types. Pressure-temperature-composition and time constraints on the origin of xenoliths, megacrysts, and host magmas are evaluated by combining petrographic and mineral chemical observations with available experimental phase-equilibria and thermobarometry, along with trace-element and Nd and Sr isotopic compositions.

Twenty-six ultramafic rock types are distinguished among an extensive suite of 709 xenoliths and megacrysts. Distinctive aspects of texture, modal mineralogy, and mineral chemistry allow division of this suite into categories of Mg-Cr-group and Al-Fe-Ti-group igneous pyroxenite, Mg-Cr-group and Al-Fe-Ti-group metamorphic pyroxenite, and associated Mg-Cr-group mantle peridotites, with hydrous equivalents of each category. Igneous pyroxenite and partial-melt-bearing peridotite inclusions have relatively high pyroxene equilibration temperatures (990-1160°C), and their textures, modal mineralogy, and mineral compositions reflect primary igneous crystallization, high-temperature deformation, or partial melting. These samples show the effects of injection and polybaric crystallization of volcanic-host-related mafic alkaline magma and the complementary effects of heating, fluid infiltration, and partial melting of surrounding mantle lherzolite. Metamorphic pyroxenites and nonmelted peridotites have relatively low pyroxene equilibration temperatures (<700-950°C), and textures, modal mineralogy, and mineral chemistry that reflect varying degrees of deformation, recrystallization, and metamorphic annealing. Similar bulk-rock and mineral compositional trends and gradational textural and modal characteristics between ultramafic rocks of igneous affinity and their metamorphic counterparts reflect a similar but older magmatic episode within the deep crust and upper mantle. The maximum depth of origin of Mg-Cr-group xenoliths is broadly restricted by that of pristine spinel lherzolite (protolith mantle) at ~70 km. Available experimental data and thermobarometric calculations indicate that all Al-Fe-Ti-group inclusions (igneous and metamorphic) may have been sampled from within +/-10 km of the base of the 40-km-thick crust. This interpretation is consistent with seismic data that show a heterogeneous crust-mantle transition zone in this region and contributes to an understanding of how magmatic underplating affects deep crustal evolution in continental terranes.

Petrogenetic relations between Hutaymah magmas, xenoliths, and megacrysts made on the basis of petrography and mineral chemistry are supported by trace-element and Nd and Sr isotopic data. Mantle inclusions that have equilibrated texturally at relatively low temperatures sample the Arabian lithospheric mantle of Proterozoic age. Inclusions of relatively high temperature affinity reflect upper-mantle processes that are cogenetic with Red Sea rift-related magmas erupted at Harrat Hutaymah over Late Tertiary to Quaternary time.

Trace-element and isotopic characteristics of igneous ultramafic inclusions record subcrustal syn-rift processes related to crystallization of mafic alkaline magmas. Partial-melt-bearing peridotite xenoliths are variably enriched in alkaline magmatic components and have isotopic signatures overlapping those of Hutaymah volcanics and cogenetic igneous inclusions. These isotopic signatures may have been acquired during recent magmatic enrichment in magma/mantle-wall-rock reaction zones. Alternatively, anhydrous and hydrous melt-bearing lherzolites could represent the source mantle for host magmas.

Trace-element and isotopic characteristics of unmelted spinel lherzolite and metamorphic pyroxenite xenoliths reveal time-integrated REE enrichment and depletion that are attributed to magmatism and subsequent metamorphism within the Arabian lithospheric mantle and associated with Proterozoic crustal formation during oceanic-arc and continental-arc-margin accretion.

Correlation and trace-element and isotopic characteristics in both syn-rift mantle-magma samples and pre-rift upper-mantle rocks suggest that Hutaymah magmatism resulted from predominantly lithospheric as opposed to asthenospheric mantle melting. In general, these results suggest that it is important to consider the effects of subcrustal lithospheric magmatism in addition to asthenospheric melting during early stages of continental rifting.

GEOCHEMISTRY OF METAPELITES OF SOUTHERN ALPS FROM LAKE MAGGIORE TO LAKE COMO (NORTHERN ITALY): PRELIMINARY RESULTS

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Metapelites are the most abundant lithology of the Southalpine basement and crop out continuously from the Ivrea Zone to the Orobic Alps. The regional metamorphism is mainly under amphibolite-facies conditions (Variscan). The granulite-facies conditions (stronalites) are localized in the northwesternmost Ivrea-Verbano Zone (IVZ). A high-temperature and low-pressure condition, with sillimanite and andalusite growth, overprints the amphibolite-facies assemblage of the Serie dei Laghi (SDL) and Lake Como region (LC).

The IVZ is composed of a mafic-ultramafic complex associated with metapelites and minor marble lenses. Southwest of the IVZ, the Serie dei Laghi occurs; it is represented by metapelites (Scisti dei Laghi) and metarenaceous sequences (Strona-Ceneri). The whole SDL is intruded by Ordovician metagranitoids and Permian granites (Graniti dei Laghi). The Southalpine Orobic basement is mostly represented by metapelites (scisti di Edolo; Filladi di Ambria; Gneiss di Morbegno p.p.) with minor occurrences of orthogneisses, amphibolites, quartzites and marbles.

Major-, trace-element and REE chemical analyses were performed on metapelites from the IVZ, SDL, and the eastern LC region. Al_2O_3 content ranges from 25 to 15 wt percent and SiO_2 from 55 to 70 wt percent. The most aluminiferous samples were from the LC whereas the most siliceous were from the SDL schists. The chemical data indicate a nearly uniform composition with respect to the major elements, except for the LC metapelites, which exhibit lower CaO and MgO contents than IVZ and SDL. Trace elements point out slight differences among the groups. Particularly, the LC and IVZ pelites show similar Ba and Sr contents, which are lower than those of the SDL. The low K/Rb ratios of all metapelites (250-500) indicate no significant depletion in LILE (DGT trend show K/Rb between 500 and 5000), as is also indicated by a Rb/Sr ratio about 1. REE patterns are homogeneous with a slightly negative Eu anomaly (Eu/Eu^*=.0.5-0.7) as well as LREE/HREE fractionation (La_N/Yb_N about 10 for SDL and LC, whereas for IVZ the ratios are 7-8). The overall trace-element and REE patterns are consistent with those of averaged shales of the upper crust (PAAS), and no significant depletion is observed as regards those elements. The strong LILE enrichment with respect to mantle abundance by factors of 10^2 is again typical of the upper crust.

We compared the studied rocks with available data from stronalites because the latter are considered to be the corresponding lithotype re-equilibrated under high-grade conditions. In a normalized rock-PAAS spidergram all the rocks show a similar trend with low depletion in K_2O, Rb, and Zr and more pronounced Cr depletion for the stronalites samples. Moreover, REE patterns display the same trends and are comparable with those of upper crust. Therefore, the amphibolite and granulite facies metapelites cannot be distinguished chemically with the available data.

U-PB AGES OF ZIRCONS FROM CHROMITITES OF THE PHLOGOPITE PERIDOTITE OF FINERO, IVREA ZONE, NORTHERN ITALY

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Ferrario and Garuti (1990) reported the unusual presence of zircons in chromitites that occur as small and discontinuous stratiform to podiform bodies within the outer zone of the phlogopite peridotite of Finero. The zircons are irregularly distributed within the chromitites. In polished sections 10-25 grains, many with dimensions as great as 400 μm, are observed in areas of < 100 mm^2. Euhedral inclusions occur in chromite, olivine and serpentinized olivine. Most zircons are subhedral to anhedral and occur between olivine and chromite. The zircons show no optical zoning and are virtually free of inclusions. However, cathode luminescence revealed sharp and often curved zoning. Microprobe investigation yielded variable concentrations of U, Hf, and Y of as much as 4000 ppm, 1.5 percent, and 700 ppm, respectively.

Four grain-size fractions, which included also fragments of coarser crystals, were analyzed. The U concentrations range between 1100 and 1240 ppm. One fraction yielded concordant ages of 204 ±4 Ma, whereas the others are slightly discordant. The data points define a discordia with an upper intercept at 207 ±5 Ma and a lower intercept at zero Ma. No evidence of an older inherited zircon component was detected.

When trying to assess the significance of the zircon ages, one has to consider the following points:

--The irregular zircon distribution suggests that Zr was introduced relatively late into a magma and did not homogenize. The zircons are not accompanied by other minerals indicative of a highly differentiated melt.

--Textural evidence indicates that zircon crystallization started relatively early, but the majority of the crystals formed after chromite and olivine.

--The presence of curved crystal faces is indicative of growth at high temperatures (>750°C), and the preservation of sharp zoning boundaries argues against a prolonged period of annealing at high temperatures.

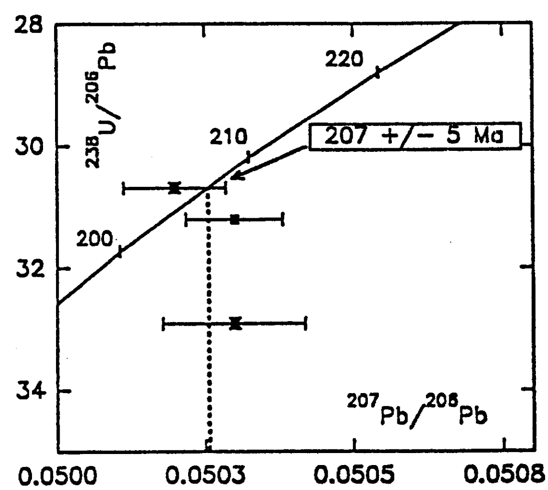
--Zircons have until now been observed only in the phlogopite peridotite, where they seem to be preferentially associated with chromite.

--According to Ferrario and Garuti (1990) the mineralogy and mineral chemistry of the platinum-group minerals, the base-metal sulfides, and alloys, as well as the presence of Mg-rich carbonates and phlogopite is best explained by the presence of an alkali-rich fluid during crystallization.

The presence of zircons is also considered to have resulted from this alkali-metasomatism. Textural relationships and the irregular zircon distribution suggest that the metasomatism probably occurred during the ascent of the magma and/or during crystallization.

Stähle and others (1990) reported $^{207}Pb/^{206}Pb$ zircon ages from syenite pegmatite dykes that crosscut the phlogopite peridotite of 225 ±13 Ma. K-Ar ages of 206 Ma were obtained by Hunziker[2] and $^{40}Ar/^{39}Ar$ plateau ages of 206.5 ±2.5 Ma by Friedrichsen (personal communication).

The Triassic event reported here coincides with the opening of the Paleotethys which was accompanied in the Eastern and Southern Alps by a widespread alkalic magmatism.



$^{238}U/^{206}Pb$ vs $^{207}Pb/^{206}Pb$ plot for zircon fractions from a chromite layer within the phlogopite peridotite of Finero.

SEISMIC VELOCITY CALCULATIONS AND STRUCTURAL ASPECTS OF THE BALMUCCIA PERIDOTITE

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The Ivrea-Verbano Zone (IVZ) is thought to be a cross section through the continental crust-mantle transition. It is not a continuous sequence because important shear zones shorten the total thickness and juxtapose different lithological units. Published geobarometric calculations indicate that the deepest part of the IVZ is exposed in Val Sesia.

The peridotitic body and its surroundings are exposed near the village of Balmuccia. An area of about 3 km^2 between Balmuccia and Isola was selected for detailed structural fieldwork. In this area, the contact between the Balmuccia peridotite and layered gabbroic rocks is exposed. In the same area, representative samples of the peridotite body were collected. The attitudes of compositional banding and foliation in the peridotite and gabbroic rocks east of the peridotite are subvertical, and strike northwest in the eastern part of the area, whereas in the western part, near the Canavese Line, a more recent foliation striking northeast is superposed. Two main high-temperature shear zones (at least amphibotite facies) were recognized in the basic complex east of the peridotite body. These join together on the Isola-Cima Lavaggio ridge. One of these shear zones shows right-lateral movement, whereas the other is a left-lateral shear zone, stretching the banding toward the southwest. The high-temperature shear zones are cut by a northeast-trending system of very narrow and abundant low-temperature shear zones (greenschist facies), with a right-lateral movement generally of a few centimeters.

About twenty samples of peridotite, showing different degrees of deformation, were collected. The crystallographic orientations of about 100 grains in each sample were measured in order to characterize the fabric dependence of seismic behaviour of the peridotite through the application of the Bunge (1985) method.

THE IGL SEISMIC NETWORK IN THE IVREA-VERBANO ZONE

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Since December 1991 the Istituto per la Geofisica della Litosfera (IGL) has been operating a local seismic network in the Northern part of the Ivrea-Verbano Zone.

The IGL network is composed of five recording stations (three components MARS88) with automatic trigger; the stations work independently and record data on floppy disks. The mean distance between two recording units is about 20 km. The seismic stations are set up to record regional earthquakes and teleseisms.

Rays coming from great distances are supposed to be near vertical at the station site, crossing vertically the geological bodies.

The locations of the recording stations were chosen in order to have a sampling of the seismic behavior of the most representative lithologies of the Ivrea Zone, which are kinzigites (Cannobina Valley), stronalites (Strona Valley), and gabbros (Mastallone Valley). The other two stations were placed on Serie dei Laghi metapelites and along the Insubric Line (Fobello and Rimella schists).

The main objectives are to investigate, as far as possible, the deep geometries of the Ivrea Body and to clarify the relationships between the geophysical and the geological Ivrea Body. These new data can be considered an integration of the data previously recorded by wide-angle and near-vertical experiments in this area (CROP-ECORS 1985 and CROP 1986).

During the five months in which the IGL network has been operating, about 25 seismic events were recorded by more than three stations.

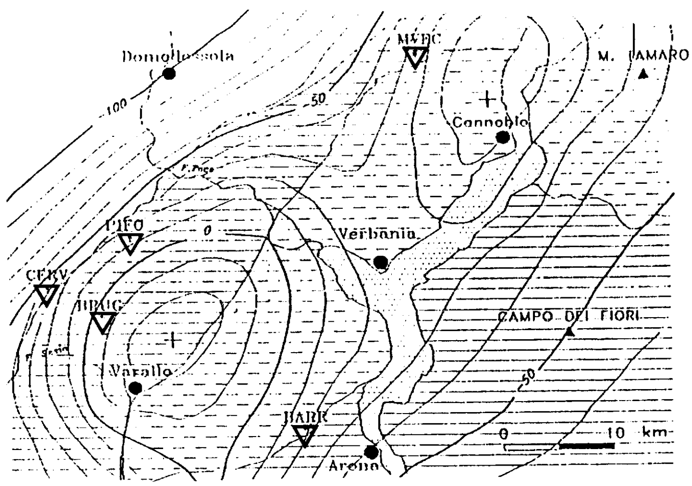

Figure 1. The IGL network: ═══ Mesozoic sediments, ‗‗‗ Serie dei Laghi, ‗ ‗ Ivrea-Verbano Zone, Austroalpine and Pennine Units, ▽ 3-components recording stations, -- 100 -- Bouguer anomaly contur lines of 10 mgal (after A. Guillarme and S. Guillarme).

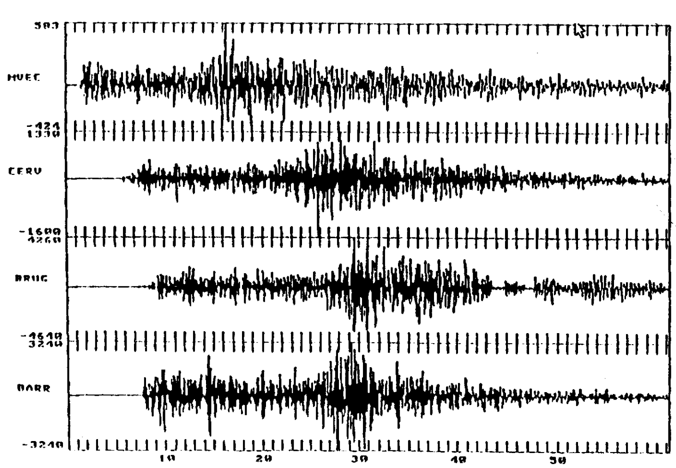

Figure 2. Seismograms of a regional earthquake recorded by four recording units (vertical component of the IGL network).

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☆U.S. GOVERNMENT PRINTING OFFICE: 1992-673-049/46051

U.S. DEPARTMENT OF THE INTERIOR

March 3, 1849