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Dedicated to the memory of Prof. Bernard Kübler and Prof. Martin Frey

Internal Liguride Units from Central Liguria, Italy: new constraints to the tectonic setting from white mica and chlorite studies

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Abstract

The Internal Liguride Units (ILU) of the Northern Apennines are interpreted as remnants of the Western Tethys oceanic lithosphere. In Late Cretaceous–Paleocene time, this lithosphere was underthrusted, underplated and later exhumed in an accretionary wedge related to an east-dipping, low-rate subduction zone. Until recently, only five IL units resulting from disruption of this lithosphere (namely Cravasco/Voltaggio, Figogna, Gottero, Colli/Tavarone and Bracco/Val Graveglia) have been recognized. A recent structural survey of the Valpolcevera-Valle Scrivia area (Central Liguria) revealed the existence of four more tectonic units: Bric Montaldo, Serra, Vallecalda and Ciaè units. Mineral assemblages, "crystallinity", polytypism and *b* cell parameter of illite, as well as the "crystallinity" of chlorite in metapelites from these units indicate that they have attained diagenetic to middle anchizonal grade and have experienced baric conditions approximating the intermediate-pressure facies series of MIYASHIRO (1961). Overall, the data on the metamorphic grade, together with the deformation character, indicate that the Valpolcevera-Valle Scrivia units belong to the ILU, but they were underplated at shallower levels than those reached by the westernmost, highest-grade units (Cravasco/Voltaggio and Figogna); their features point to metamorphic conditions similar to those of the easternmost units (Gottero, Colli/Tavarone and Bracco/Val Graveglia). This study shows the reliability of illite "crystallinity" as a tool to estimate thermal conditions over the entire very low-grade metamorphic zone; it appears sensitive enough to reveal even small differences in grade between different tectonic units.

Keywords: Central Liguria, Liguride units, very low-grade metamorphism, tectonics.

Introduction

Many terrains are made up of mudstones, shales, slates, phyllites and sandstones that have experienced diagenesis to very low-grade metamorphic conditions. To these rocks the classical geothermometers and geobarometers cannot be applied. However, several kinds of semiquantitative thermometers and barometers based on illite "crystallinity", proportion of smectite in illite-smectite, chlorite "crystallinity" and composition, and illite b cell parameter, have been proposed and currently used (FREY, 1987 and literature cited therein; MERRIMAN and FREY, 1999; MERRIMAN and PEACOR, 1999). Recently, these methods have been critically reviewed by ESSENE and PEACOR (1995), who showed that they are not based on equilibrium reactions and therefore cannot be used uncritically and without appropriate caveats. Nonetheless, that study concluded that clay minerals systems can be useful in estimating reaction progress. In particular, they are sensitive indicators of the metamorphic grade of systems that have similar thermal or tectonic histories, bulk compositions or textures. Within these constraints, these sheet silicates are still commonly used in most studies of rocks affected by diagenetic or very-low grade metamorphic conditions (ÁRKAI et al., 1995; LEONI et al., 1996; SCHEGG and LEU, 1996; OFFLER et al., 1998a and 1998b).

The Northern Apennines are a typical "fold and thrust" belt consisting of several tectonic units belonging to different paleogeographic and structural domains (MARRONI and PANDOLFI, 1996). Among these, the Internal Liguride Units (hereafter referred to as IL units) are interpreted

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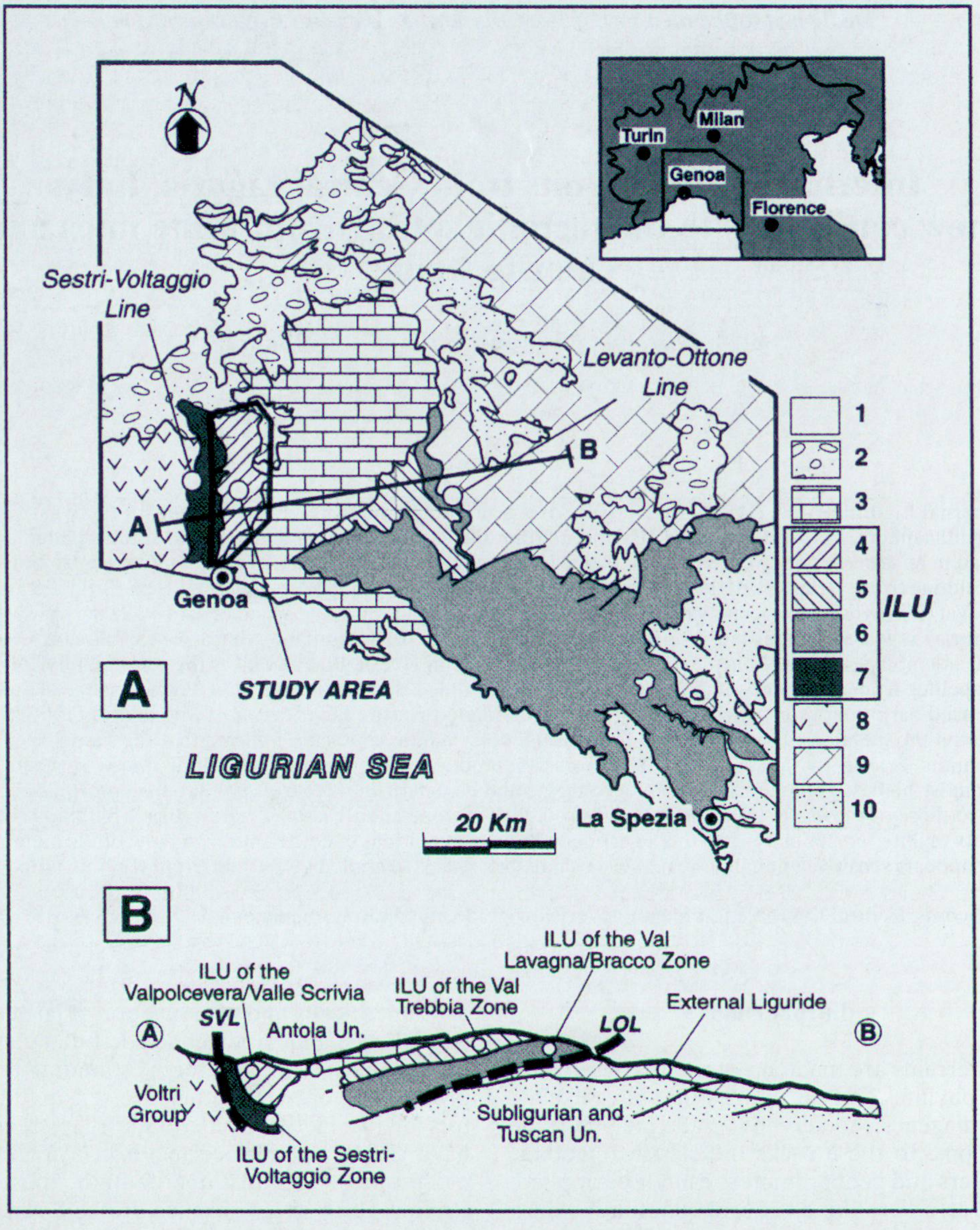

Fig. 1 Geological setting of the Internal Liguride Units (ILU), Northern Apennines, Italy. (A) Tectonic sketch map of the Northern Apennines. 1. Pliocene–Quaternary deposits; 2. Post-orogenic sedimentary sequences of the Tertiary Piemontese and Ranzano Basins; 3. Antola Unit; 4. ILU of the Valpolcevera and Valle Scrivia zone (Ciaè Unit, Vallecalda Unit, Serra Unit and Bric Montaldo Unit); 5. ILU of the Val Trebbia zone (Portello Unit, Vermallo Unit and Due Ponti Unit); 6. ILU of the Val Lavagna/Bracco zone (Gottero Unit, Colli/Tavarone Unit and Bracco/Val Graveglia Unit); 7. ILU of the Sestri-Voltaggio zone (Cravasco/Voltaggio Unit and Figogna Unit); 8. Voltri Group; 9. External Liguride Units; 10. Subligurian and Tuscan Units. (B) Schematic geological section (not to scale) of the Northern Apennines showing the location of the Internal Liguride Units in the nappe pile. Symbols as in the tectonic sketch map. SVL: Sestri-Voltaggio Line; LOL: Levanto-Ottone Line.

as remnants of the Western Tethys oceanic lithosphere (DECANDIA and ELTER, 1972). Until recently, only five units (Cravasco/Voltaggio, Figogna, Gottero, Colli/Tavarone and Bracco/Val Graveglia) have been recognized, all of them cropping out in the far north-western sector of the mountain chain, at the junction of the Alps and Apennines. This area is bounded by two major tectonic lines, namely the Sestri-Voltaggio and Levanto-Ottone Lines, both interpreted as first-order discontinuities at the boundaries of these belts (SCHOLLE, 1970; ELTER and PERTUSATI, 1973) (Fig. 1). In the Valpolcevera–Valle Scrivia–Val Trebbia area, the IL units are overthrust by the Antola Unit, which consists of late Cretaceous–Paleocene Helminthoid Flysch. Along the Levanto-Ottone Line, the IL units are superposed on the External Liguride Units, characterized by different lithostratigraphic and structural features (MARRONI et al., 1992 and references therein).

The superposition of Antola Unit over the Figogna Unit, in the Valpolcevera and Valle Scrivia area, and over the Gottero Unit, in the Val Trebbia area, was essentially regarded as a direct one (CNR, 1982), until recent field-mapping and structural investigations (DUCCI et al., 1997; ELLERO, 2000) indicated a more complex tectonic pattern. Such a pattern includes a stack of four tectonic units sandwiched between the Antola and the Figogna units (ELLERO, 2000) and a group of three tectonic units sandwiched between the Antola and Gottero units (DUCCI et al., 1997).

This paper summarizes results of a metamorphic study carried out on the K-white micas and chlorites in shales from the Valpolcevera–Valle Scrivia area of the Northern Apennines belt, Central Liguria (NW Italy). The data collected are used to verify the structural setting proposed by ELLERO (2000).

Geological setting

The IL units are characterized by a Jurassic ophiolite sequence overlain by a sedimentary cover ranging in age from Middle Jurassic to Early Paleocene. The ophiolite sequence includes serpentinized ultramafic rocks and gabbros, covered by a volcano-sedimentary complex consisting of different types of ophiolite breccias, interfingering with basaltic lavas and minor cherts. This sequence is overlain by a sedimentary cover made up of pelagic deposits (MARRONI et al., 1992) that comprise cherts (Middle Callovian–Tithonian), Calpionella Limestone (Berriasan–Valanginian) and Palombini Shale (Valanginian–Santonian). These formations are overlain by trench deposits, which include the Val Lavagna Shale (Campanian–Early Maastrichtian) and the Monte Gottero Sandstone (Late Maastrichtian–Early Paleocene). The top of the IL sequence is represented by the Bocco Shale (Early Paleocene), also known as the Colli/Tavarone Formation, which is regarded as a lower slope deposit. This sedimentary sequence, showing a transition from pelagic to trench and to lower slope deposits, is interpreted as recording a trenchward movement of the oceanic lithosphere (TREVES, 1984).

During Pre-Oligocene orogenesis, the sequence of the IL Domain was deformed, metamorphosed and tectonically disrupted into several units. Owing to such a deformation history, involving frequent thrust and detachment faults, each IL unit is characterized by an incomplete and different portion of the whole succession, except for the Colli/Tavarone Unit (MARRONI and MECCHERI, 1993), which shows a complete sequence ranging from the ophiolite to the Bocco Shale. The present setting, which results from three main deformation events, shows the IL units succeeding each other eastward from the Sestri-Voltaggio Line in the following order: Cravasco/Voltaggio, Figogna, Gottero, Bracco/Val Graveglia and Colli/Tavarone. During the most important deformation phase, when the metamorphic climax occurred, the succession within the tectonic pile was exactly the same, except for the positions of the Bracco/Val Graveglia and Colli/Tavarone units, which were inverted (MARRONI and PANDOLFI, 1996). The metamorphic grade of the IL units, in the ophiolitic sequences (where present) (CORTESOGNO and HACCARD, 1984; LUCCHETTI et al., 1990; HOOGERDUIJN STRATING, 1991) and in sedimentary sequences (LEONI et al., 1996), is consistent with this tectonic setting. It ranges from the advanced diagenesis of the shallowest unit to the HP-LT conditions (low-temperature blueschist facies) of the deepest unit in the tectonic pile. Based on mica parameters calibrated through a comparison with data from metabasite assemblages, LEONI et al. (1996) estimated the following approximate values of temperature and pressure: 160–210 °C, 2–3 kbar (Bracco/Val Graveglia Unit); 200–250 °C, 2–3 kbar (Colli/Tavarone Unit); 235–285 °C, 4 kbar (Gottero Unit); 270–320 °C, 6 kbar (Figogna Unit); 300–350 °C, ca. 7 kbar (Cravasco/Voltaggio Unit).

As pointed out earlier, in the Valpolcevera–Valle Scrivia area one of the IL units, namely Figogna Unit, is overthrust by the Antola Unit. Previous interpretations of this zone involved either the Antola Unit directly superposed on the Figogna Unit, the ophiolitic sequence of which is stratigraphically overlain here by a thick turbiditic sequence (= Busalla Flysch; CORTESOGNO and HACCARD, 1984), or a distinct tectonic unit (= Valpolcevera Unit; MARINI, 1989) placed between Antola and Figogna units. Lacking any specific study on the metamorphic grade, the involved sedimentary sequences in both cases were as-

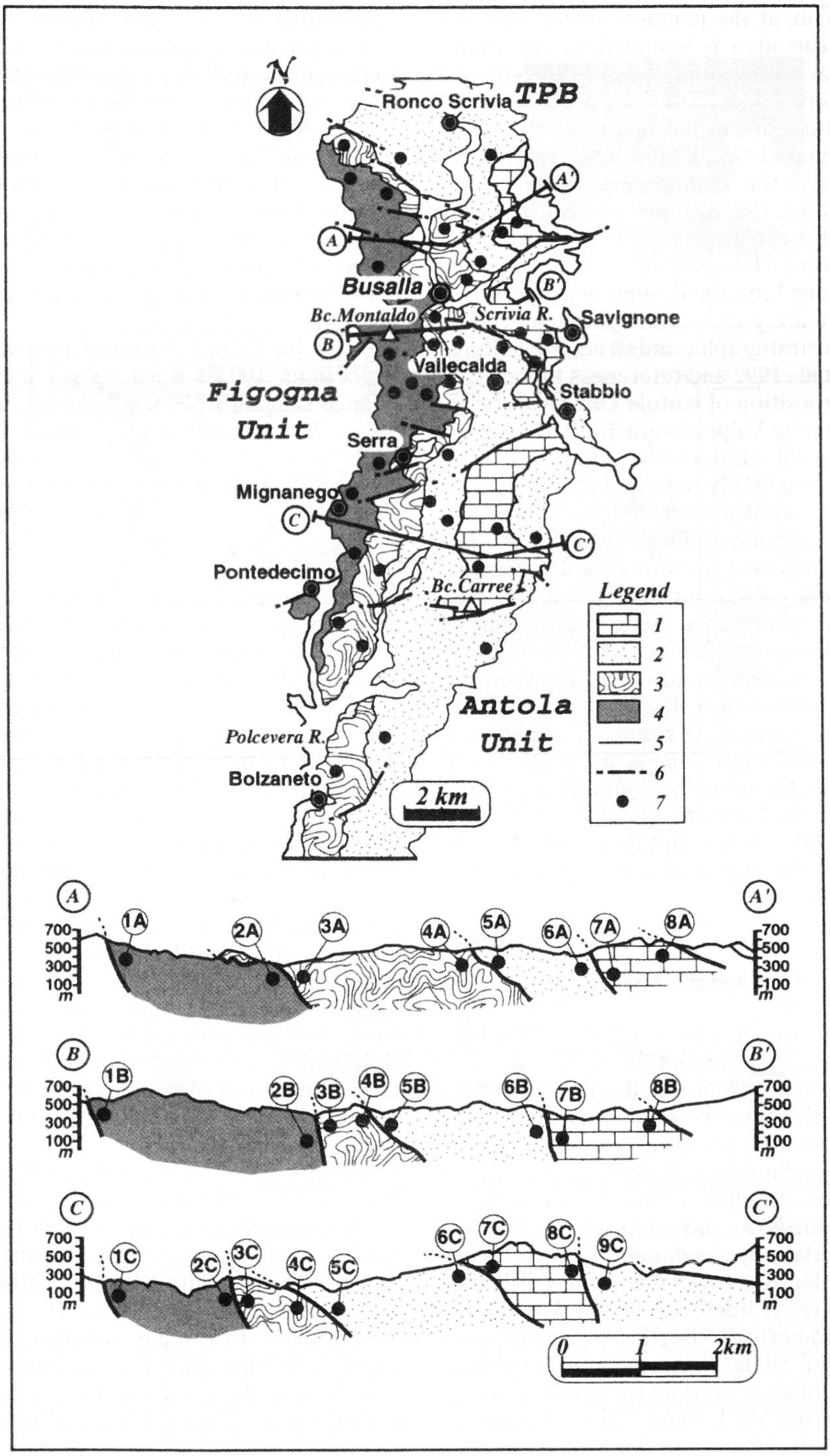

Fig. 2 Tectonic sketch map of the Valpolcevera-Valle Scrivia zone and schematic geological sections. 1. Ciaè Unit; 2. Vallecalda Unit; 3. Serra Unit; 4. Bric Montaldo Unit; 5. Main thrusts; 6. Main faults; 7. Sample location; TPB= Tertiary Piemontese Basin.

sumed to have been subjected to the same metamorphic conditions as the Figogna Unit (low-grade blueschist facies).
In the study area, the IL units are unconformably overlain by the post-orogenic succession of the Tertiary Piemonte Basin, the older deposits of which are represented by the Early Oligocene, continental Val Borbera Conglomerates.

Deformation history

In a recent detailed field-mapping and structural study of the Valpolcevera–Valle Scrivia area, ELLERO (2000) presented evidence for the existence of four distinct tectonic units, sandwiched between the Figogna and Antola units (Figs 1b and 2). These units, which are hereafter reported, from bottom to top, as the Bric Montaldo, Serra, Vallecalda and Ciaè units, crop out along four belts having approximately a N–S direction, separated from each other by east-dipping thrust planes (Fig. 2). The metamorphosed succession of these units was primarily represented by Late Cretaceous turbiditic deposits, which in the Serra Unit are overlain by pebbly mudstones of Late Cretaceous to Paleocene age. The mega-, meso-, and micro-structural analyses of the Valpolcevera-

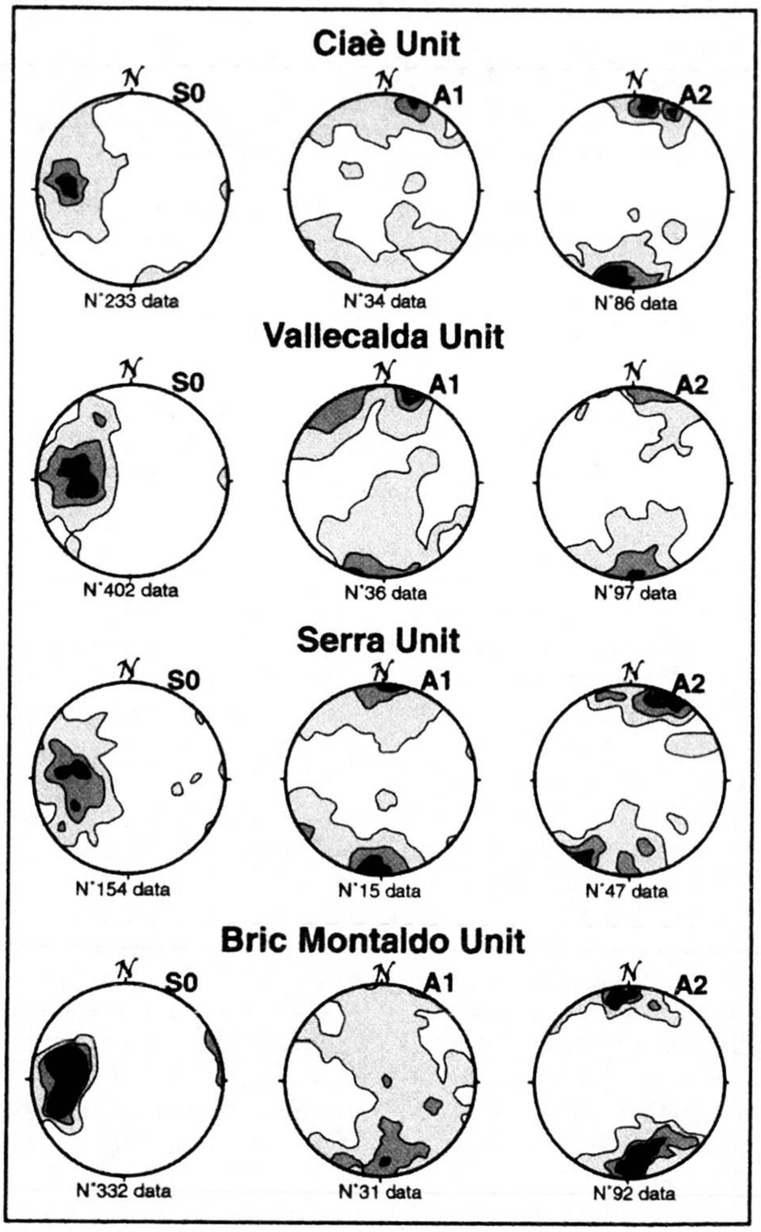

Fig. 3 Equal-area, lower hemisphere stereographic representation of S0 , A1 and A2 structural data of the Valpolcevera-Valle Scrivia Internal Liguride Units. *Ciaè Unit*: S0 contours 1%, 3%, 5%; A1 contours 1%, 3%, 5%; A2 contours 1%, 4%, 6%. *Vallecalda Unit*: S0 contours 1%, 3%, 5%; A1 contours 0.5%, 2.5%, 5%; A2 contours 1%, 3.5%, 7%. *Serra Unit*: S0 contours 1%, 3%, 5%; A1 contours 1%, 2.5%, 4%; A2 contours 1%, 3%, 5%. *Bric Montaldo Unit*: S0 contours 1%, 3%, 5%; A1 contours 0.5%, 2%, 3%; A2 contours 1%, 2.5%, 4%.

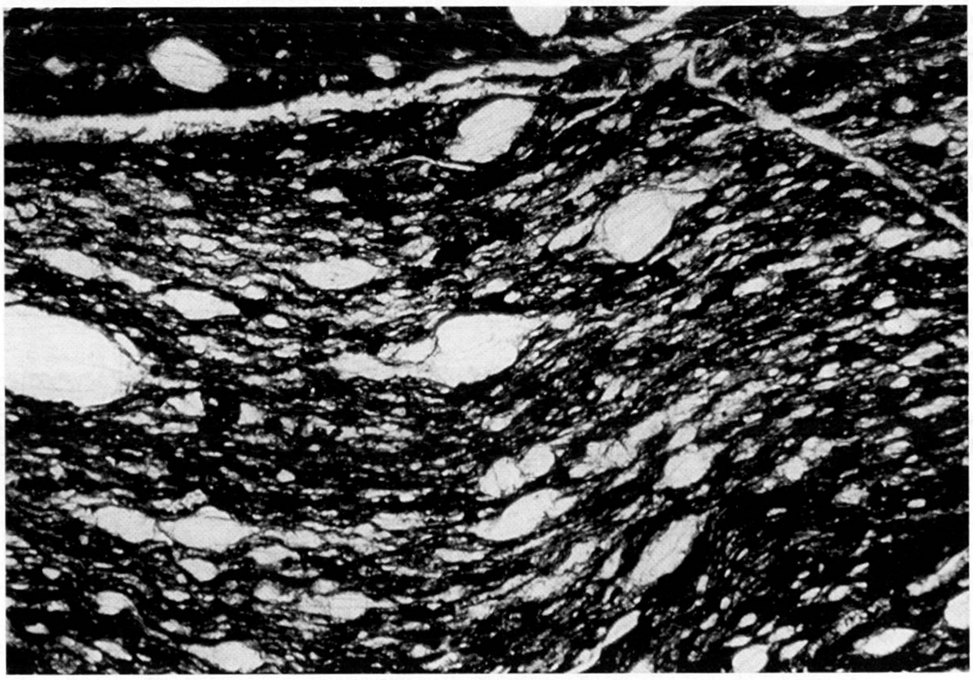

Fig. 4 Photomicrograph of a metapelite from the Bric Montaldo Unit illustrating the S_1 slaty cleavage; such a cleavage appears defined by aligned white mica and chlorite flakes and elongated quartz-albite-white mica aggregates showing the effects of pressure-solution parallel to the cleavage. Pressure shadows around detrital minerals have infillings of fibrous minerals such as quartz, phyllosilicates and calcite. A left shear sense is shown by σ and δ kinematic indicators. (Long dimension: 0.5 mm).

Valle Scrivia units show that they have been affected by deformation events similar to those recognized in the well-established IL units. The most significant events can be assigned to three main phases, D1, D2 and D3. Whereas all the tectonic contacts are deformed by the D3 deformation phase, the correlation of D1 and D2 in the studied units is based on the geometry and structural elements proposed for the area (e.g. HOOGERDUIJN STRATING, 1991).

The first deformation phase (D1) is characterized by folds (F1) with approximately similar geometry (classes 1c, 2 and 3 of RAMSAY, 1967). In the Bric Montaldo and Serra units the F1 folds are isoclinal and strongly non-cylindrical, whereas in the Vallecalda and Ciaè units they are cylindrical and appear to range from tight to close folds. In the deepest units (Bric Montaldo and Serra), the limbs of these folds show well developed boudinage and necking, sometime producing pinch-and-swell structures or boudin-trains of competent rocks in a shaly matrix. The strike of A1 axes ranges from N180E to N20E with a low dipping (Fig. 3).

The F1 folds are associated with a conspicuous S1 axial-plane foliation, which in the shales shows the characteristics of a slaty cleavage; it is particularly well developed and penetrative in the deepest units. Such a slaty cleavage (Fig. 4) is characterized by the synkinematic recrystallization, under peak metamorphic conditions, of the following mineral assemblage: Ms + Chl + Qtz + Calc ± Ab ± I/S (mixed-layer illite/smectite).

During the D1 phase, cataclastic shear zones of greatly variable thickness developed parallel to S1 foliation. To the D1 deformation phase have been ascribed both the tectonic contact between Vallecalda and Ciaè units and that between Bric Montaldo and Serra units (ELLERO, 2000); these contacts, slightly modified by the subsequent D2 deformation phase, are marked by foliated cataclasites. Kinematic indicators and macro- and meso-structures suggest a west-verging tectonic transport during the D1 deformation, which agrees with the pattern suggested by VAN ZUTPHEN et al. (1985), VAN WAMEL (1987), MARRONI (1991), MARRONI and PANDOLFI (1996) for the IL units.

The D1 phase was followed by a weaker D2 deformation phase, distinguished by overturned and asymmetric F2 folds having approximately parallel geometry (classes 1b, 1c and 2 of RAMSAY, 1967). In all the studied units, the strike of A2 axes is about N180E (Fig. 3). Superposition of these structures on the F1 folds of the previous deformation produced interference structures of the type 3 (RAMSAY, 1967) or type G (THIESSEN and MEANS, 1980; THIESSEN, 1986). At the meso-scale, the F2 folds are everywhere associated with low-angle, brittle shear zones. After restoration from later folding phases, normal motion along these brittle shear zones is indicated by displacement of markers as well as shear sense criteria (slickenfibers, extension fractures, etc.). Associated with the F2 folds is a S2 sub-horizontal axial plane foliation recognized in shales as a crenulation cleavage. This cleavage is not accompanied by syntectonic recrystallization of metamorphic minerals, but is characterized by a mere mechanical re-arrangement of mineral grains. Moreover, the occurrence of dark seams of insoluble material along dissolution surfaces in the hinge zone of F2 folds suggest that pressure solution was an active mechanism during the D2 phase. Overall, the structural features of the D2 phase, such as the folds with sub-horizontal axial-planar foliation and the association of such folds with low-angle, normal shear zones are features consistent with vertical shortening occurring in an extensional tectonic setting.

The D2 deformation phase is regarded as responsible for the contact between Serra and Vallecalda units (ELLERO, 2000). This contact is represented by cataclastic shear zones, slightly undulated by F3 open folds and characterized by S-C structures pointing to top-to-west sense of shear.

The D2 phase was followed by a very low strain phase, D3, characterized by F3 open, concentric folds, developed on a hm-scale, with sub-vertical axial planes trending approximately N–S. Associated with the F3 folds is a well-spaced disjunctive cleavage, which is only developed in the hinge zones.

Owing to the lack of radiometric dating of the low-grade metamorphism, the age of the deformation phases is constrained by the age of the youngest formation of the Serra Unit and by the relationships of the deformation structures with the post-orogenic deposits of the Tertiary Piemontese Basin (DI BIASE et al., 1997). These ages imply that the D1 and D2 deformation events occurred from Early Paleocene to Late Eocene. The age of the D3 phase is poorly constrained. The F3 folds are probably related to early stages of continental collision, which occurred during the Lower Oligocene, as suggested by the presence of folds with the same attitude and style in the deposits of the Tertiary Piemonte Basin (ELLERO, 2000).

As already stated, the polyphase deformation pattern observed in the Bric Montaldo, Serra, Vallecalda and Ciaè units can be compared with that recognized in the well-established IL units (MARRONI and PANDOLFI, 1996, and references therein). This pattern has been interpreted as consistent with the incorporation of oceanic lithosphere slices in an accretionary wedge related to an east-dipping, intraoceanic subduction zone. Within this framework, the first and strongest deformation phase (D1) has been ascribed to coherent underplating of the IL sequences at shallow structural levels of the accretionary wedge. The subsequent, less intense deformation (D2 phase) has been related to exhumation of the IL units during the extension driven by continuous underplating of oceanic lithosphere at deep structural levels of the accretionary wedge (MARRONI and PANDOLFI, 1996).

Methods

Sampling was carried out in the carbonate-poor, hemipelagic metapelites found at the top of the metaturbidites within each of the Valpolcevera-Valle Scrivia units. Such sediments have very uniform lithological and sedimentological characteristics throughout the investigated sequences, which enable the collection of highly homogeneous samples. Altogether 57 samples of metapelitic rocks were collected along three traverses approximately trending E–W (Fig. 2), at localities distant from the cataclastic shear zones that affect the studied units.

Micro-structural and textural characteristics of the rocks were investigated using transmitted, optical microscopy. Determination of the mineralogy was carried out on powders of whole-rock samples, whilst < 2 μm fraction samples were investigated both on oriented aggregates and randomly oriented powders, using a Philips PW 1710 automatic diffractometer equipped with a long fine-focus Cu tube. The < 2 μm fraction was prepared by sedimentation from powders obtained after gentle grinding of rock chips for short times (< 3 minutes). This avoided appreciable comminution of clastic phyllosilicates and their inclusion in the "clay fraction". Owing to the very low contents of carbonate and organic matter, no preliminary treatment was applied to remove these components.

The illite and chlorite "crystallinity" indices (half-height peak width expressed as $\Delta 2\theta$ of the 10 Å and the 7 Å reflections, respectively) were measured from diffractometer traces on charts obtained for the < 2 μm fraction samples sedimented on glass slides. Care was taken to avoid thin slides. The amount of clay on each slide was at least 3 mg/cm^2 (LEZZERINI et al., 1995). Measurements were performed on air-dried specimens and also after ethylene glycol solvation.

The (002) reflection of chlorite was selected because: (a) it appears as the strongest peak of the mineral; (b) it is free from any effect of overlapping with the (001) peak of kaolinite, since this mineral is never present in detectable amounts: (c) unlike the (001) reflection, its measurement is not sensitive to the presence of the illite/smectite mixed-layer minerals observed in some units.

Each sample was run at the following instrumental settings: Cu$K\alpha$ Ni-filtered radiation: 40 kV; 20 mA; slits: 1/2° divergence and scatter, 0.2 mm receiving; continuous scanning; scan speed: 0.25° 2θ per minute; chart speed: 1° 2θ = 50 mm on paper; time constant: 4 seconds.

Following the same procedure applied in the previous studies on the IL units (Leoni et al., 1996) the calibration of machine results was carried out against those of Kübler's laboratory (Université de Neuchâtel) using three standards provided by him.

The mica polytype composition was investigated on randomly oriented powder samples by the Maxwell and Hower (1967) method measuring the ratio of 2.80 Å to 2.58 Å peaks intensities on chart. It is well known that all the XRD techniques reported in literature for determining the relative amounts of mica polytypes have rather low precision (Frey, 1987 and references therein). Dalla Torre et al. (1994) stated that out of the methods available, the method proposed by Caillere et al. (1982) is the most accurate. Despite this, the method of Maxwell and Hower (1967) was adopted in the present work since we wanted to gather data comparable with those obtained in the previously studied Internal Liguride units (Leoni et al., 1996).

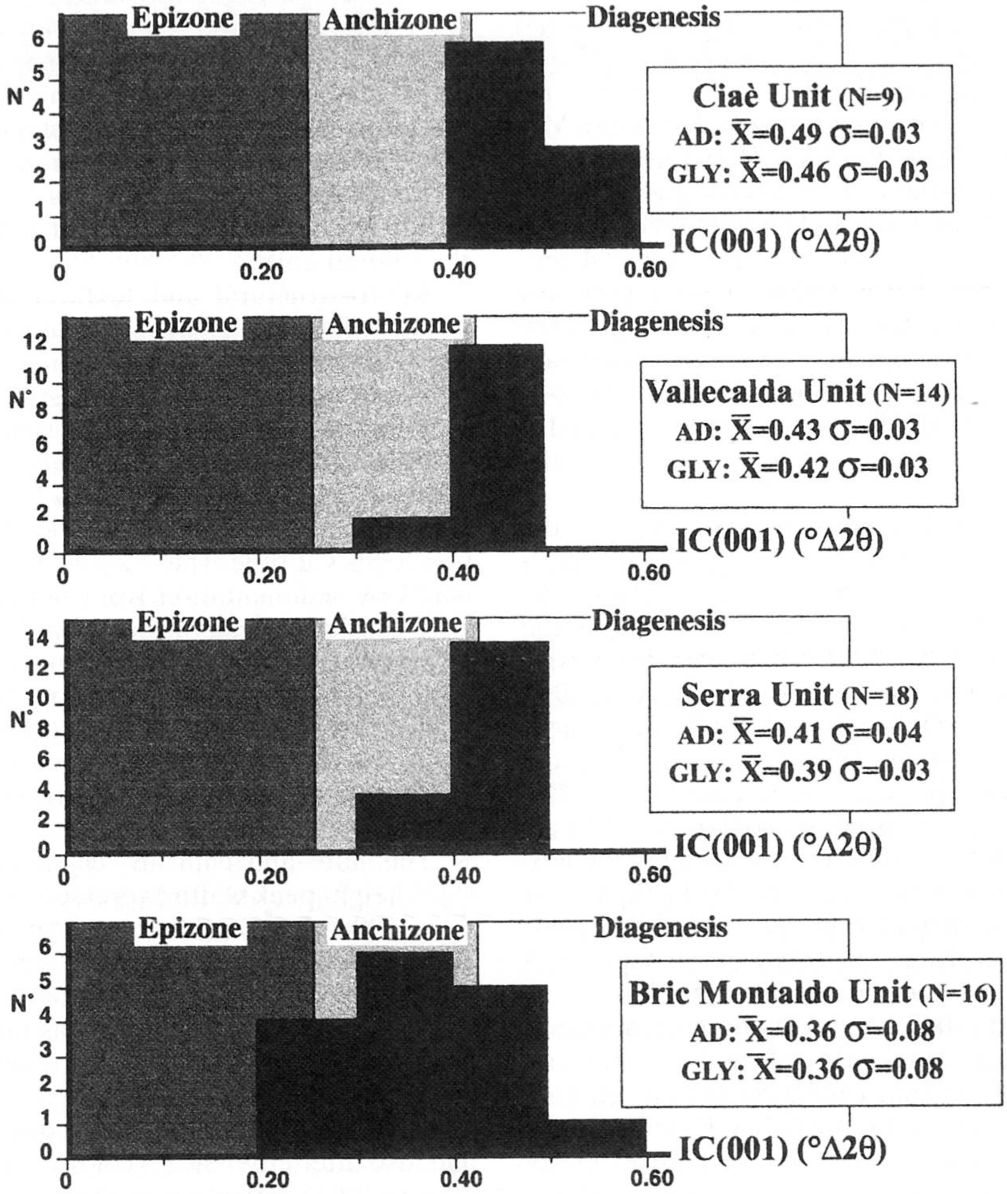

Fig. 5 Illite "crystallinity" index (IC) distribution in the Valpolcevera-Valle Scrivia Internal Liguride Units. IC boundaries between metamorphic zones from Kübler (1984 and 1990). $\bar{X}$ = average value; σ = standard deviation; AD = values from air-dried slides; GLY = values from glycolated samples; N = number of examined samples.

The mica *b* cell parameter was calculated from the (060, $\bar{3}31$) spacing using the (211) quartz reflection as an internal standard; the positions of mica and quartz reflections were determined on randomly oriented powder samples run by step scanning from 59° to 63° 2θ (time/step = 9.6 sec/ 0.01°).

The illite/smectite mixed-layer mineral was identified through detailed analysis of the positions, shapes, and intensities of mica reflections on XRD patterns registered on samples before and after glycolation (ŚRODOŃ, 1984).

Results and discussion

MINERALOGICAL COMPOSITIONS AND PETROGRAPHIC-MICROSTRUCTURAL OBSERVATIONS

The rocks studied are metapelites containing mineral assemblages chiefly consisting of illite and chlorite with subordinate amounts of quartz. Calcite is present in small amounts and mixed-layer illite/smectite minerals (I/S) were found only in Vallecalda, Ciaè and Serra units. In the first two units, this phase is present in minor amounts, in the last unit it is very rare. No kaolinite or discrete smectite was observed. Paragonite is completely absent, whereas it represents an important metamorphic phase in the highest-grade IL units (Cravasco/Voltaggio, Figogna and Gottero units; LEONI et al., 1996). K-feldspar and plagioclase occur as minor components; accessory minerals are apatite, rutile, zircon and pyrite.

Within the same specimen, plagioclase, K-feldspar, apatite, rutile, zircon and pyrite occur only as detrital minerals, whereas K-white mica, chlorite, quartz and calcite are present both as detrital and metamorphic minerals crystallized during the D1 phase; in the Bric Montaldo Unit this holds true also for albite. The metamorphic parageneses, as inferred from optical observations as well as X-ray powder diffraction analysis of bulk samples and < 2 μm fractions, are Ms + Chl + Qtz ± Ab + Calc in metapelites of the Bric Montaldo Unit and Ms + Chl + I/S + Qtz + Calc in metapelites of Serra, Vallecalda and Ciaè units.

In thin section, the most evident planar anisotropy is represented by the S1 axial plane foliation, which is markedly penetrative (as in the Bric Montalto Unit). In the metapelites such a foliation attains the character of a slaty cleavage, which is marked by an anastomosing network of aligned phyllosilicates and by films of opaque minerals wrapped around lenticular domains containing single crystals or polycrystalline aggregates of detrital minerals (chlorite, quartz and feldspars). These detrital minerals appear randomly oriented or, more often, flattened and elongated parallel to the S1 foliation. Pressure shadows around detrital minerals and pyrite framboids are well developed, showing infillings of fibrous minerals such as quartz, phyllosilicates and calcite (pressure shadows of pyrite-type, RAMSAY and HUBER, 1983) (Fig. 4).

Intracrystalline deformation is evidenced by deformation bands observed in some quartz grains and by twinning in calcite. These twins belong to the type II of BURKHARD (1993), which has been ascribed to strong syn- or post-metamorphic deformations under conditions ranging from 150 to 300 °C.

Microstructural features observed point to non-coaxial deformation with top-to-west sense of shear. The effects of D2 phase deformation are superimposed on those of D1 phase; the S1 slaty cleavage appears moderately to strongly folded and a S2 axial plane foliation is developed (Fig. 4), which can be recognized as a convergent, fanning crenulation cleavage (GRAY, 1977). Processes of mechanical re-arrangement of mineral grains and development of pressure solution structures appear to be largely involved. Pressure solution mostly produced a common concentration of opaque minerals on the S2 foliation planes.

Illite "crystallinity"

The distribution of illite "crystallinity" index (IC) values, measured on air-dried specimens, is shown in figure 5. Glycol treatment appears not to affect appreciably the IC values in the Bric Montaldo Unit, but a small, systematic difference between values from treated and untreated specimens is apparent for the other units.

IC varies from 0.36 (as °Δ2θ) in the Bric Montaldo Unit to 0.49 in the Ciaè Unit. Assuming the IC values proposed by KÜBLER (1984, 1990) as characteristic of the diagenetic-zone/anchizone and anchizone/epizone boundaries (0.42 and 0.25 as °Δ2θ, respectively), the data collected in the present study suggest a middle anchizonal grade for the Bric Montaldo Unit, upper diagenetic to lower anchizonal conditions for the Serra and Vallecalda Units and diagenetic conditions for the Ciaè Unit.

Transects across the four units reveal a gradually lower grade to the east (Fig. 6). Considering that in all the units the syntectonic recrystallization developed during the most intense D1 deformation phase and assuming that during this phase the metamorphic gradient was similar in the various units, this pattern could be interpreted as related to the depths of burial of the units, which most likely were progressively shallower from the west to the east.

Illite polytypes

The polytypic composition of illite in the various units is illustrated in figure 7. The $2M_1$ polytype average frequency appears to range from 68% in the Vallecalda Unit to 83% in the Bric Montaldo Unit; the Ciaè and Serra units have $2M_1$ average frequency values of 73 and 78%, respectively. According to a diagram presented by BRAUCKMANN (1984) and modified by FREY (1987), polytype frequencies of 60–70% and 100% $2M_1$ appear to mark the lower and upper limits of the very-low-grade metamorphism (= anchizone), respectively. Thus, the observed $2M_1$ polytype contents indicate conditions covering the entire anchizone, similar to the the grade suggested by the illite "crystallinity" (though slightly higher). As already observed by LEONI et al. (1996) in other IL units, illite "crystallinity" is a more sensitive monitor of metamorphic grade than muscovite polytypism, because it is able to discriminate between diagenetic (Ciaè Unit) and upper diagenetic to lower anchizonal conditions (Serra and Vallecalda units) (Fig. 5).

Illite *b* cell parameter

The distribution of illite *b* cell parameter values within metapelites of the Valpolcevera-Valle Scrivia units is shown in figure 8. The average value ranges from 9.000–9.002 Å in the Vallecalda and Ciaè units to 9.010–9.011 Å in the Serra and Bric Montaldo units.

It is well known that *b* cell dimension of white K-micas is predominantly a function of celadonite content, which, in turn, is mostly a function of

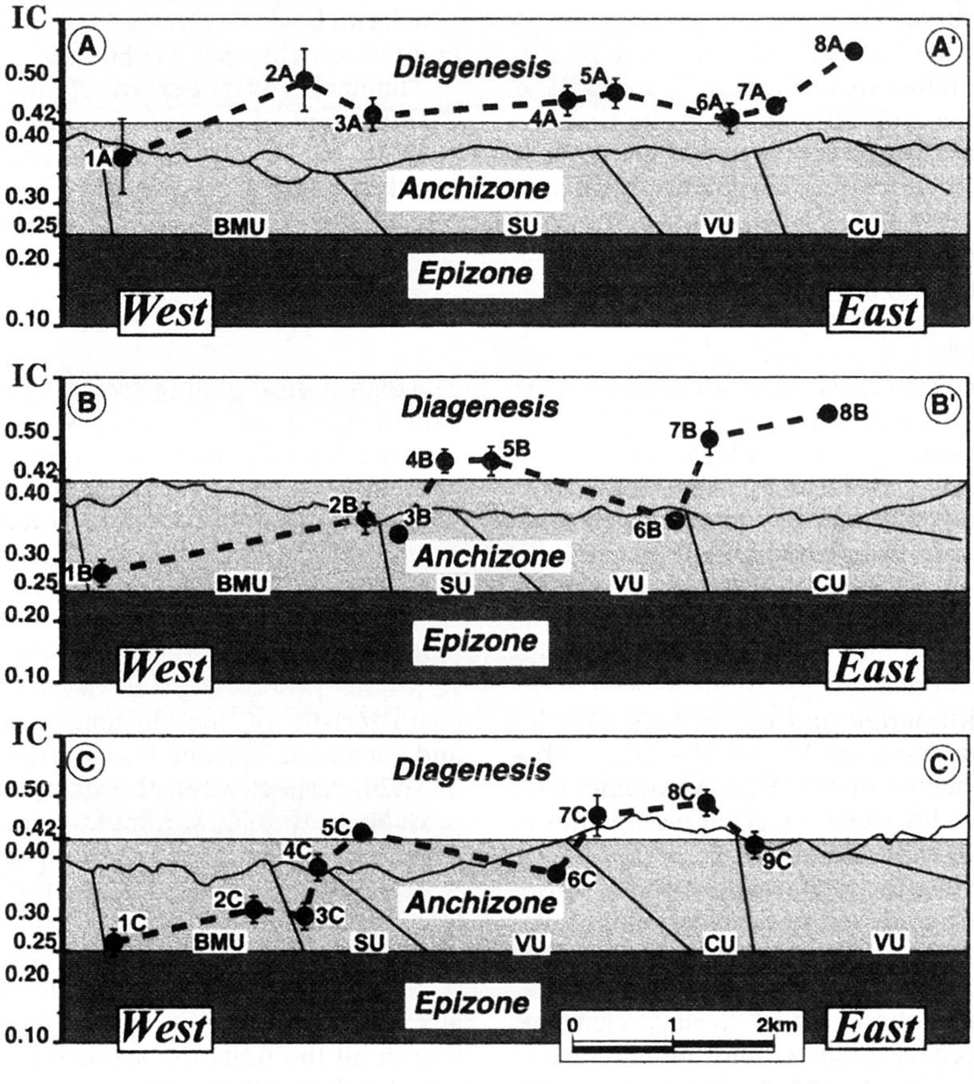

Fig. 6 Variation of the illite "crystallinity" index value in E–W transects across the Valpolcevera and Valle Scrivia Internal Liguride Units (traverses AA', BB' and CC' of figure 2). IC boundaries between metamorphic zones from KÜBLER (1984 and 1990). BMU = Bric Montaldo Unit; SU = Serra Unit; VU = Vallecalda Unit; CU = Ciaè Unit.

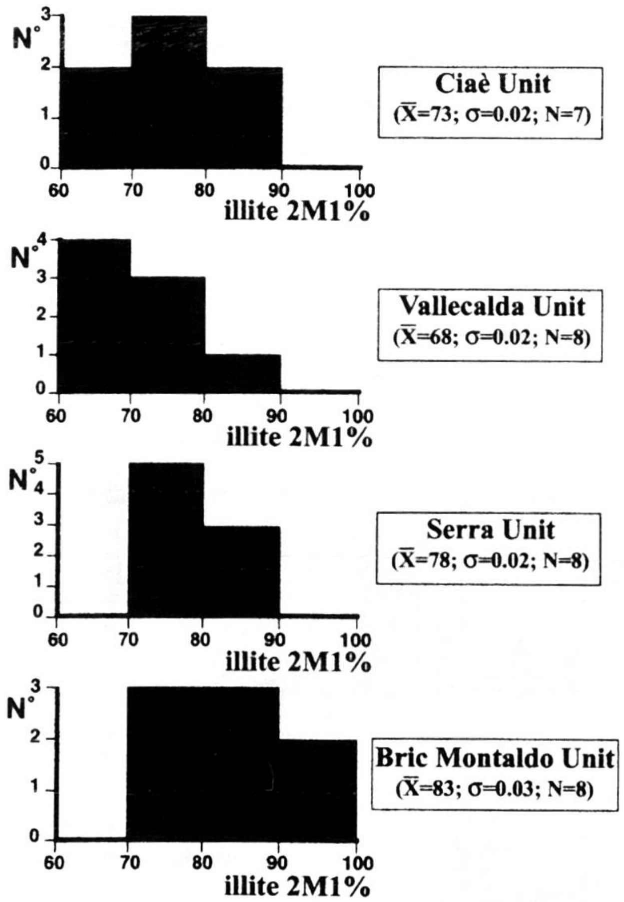

Fig. 7 Frequency distribution of illite $2M_1$ polytype in the Valpolcevera-Valle Scrivia Internal Liguride Units. X̄ = average value; σ = standard deviation; N = number of examined samples.

pressure (GUIDOTTI, 1984 and literature therein); therefore, provided that certain compositional and mineralogical constraints are fulfilled (GUIDOTTI and SASSI, 1976), this parameter should be applied to gain general information on the pressure conditions (GUIDOTTI and SASSI, 1986). Originally, K-mica geobarometry was used for low-T greenschist facies metapelites (SASSI and SCOLARI, 1974). Later, PADAN et al. (1982) extended it to the higher-T part of anchizone. In the previous studies of the ILU metamorphic grade (LEONI et al., 1992, 1996, 1998), the authors went even further and used illite *b* cell parameter values, calibrated with respect to pressure values deduced from assemblages in the associated metabasites, to estimate the pressure conditions experienced by a low anchizonal-late diagenetic grade metapelite (Palombini Shale). LEONI et al. (1996) provided a detailed discussion and observed that in this case the assessment of the main baric types of MIYASHIRO (1961) should be made on the basis of the *b* cell parameter boundaries suggested by FRANCESCHELLI et al. (1989) for Al-rich assemblages. In fact, the Palombini Shale clay fraction has Al-saturated or slightly super-saturated compositions (with respect to muscovite and/or paragonite), even if Al-rich phases (such as kaolinite or pyrophyllite) are not present in detectable amounts. Application of this scale gives pressures consistent with deformation style and geological setting of the units. By contrast, application of the *b* cell parameter boundaries proposed by GUIDOTTI and SASSI (1986) for Al-intermediate high-variance assemblages produces implausible pressure estimates. The metapelites from the Valpolcevera-Valle Scrivia units have compositions and mineral assemblages similar to the Palombini Shale of the other IL units. Further, they record similar deformation events, which probably developed at different times and different depths, but in the same geodynamic setting. It seems reasonable, therefore, to use for them the same correlation of *b* cell parameter with baric type (FRANCESCHELLI et al., 1989) applied to the Palombini Shale. Assuming Franceschelli's *b* cell parameter boundaries, the histograms of figure 8 clearly show that all the metapelites of the Valpolcevera-Valle Scrivia units belong to the intermediate pressure facies. Despite relatively large standard deviations, a progression in the mean *b* cell parameter values from the Ciaè and Vallecalda units to the Serra and Bric Montaldo units can be recognized. This is in full agreement with the trend in metamorphic grade shown by IC and polytypic composition parameters.

A distinct change in the mean *b* cell parameter value distribution is apparent between Serra and Vallecalda units (Figs 8 and 11), separated by a shear zone developed during the D2 phase. Such a boundary is then the border between fairly different baric conditions, marking the group of the Bric Montaldo and Serra units and the group of the Vallecalda and Ciaè units, respectively. This change in P conditions strongly suggests that this cataclastic shear zone represents a low-angle normal fault, where a small amount of crustal thinning occurred during the exhumation of the IL units.

CHLORITE "CRYSTALLINITY"

The distribution of chlorite "crystallinity" index (ChC) values in the Valpolcevera-Valle Scrivia units is shown in figure 9. For this mineral only the values from air-dried specimens have been taken into account, since the ethylene glycol treatment does not appear to appreciably influence the parameter's measures, not even in the lowest grade units.

ChC values vary from 0.26 (as $°\Delta 2\theta$) in the Bric Montaldo Unit to 0.40 in the Ciaè Unit, fol-

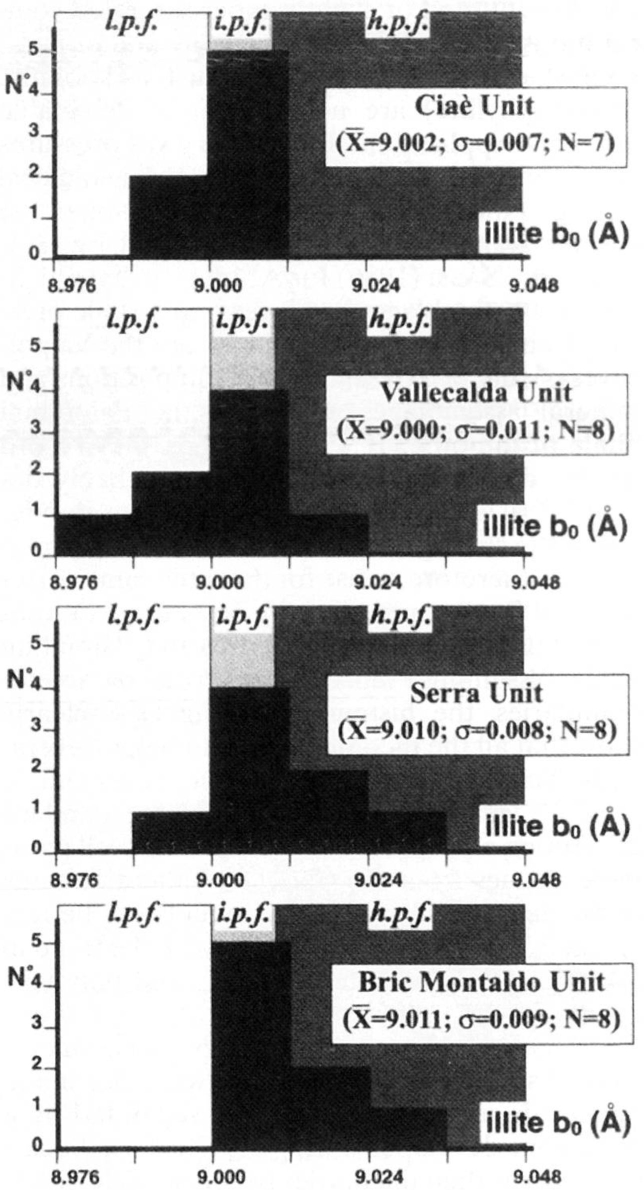

Fig. 8 Distribution of illite *b* cell parameter (b_0) in the Valpolcevera-Valle Scrivia Internal Liguride Units. b_0 boundaries between the pressure facies series of MIYASHIRO(1961) are from FRANCESCHELLI et al. (1989) for Al-rich low-variance assemblages. l. p. f. = low pressure facies; i. p. f. = intermediate pressure facies; h. p. f. = high pressure facies. $\bar{X}$ = average value; σ = standard deviation; N = number of examined samples.

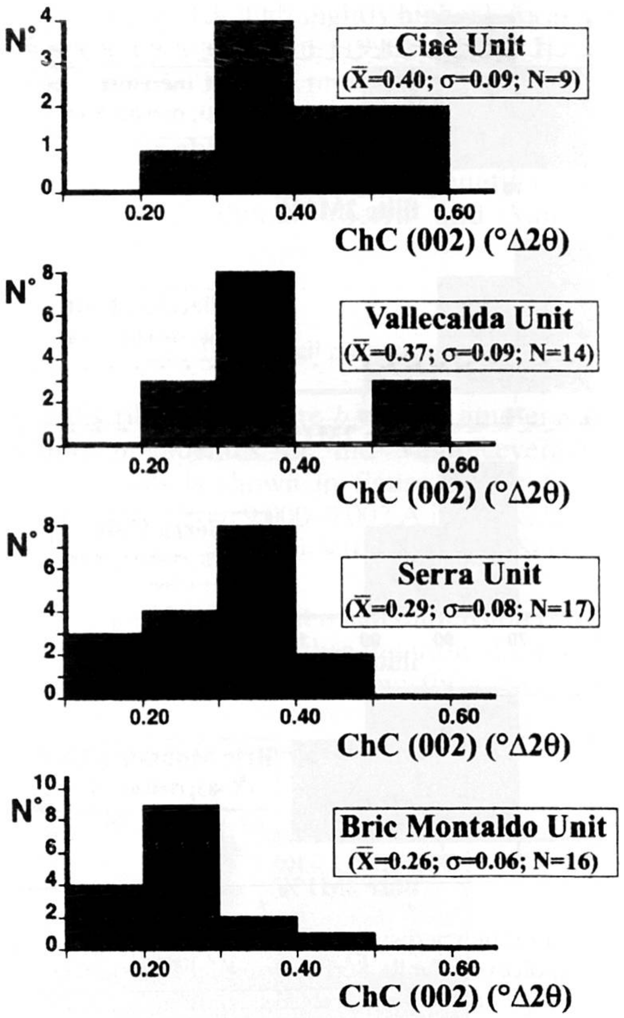

Fig. 9 Chlorite "crystallinity" index (ChC) distribution in the Valpolcevera and Valle Scrivia Internal Liguride Units. $\bar{X}$ = average value; σ = standard deviation; N = number of examined samples.

lowing approximately the same trend as shown by illite "crystallinity" and $2M_1$ polytype values. This results in a good correlation coefficient between ChC and IC (r = 0.77). However, under the same metamorphic conditions, the chlorite "crystallinity" index is systematically lower than illite index.

Use of these data to assign the Valpolcevera-Valle Scrivia units to the diagenetic zone, anchizone or epizone is not straightforward, since at present no widely accepted ChC scale is available. The most detailed studies on the subject of ChC (ÁRKAI, 1991; ÁRKAI et al., 1995; ÁRKAI et al., 1996) assert that ChC method is a tool as trustworthy as the IC method, though less sensitive than the latter for identifying differences in metamorphic grade (ÁRKAI et al., 1995). According to these studies chlorite "crystallinity" can be considered a useful complementary tool, especially where the interpretation of illite "crystallinity" is hindered by disturbing factors (i.e. the presence of discrete or mixed layer paragonitic phases, margarite, etc.). In the present study, application of ÁRKAI's (1995) ChC scale produces results largely coincident with those given by KÜBLER's (1990) IC scale. However, since the interpretation of illite "crystallinity" in the present case is not hindered by any disturbing factor, KÜBLER's (1990) IC scale has been applied to precisely assess the metamorphic grade of each unit. Chlorite "crystallinity" has been merely employed to

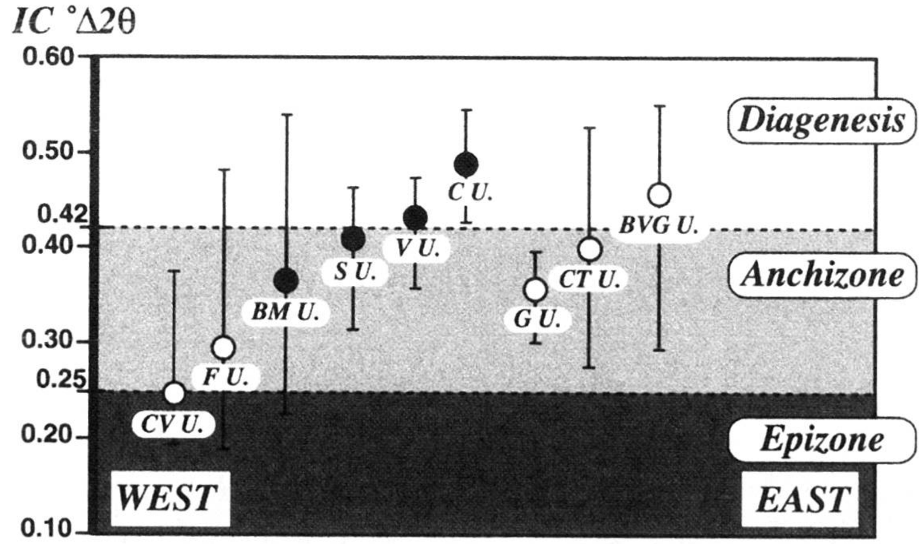

Fig. 10 Illite "crystallinity" index distribution and metamorphic zonation in the Internal Liguride Units along an ideal west to east transect. IC boundaries between metamorphic zones are from KÜBLER (1984 and 1990). CV U. = Cravasco/Voltaggio Unit; F U. = Figogna Unit. BM U. = Bric Montaldo Unit; S U. = Serra Unit; V U. = Vallecalda Unit; C U. = Ciaè Unit. G U. = Gottero Unit; CT U. = Colli/Tavarone Unit; BVG U. = Bracco/Val Graveglia Unit. The IL units of the Valpolcevera-Valle Scrivia zone are distinguished by full circles (data from the present study); open circles mark other IL units (data from LEONI et al., 1996). (Circles = mean values; vertical lines = ranges).

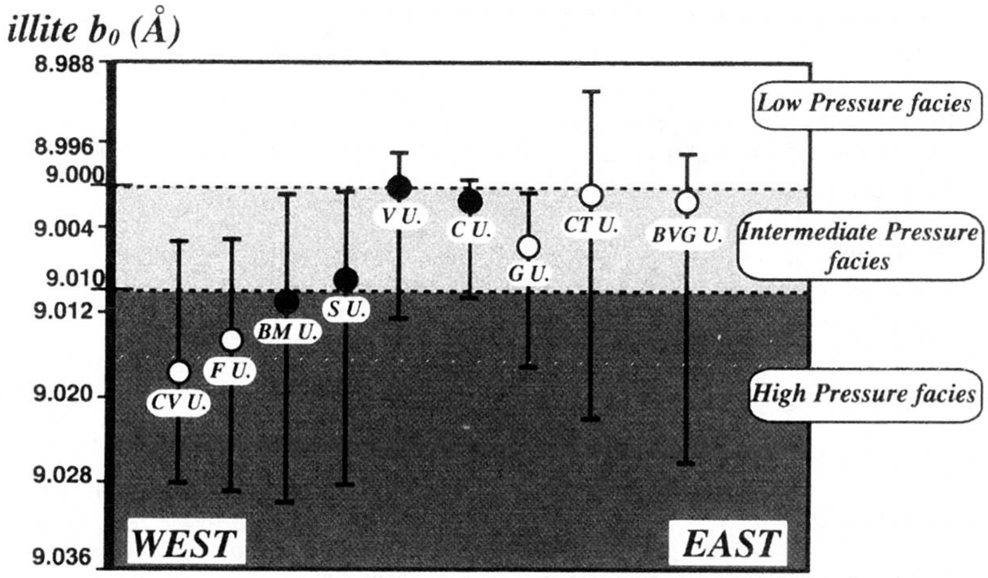

Fig. 11 Illite *b* cell parameter (b_0) distribution and succession of baric types in the Internal Liguride Units along an ideal west to east transect. The b_0 boundaries between the pressure facies series of MIYASHIRO (1961) are from FRANCESCHELLI et al. (1989) for Al-rich low-variance assemblages. Symbols as in figure 10.

check the general pattern of decreasing metamorphic grade from west to east established using mica parameters.

Concluding remarks

The clay mineral assemblages observed and crystallochemical parameters of illite and chlorite obtained from rocks in the turbiditic sequences of the Valpolcevera-Valle Scrivia zone (Central Liguria, NW Italy), support the geological setting suggested by ELLERO (2000). Such sequences cannot be considered in stratigraphic continuity with the underlying Figogna Unit, as previously suggested by CORTESOGNO and HACCARD (1984). The latter unit has a metamorphic grade characterized by thermal conditions corresponding to the upper anchizone (T = 270–320 °C; LEONI et al., 1996) and pressures typical of the low-grade blueschist facies (P = 6 kbar; LEONI et al., 1996), distinctly higher than those of the structurally deepest units of the Valpolcevera-Valle Scrivia zone (i.e. Bric Montaldo Unit and Serra Unit).

The structural setting suggested by MARINI (1989), which assumed a single unit sandwiched between Figogna and Antola units, is also rejected. The present study clearly shows that the metamorphic grade is not uniform across the Valpolcevera-Valle Scrivia zone , but varies from middle anchizonal in the west to diagenetic in the east, with evident changes in grade between the different units proposed by ELLERO (2000) (Fig. 6).

The considerable difference in the mean *b* cell parameter value, and thus in the baric conditions, between the Serra and the Vallecalda units suggests that their boundary represents a low-angle normal fault, where a small amount of crustal thinning occurred during the exhumation of the IL units.

Overall, the data collected imply that the Valpolcevera-Valle Scrivia units were underplated at distinctly shallower levels than those reached by the IL westernmost units (units of the Sestri/Voltaggio zone, namely Cravasco/Voltaggio Unit and Figogna Unit) (Figs 10 and 11). The former have characteristics that point to a metamorphic history similar to that of the IL easternmost units. More precisely, the metamorphic grade of Bric Montaldo and Serra units matches fairly well that of the Gottero Unit, whereas the metamorphic conditions estimated for the Vallecalda and Ciaè units are more akin to those established by LEONI et al. (1996) for Colli/Tavarone and Bracco/Val Graveglia units.

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