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The crystalline basements of the Italian eastern Alps: a review of the metamorphic features

FRANCESCO PAOLO SASSI[1,2]*, BERNARDO CESARE[1,2], CLAUDIO MAZZOLI[1,2], LUCA PERUZZO[2], RAFFAELE SASSI[1] and RICHARD SPIESS[1,2]

[1] Dipartimento di Mineralogia e Petrologia, Università di Padova, Corso Garibaldi 37, 35137 Padova
[2] Istituto di Geoscienze e Georisorse, CNR, Sezione di Padova, Corso Garibaldi 37, 35137 Padova

ABSTRACT. — We briefly review the state of the art on the metamorphic evolution of the crystalline basements of the Eastern Alps, with emphasis on the Italian sector. For each of the main structural units, Penninic, Austroalpine and Southalpine, we present a short outline followed by the most recent results obtained by the research team of metamorphic petrology operating at the University of Padova.

RIASSUNTO. — Questo lavoro riassume lo stato delle conoscenze sull'evoluzione dei basamenti cristallini delle Alpi Orientali, con particolare attenzione al settore Italiano. Per ciascuna delle principali unità strutturali, Pennidico, Austroalpino e Sudalpino, viene presentata una breve descrizione seguita dai più recenti risultati ottenuti dal gruppo di ricerca di petrologia metamorfica operante presso l'Università di Padova.

KEY WORDS: *Eastern Alps, metamorphic events, metamorphic features, metamorphic petrology.*

INTRODUCTION

This paper is a review of the present knowledge on the crystalline basements (**CB**s) of the Italian Eastern Alps (**EA**), addressed to outline their main metamorphic features and to highlight some recent scientific results obtained by the authors.

Therefore, the present paper is not an exhaustive and homogeneous picture of the CBs of the EA, but mainly reflects the scientific research carried out by the metamorphic petrology team at the University of Padova.

In order to shorten the text as much as possible, the following abbreviations have been used:

AA = Austroalpine; **CB** and **CBs** = Crystalline Basement(s); **CC** = Carbonate Complex; **CG** = Centralgneiss; **DAV** = Defereggen-Anterselva-Valles; **EA** = Eastern Alps; **IL** = Insubric (or Periadriatic) Line; **KV** = Kalkstein-Vallarga; **LPC** = Lower Pelitic Complex; **OCB** = Old Crystalline Basement; **PE** = Penninic; **SA** = Southalpine; **SC** = Schneeberg Complex; **TW** = Tauern Window; **UPC** = Upper Pelitic Complex; **VSC** = Volcano-Sedimentary Complex.

REGIONAL GEOLOGICAL OUTLINES

CBs are rock complexes, which formed before various stages of Late Carboniferous-Permo-Triassic transgressions. They occur in

* Corresponding author, E-mail: francesco.sassi@unipd.it

each of the three major structural units of the EA, *i.e.* the Penninic, the Austroalpine and the Southalpine units (from the deepest to the shallowest; Figs. 1, 2, 3).

Before the Alpine orogenesis, the PE-CB was part of the southern margin of the European plate, which collided in late-Mesozoic to Tertiary times with a promontory of the Africa plate (the Adria microplate) leading to the closure of the PE-Tethyan Ocean. The AA and the SA-CBs were located in the northern margin of the Adria microplate. All these CBs were involved in the Alpine orogeny, and parts of them were also affected by a variously aged Alpine metamorphism. Specifically, the PE-CB fully underwent the Tertiary metamorphism, whereas only parts of the AA-CBs were affected by various stages of Alpine metamorphic overprint of different intensities. In some cases these overprints completely obliterated the pre-Alpine metamorphic features (as in the Monteneve/Schneeberg Complex); in other areas, as in Pusteria north of the Defereggen-Anterselva-Valles fault, the pre-Alpine metamorphic features partially survived to the Alpine metamorphic overprint. Overall, large parts of the AA-CBs, as well as the whole SA-CB, escaped the Alpine metamorphic overprint.

The major thrust contact in the considered area is the tectonic boundary between the PE (to the north) and the AA (to the south). It represents the contact between the northern margin of the Adria microplate and the ophiolitic sequence resulting from the closure of the PE-Tethyan ocean. The latter sequence tectonically overlies the rocks of the European southern continental margin, specifically the Variscan granitoids, and their probable Palaeozoic cover. The northern margin of the Adria microplate is cut by the EW trending tectonic Insubric Line (**IL**), which separates the AA from the SA Alpine structural domains. This fault, a dextral transpressive strike-slip fault (Laubscher, 1983; Schmid *et al.*, 1989), was strongly active during the Alpine orogenesis. However, evidence exists that a significant part of the vertical offset is pre-Alpine (Sassi *et al.*, 1994).

Two major E-W trending tectonic lines also cut the AA-CB block: the above-mentioned DAV and the Kalkstein-Vallarga faults. The DAV delimits towards the south the Tertiary metamorphic overprint. These two faults merge westwards close to the IL. A western equivalent of the DAV may be seen in the Giovo-Jaufen fault (Spiess, 1995).

THE PENNINIC UNITS OF THE TAUERN WINDOW

General outlines

The Tauern Window is the largest tectonic window of the Alps, and exposes rocks of palaeo-European affinity along with the oceanic units, which separate them from the overlying AA nappes (e.g. Frisch *et al.*, 1993, and references therein). The PE units are composed of a polymetamorphic pre-Variscan basement (Habach-Storz and Stubach Groups; Neubauer *et al.*, 1999, and references therein), of a Variscan batholith corresponding to the Centralgneiss (e.g. Finger *et al.*, 1993), of its (para)autochthonous metasedimentary and metavolcanic cover (Lower Schieferhülle) and of the allochthonous oceanic sequences of the Upper Schieferhülle (Morteani, 1974; Finger *et al.*, 1993; Frisch *et al.*, 1993; Lammerer and Weger, 1998, and references therein).

The TW is a type-area for the study of the metamorphic P-T-t paths associated with continental collision, subduction and exhumation (see Spear, 1993): in its central-southern sector, metabasites and metasediments of the Eclogite Zone allowed reconstruction of a P-T loop which developed during the Alpine orogeny and records progressive subduction up to P>20 kbar followed by a multi-stage decompression history (see Kurz *et al.*, 1998 and Hoinkes *et al.*, 1999 for recent reviews of the extensive literature on the Eclogite Zone). Along the Alpine decompressional path, rocks of the TW often display a slight rise in temperature, up to 650°C, accompanied by extensive post-tectonic recrystallization. Such a

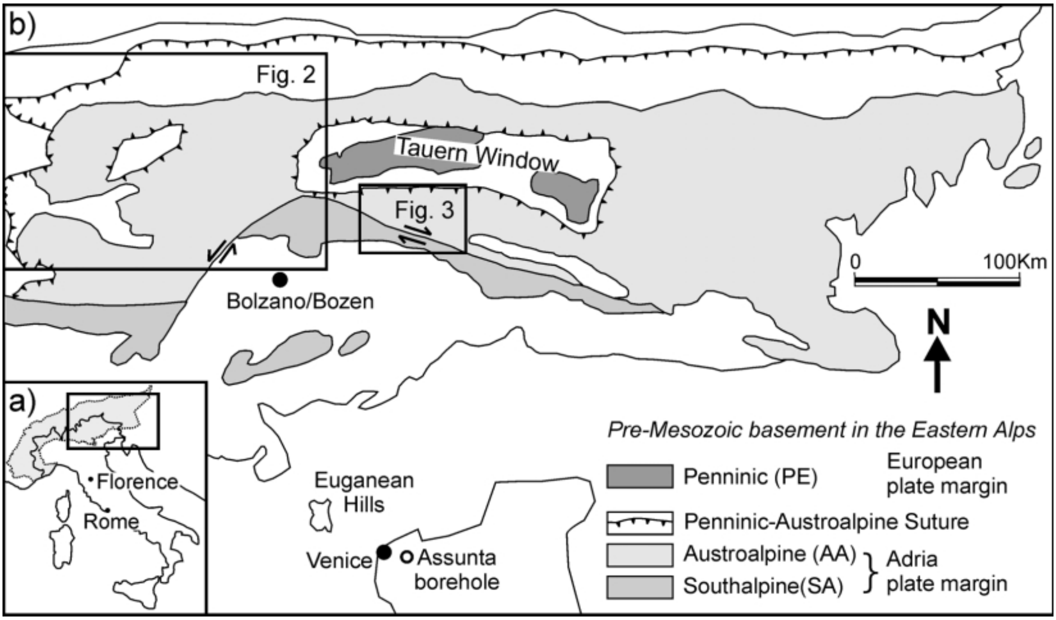

Fig. 1 – Simplified sketch map of the Eastern Alps, showing the main structural units, the location of Figs. 2 and 3 and the Assunta borehole.

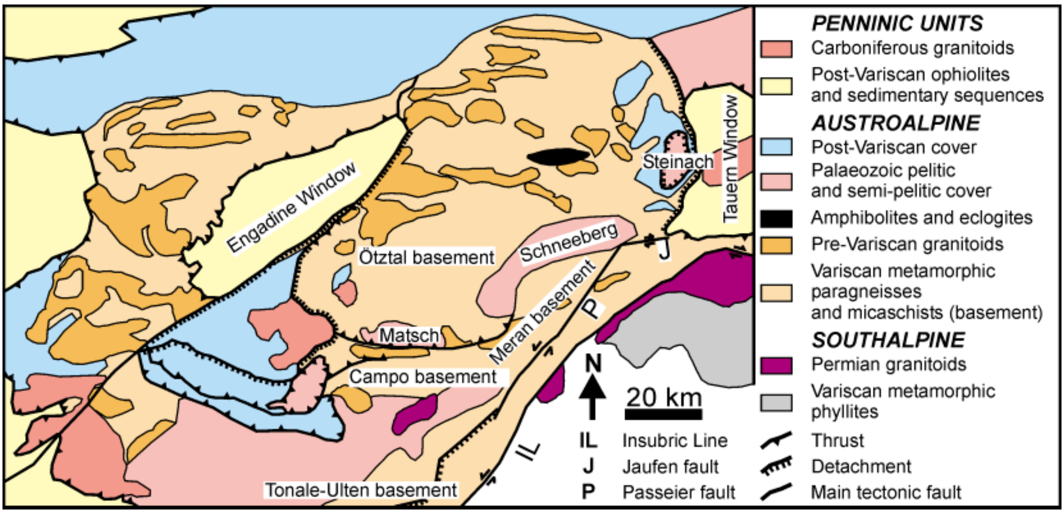

Fig. 2 – Geological sketch map of the western Astroalpine area (from Spiess *et al.*, 2001a, with changes).

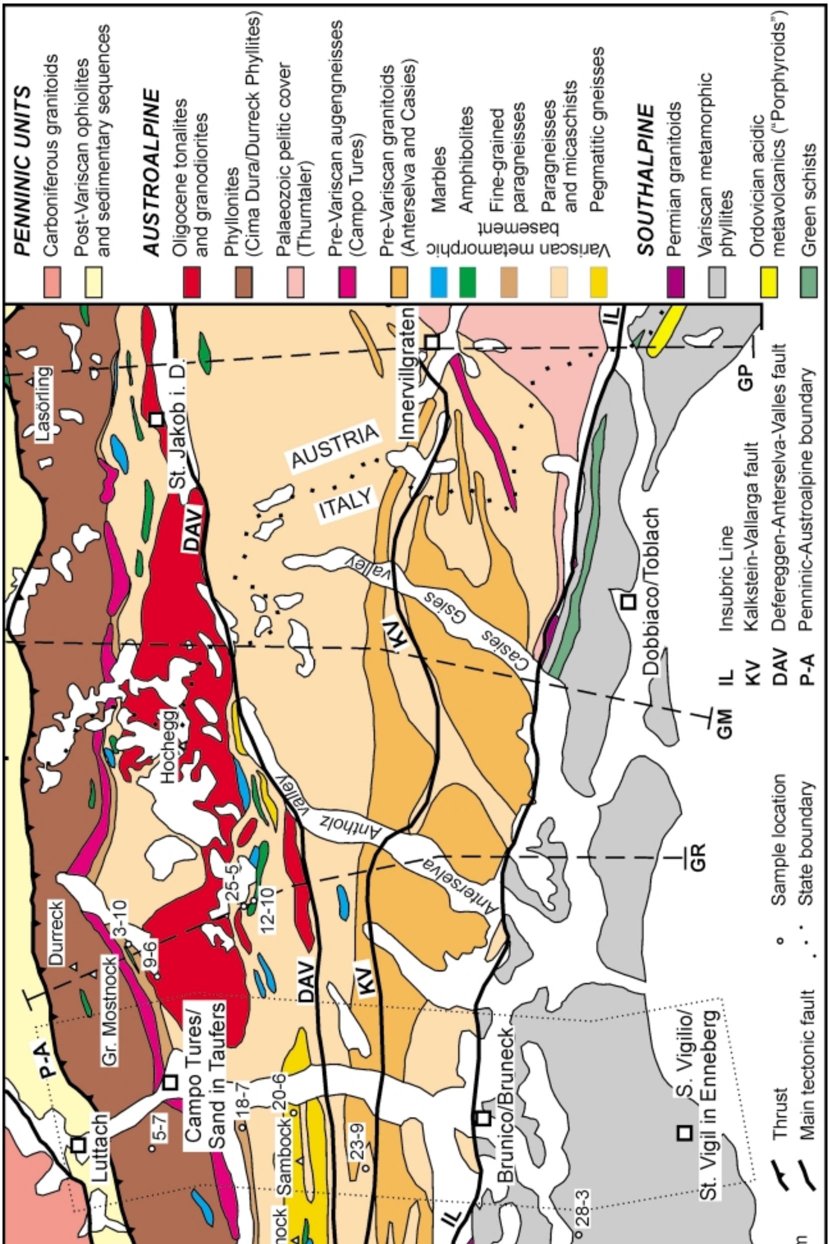

Fig. 3 – Geological sketch map of the eastern Astroalpine area, with the location of the geological sections shown in Fig. 4 (dashed lines GR, GM, GP), the CROP profile (dotted line) and the ten rock samples on which petrophysical measurements have been carried out (from Mazzoli *et al.*, 2003, with changes).

thermal peak and zoneography (see e.g. Hoernes and Friedrichsen, 1974) have been defined as the «Tauern Metamorphism» (Sander, 1921) and is considered Oligocene in age (Christensen *et al.*, 1994).

Concerning the SW sector of the TW, partly outcropping in the Italian territory, two aspects can be pointed out: 1) the Alpine P-T-t paths do not show evidence for P>10 kbar (e.g. Selverstone *et al.*, 1984), i.e., no eclogites have been found so far; 2) most of the geologic information is restricted to the peripheral Lower and Upper Schieferhülle units, since thermobarometric data from the CG are limited to the Oligocene event of the Tauern Metamorphism.

In the TW special attention has been devoted to the interactions between metamorphism, fluids and deformation (e.g. Friedrichsen and Morteani, 1979; Brunsmann *et al.*, 2000, 2001; Steffen *et al.*, 2001; Selverstone and Hyatt, 2003) with substantial support from fluid inclusion studies (e.g. Luckscheiter and Morteani, 1980; Selverstone *et al.*, 1992, 1995; Axen *et al.*, 2001). These works have focused on the behaviour of either metabasites or graphitic metasediments, describing fluid-rock-deformation interactions both at HP conditions and during the later exhumation and thermal relaxation of the rocks.

Some recent petrological highlights

Some recent results obtained by the team of Padova are shortly presented below.

– As summarized by Hoinkes *et al.* (1999) the rocks of the SW TW hardly preserve any evidence for the ***compressional path related to Alpine subduction***. One exception is represented by the Ms-Pg association (Fig. 5a) found in some Grt-Cld-bearing schists of the Lower Schieferhülle (Mazzoli *et al.*, 2001). The microstructural, microchemical and TEM investigation of this peculiar association provide further constraints to the Ms-Pg solvus and to the reactions involving the K-Na white micas, and indicate that it formed by an increase in pressure related to the Eo-Alpine metamorphism.

– Within the CG complex of the SW TW, the ***discovery of fresh ultramafic cumulates within the Variscan granitoids has been recently reported***. These rocks and the intruding metagranodiorites have been dated by SHRIMP on zircons at 309±5 and 295±3 Ma, respectively (Cesare *et al.*, 2002a). Therefore, the cumulates attest for the early stages of late Carboniferous calc-alkaline plutonic activity. Additionally, these ultramafics show evidence of a complex Alpine metamorphic history, ranging from coronitic to complete amphibolitization. The P-T conditions of the two-stage, pseudomorphic and coronitic alteration have been constrained at P = 9.4 kbar, T = 660°C and P = 12 kbar, T = 790°C (Gomez-Pugnaire, unp. data), and represent the first evidence of P>10 kbar from within the CG and from the SW TW. Research on the metagranitoids of the CG has also led to new results on fluid-rock interactions. A study of H_2O-CO_2-NaCl fluid inclusion by Cesare *et al.* (2001) supports the conclusion that some discordant Bt-Pl-bearing veins formed by a mechanism of synmetamorphic veining during the isothermal decompression, which affected the granitoids.

THE AUSTROALPINE BASEMENTS

General outlines

The AA-CB is a polymetamorphic, amphibolite facies, pre-Alpine basement, on which a Permo-Triassic cover, mainly affected by low-grade metamorphism, locally occurs. The prevailing rock types making up this basement are paragneisses and micaschists (locally grading to migmatites), in which orthogneisses, amphibolites, quartzites and marbles are interlayered. Eclogites, metabasites and metaultramafics locally occur.

The structural setting is quite complex, due to the overlapping of Alpine folding, thrusting and faulting, onto rocks previously affected by variously aged pre-Alpine deformation and metamorphism. As a consequence, the original rock sequences were variously dismembered,

tectonically transposed and shortened, so that the same rock types acquired different petrographic features, making it difficult to reconstruct the original stratigraphic sequences.

The existence of a «Caledonian» regional event, including eclogite production, metamorphism, magmatism and deformational activity, has been debated for a long time. After the first proposal by Sassi and Zanferrari (1972) and Purtscheller and Sassi (1975), this idea having been supported also by radiometric age data (Borsi *et al.*, 1973; Sassi *et al.*, 1985, and references therein; see Section «The western area» for more recent data), found increasing international agreement (Bögel *et al.*, 1979; Sassi and Schmidt, 1982). Today, this event, between 520 and 450 Ma, is widely accepted and better defined (e.g. Becker *et al.*, 1987; Ebner *et al.*, 1987; Frisch *et al.*, 1987; Sassi *et al.*, 1987; as well as many papers in von Raumer and Neubauer, 1993; and more recent literature quoted in the Section «The western area»).

The main characteristics of the AA-CBs vary from west to east, so that it is convenient to describe separately the western and the eastern areas. The former is mainly characterized by the abundance of Upper Ordovician granitoids (now orthogneisses), some significant pre-Permian marble horizons, the vestiges of the so-called «*Schlingen tectonics*», and the presence of an important belt affected by amphibolite facies Upper Cretaceous metamorphism related to high and intermediate P conditions (Schneeberg Complex). The eastern area is characterized by Tertiary granitoid bodies intruded and shaped along an E-W lineament, the presence of pre-Westphalian phyllitic sequences, and the occurrence of a Tertiary, low-grade metamorphic overprint localized in the lowermost (and northernmost) part of the AA structural unit and bounded southward by the DAV fault.

The western area

Here the basement is chiefly formed by distinct units (Fig. 2). We distinguish the Ötztal basement with the overlying Mazia/Matsch nappe in the NW, which is confined southeastwards by the SC and the underlying Merano basement, and to the south by the Campo and the Tonale-Ulten basements. There are significant differences between both the lithological assemblages and the metamorphic evolution preserved within these units. Large parts of these CBs have been involved in the Variscan orogeny, and only some units were pervasively overprinted by the Alpine event. As a consequence, the Variscan and the Alpine metamorphic evolutions are relatively well understood, whereas the knowledge of the pre-Variscan «Caledonian» evolution is still patchy.

Evidence for an extensional tectonic regime in late Cambrian times tracing the beginning of the «Caledonian» cycle comes from geochemical and isotopic data of metabasites of the Ötztal basement (Miller and Thöni, 1995). The magma source of these metabasites had a MORB-type affinity, and their emplacement is constrained between 530 and 521 Ma by Sm-Nd mineral isochrons (Miller and Thöni, 1995). The metabasic rock suite of the central Ötztal basement may be regarded as an equivalent of the lithostratigraphic unit that Frisch *et al.* (1987, 1990) and Neubauer *et al.* (1989) called the ophiolitic Spike complex in the eastern AA. A compilation of Neoproterozoic to early Ordovician ages (mostly U-Pb and Sm-Nd on zircons) by Neubauer (2002) refer to events of subduction, ophiolite formation and possible rifting in the Central and Southeast European mountain belt.

The most striking feature of the «Caledonian» evolution is the high thermal regime established during the Ordovician at about 450 Ma. In the Ötztal basement this resulted in crustal anatexis in the Winnebach (Hoinkes, 1973; Söllner and Schmidt, 1981; Söllner and Hansen, 1987; Chowanetz, 1991) and the Reschenpass areas (Schweigl, 1995), as well as in an extensive intrusion of granitoid melts (Borsi *et al.*, 1980; Sassi *et al.*, 1985; Thöni, 1986; Hoinkes *et al.*, 1997; Thöni, 1999), with a geochemical and an isotopic signature that largely supports a crustal origin.

A key point of the Variscan metamorphism

is the high thermal gradient that characterises its peak metamorphic conditions, which was first recognized by Sassi (1972) in the Steinach phyllites. The best place to study this pre-Alpine HT/LP metamorphism is the Matsch nappe, where metamorphic conditions change from lower greenschist to upper amphibolite facies within a ≤1 km thick metapelitic sequence (Gregnanin and Piccirillo, 1972; Toto, 2002). Recently Schuster *et al.* (2001) have proposed a Permian age for this metamorphism and for that of the Ötztal basement, but so far no age data confirm this hypothesis.

The HT-peak during the Variscan metamorphism was reached over a very short time interval following decompression. This is suggested by Sm-Nd dating of eclogites in the Ötztal basement (360 Ma: Miller and Thöni, 1995), garnet growth during decompression (343 Ma: Schweigl, 1995) and garnet decomposition at the thermal peak (331 Ma: Schweigl, 1995).

It is important to point out that Variscan extension in the Ötztal basement was accompanied by subduction elsewhere in the AA basement. This is supported by the reconstruction of the metamorphic evolution of the Tonale-Ulten unit, a lower crustal section (Morten and Obata, 1983; Godard *et al.*, 1996; Martin *et al.*, 1998; Bargossi *et al.*, 2003) that underwent eclogite facies metamorphism with widespread anatexis, and is characterized by the abundant occurrence of ultramafic bodies. U-Pb dating of zircons (Gebauer and Grünenfelder, 1978) and Sm-Nd plus Rb-Sr systematics of peridotites, eclogites and associated migmatites (Tumiati *et al.*, 2003) suggest an isotopic homogenisation at 330 Ma during subduction (Nimis and Morten, 2000).

The characteristics of the Eo-Alpine metamorphism within the AA-CB are particularly well exposed in the SC and in the underlying Merano/Meran basement. Here, crystallisation of staurolite (Zanettin and Justin-Visentin, 1971; Hoinkes *et al.*, 1987) and complete resetting of Rb-Sr white mica ages (Satir, 1975; Del Moro *et al.*, 1982; Thöni, 1983) testify for Alpine amphibolite facies peak conditions, as previously suggested by Zanettin and Justin-Visentin (1971). The occurrence of a major deformation event during the Eo-alpine metamorphism within the SC-Merano basement has been debated for a long time (Van Gool *et al.*, 1987). A major contribution for the solution of this problem was given by Schmid and Haas (1989), who recognized that large scale fold structures (hitherto considered to be of Variscan age) at the SW-end of the SC are associated with Alpine mylonites along an intrabasement detachment zone. It is now ascertained that the Eo-alpine metamorphism evolved from high pressures (Sassi, 1972; Hoinkes *et al.*, 1991; Spiess, 1991a; Gregnanin and Valle, 1995; Gregnanin *et al.*, 1995; Konzett and Hoinkes, 1996) associated with intense shearing towards the west (Sölva *et al.*, 2001), to amphibolite facies conditions during uplifting and extension (Spalla 1990, 1993; Gregnanin and Valle, 1995; Gregnanin *et al.*, 1995; Sölva, 2001). The metamorphic peak was reached at about 90 Ma, whereas cooling below amphibolite facies conditions occurred during exhumation at ca. 80 Ma (Thöni, 1983, 1986, 1999). The distribution of the amphibolite facies metamorphism within the SC-Merano basement is controlled by the evolution of Cretaceous low angle normal faults relating to exhumation of the deeper crustal basement (Dibona *et al.*, 2003).

The eastern area

In the eastern area (Fig. 3) the AA-CB mostly consists of medium to high grade rock sequences, tightly folded with steep EW-striking axial planes (Fig. 4), and phyllitic sequences squeezed into fold cores. Readers are referred to Sassi and Zirpoli (1989) and Mazzoli *et al.* (2000) for the medium- to high-grade areas, and to Neubauer and Sassi (1993) and Sassi *et al.* (1994) for the phyllitic sequences. A description of the area can be found in Mazzoli *et al.* (2003).

Notwithstanding the widespread polymetamorphism and polycyclic tectonic

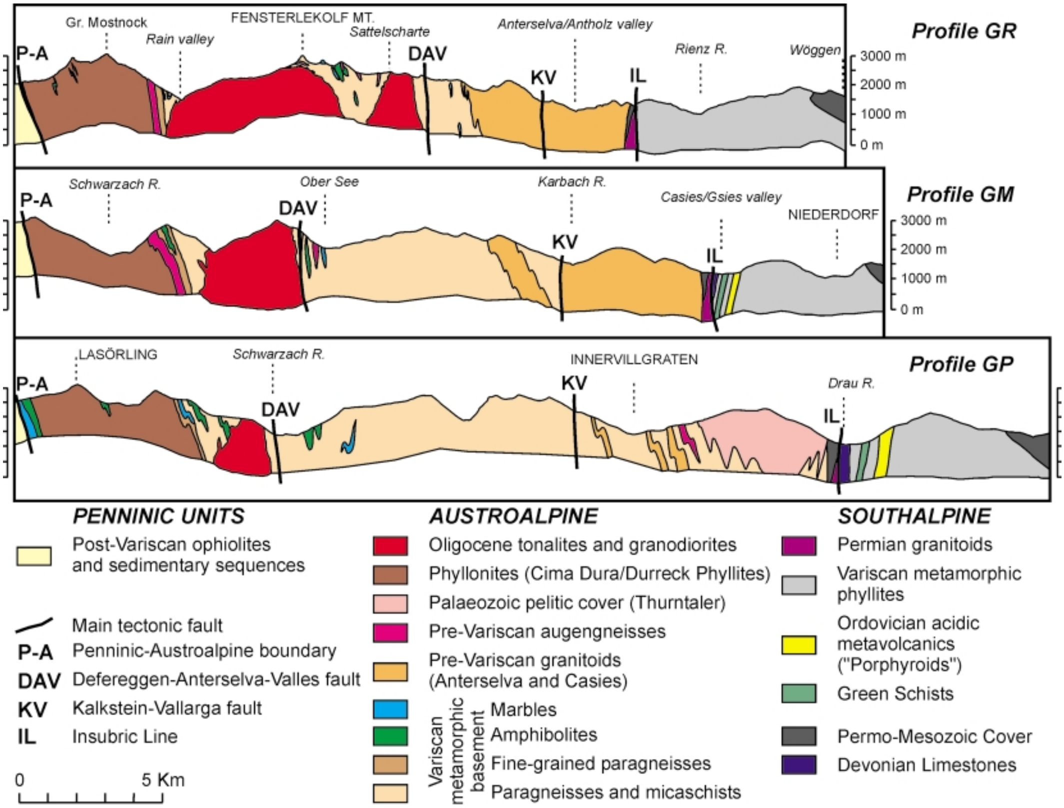

Fig. 4 – Geological cross sections GR and GP respectively show a «granitoid»-rich and a «granitoid»-poor situation, whereas GM represents a situation with an intermediate amount of «granitoids», in the area of Fig. 2. The sections GM and GP are respectively the profiles D and E of Borsi *et al.* (1978), slightly modified and simplified (taken from Mazzoli *et al.*, 2003, with changes).

reworking, some systematic similarities do exist among the rock sequences outcropping in the various sectors of the AA-CB, and some lithologic elements can be used as key-horizons for inter-sector correlations. On this basis, an interpretative lithostratigraphic sequence has been proposed (Sassi and Zirpoli, 1989), and data supporting this model can be found in Becker *et al.* (1987), Ebner *et al.* (1987) and Frisch *et al.* (1987). This sequence considers: *a)* an old crystalline basement, assumed to be pre-Caradocian (**OCB**); *b)* a lower pelitic-psammitic complex, assumed to be Ordovician (**LPC**); *c)* a volcano-sedimentary complex, assumed to be mainly Upper Ordovician (**VSC**); *d)* an upper pelitic-psammitic complex, assumed to be Silurian (**UPC**); *e)* a carbonate complex, assumed as Silurian-Devonian (**CC**).

Roughly, OCB, LPC and VSC mainly occur as medium-grade rocks to the north of the DAV fault; VSC, UPC and CC make up the AA phyllitic complexes (Neubauer and Sassi, 1993; Sassi *et al.*, 1994), and probably parts of the so-called Cima Dura/Durreck Complex (Mazzoli *et al.*, 1993, 1994), and the SC mentioned in the Section «The western area».

The OCB mainly consists of paragneisses and micaschists (and locally migmatites), in which several rock types are conformably

interlayered: acidic sheet-like gneisses, amphibolites and quartzites. Eclogites locally occur as boudins. Some amphibolites are genetically related to retrograde hydration of eclogites, others display intimate field relationships with the sheet-like acidic gneisses and marbles (in the VSC), most of them are conformably interlayered within the paragneisses (in the OCB). Metagranitoids (mainly granodioritic orthogneisses) make up numerous and variously sized bodies, interpreted as Upper Ordovician igneous intrusions in the OCB (Borsi *et al.*, 1973; Peccerillo *et al.*, 1979; Mazzoli and Sassi, 1992). It is worth to point out that the Upper Ordovician magmatism is volumetrically the most important magmatic activity recorded in the EA. It developed in both plutonic and volcanic conditions. The latter products are the protoliths of the above-mentioned sheet-like acidic gneisses (and probably of a part of the amphibolites) which have been described as forming a volcanic plateau within the VSC. As a whole, the Upper Ordovician magmatic rocks have been interpreted as a typical granite-rhyolite association (Bellieni and Sassi, 1981) of calc-alkaline affinity belonging to the «Caledonian» cycle.

The pre-Alpine metamorphic effects are mostly Variscan but vestiges of the «Caledonian» metamorphism have also been recognized (Borsi *et al.*, 1973; Sassi and Schmidt, 1982; Sassi *et al.*, 1987). To the south of the DAV fault, the attribution of the mineral assemblages to the Variscan or pre-Variscan events is still debated (e.g. Schulz *et al.*, 1993, and references quoted therein), and further specific radiometric geochronological work is necessary. Recent Pb-Pb evaporation analyses display Cambrian to early Ordovician ages of protolith formation (Schulz and Bombach, 2003). Sm-Nd data suggest a Cretaceous age for the eclogite metamorphism in the Schobergruppe (Linner, 1999).

As concerns Alpine metamorphism, disregarding the possible Cretaceous overprint (Borsi *et al.*, 1973; Stöckhert, 1984; Prochaska, 1981), Tertiary Alpine overprint occurs to the north of the DAV fault. It affected a large part of OCB, but also part of LPC and VSC.

Numerous «Periadriatic» plutons intruded the AA-CB during the Oligocene (Borsi *et al.*, 1978, 1979; Romer and Siegesmund, 2003). The largest of them is Vedrette di Ries/Rieserferner (Bellieni *et al.*, 1981; Steenken *et al.*, 2000). The EW alignment of these plutonic bodies along a belt in which a sheaf of tectonic lines occur (the major of which being the DAV), and their general EW elongated shape, indicate a strong structural control on uprise and emplacement of the magmas (Borsi *et al.*, 1978; Blanckenburg *et al.*, 1998).

Some recent petrological highlights

Some recent results obtained by the team of Padova are shortly presented below.

– A particular geodynamic setting is required to explain *Variscan* ***extensional tectonics in the Ötztal basement*** and HT/LP metamorphism in the Matsch nappe ***contemporaneous to*** *Variscan* ***subduction*** of crustal rocks in the Tonale-Ulten basement. A potential explanation for such a scenario is that extension and high T metamorphism were triggered by crustal-mantle lithosphere decoupling in an overall compressional regime (Spiess *et al.*, 2001a).

– Reconstruction of the ***P-T-t trajectory in metapelites of the Ötztal basement*** suggests that thermal relaxation leading to a high thermal gradient during the Variscan metamorphic peak happened after almost isothermal thinning of a strongly shortened crust to half of its original thickness (Spiess *et al.*, 2000: Fig. 5b).

– Spiess (1995), Spiess *et al.* (2001b) and Viola *et al.* (2001) recognised that the evolution of Tertiary sinistral transpressive faults relates to the indentation of the Southern Alps and influenced the distribution of the ***amphibolite facies metamorphism within the SC-Merano basement***.

– The ***boundary between the Merano basement and SC*** has been studied at the western end of the SC (Peruzzo, 1998). In

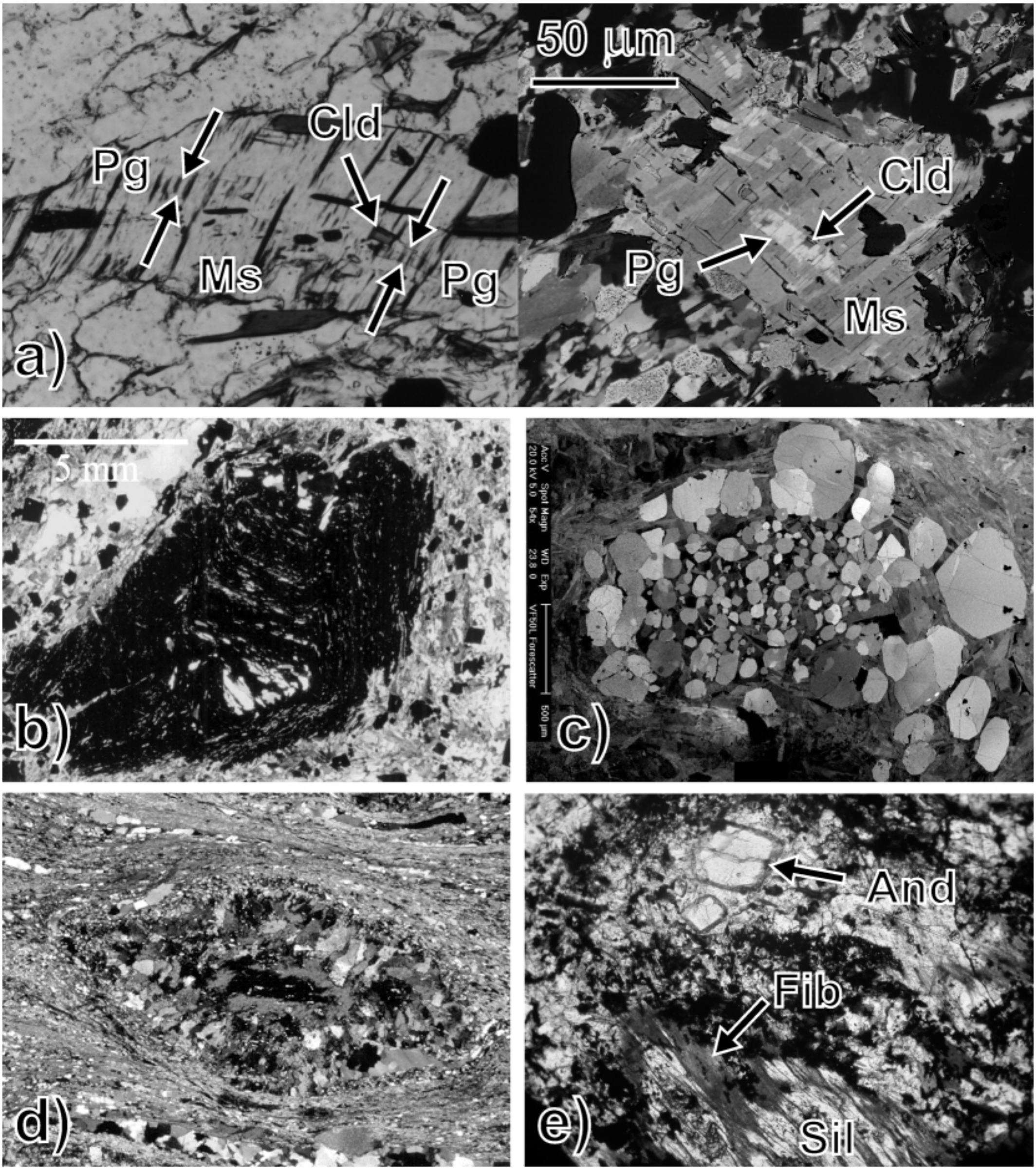

Fig. 5 – a) Photomicrographs of the Ms-Pg associations found in the Grt-Cld-bearing schists of the Lower Schieferhülle (Mazzoli *et al.*, 2001). b) Garnet porphyroblast grown within metapelites of the Ötztal basement: the episodic growth of the porphyroblast, revealed by the systematic interrelationship between inclusion trail geometry and changing nature and composition of minerals forming the inclusion trails, allowed a complete reconstruction of the Variscan P-T-t trajectory (taken from Spiess *et al.*, 2000). c) SEM Orientation Contrast image of type 1 garnet porphyroblast from SC (Spiess *et al.*, 2001c). d) K-feldspar porphyroclast rimmed by myrmekite in mylonitic orthogneisses from the contact aureole of Vedrette di Ries (Cesare *et al.*, 2002b). e) Metapelitic xenoliths trapped within trachytes from the Euganean Hills. Fibrolite (Fib) nucleating at the grain boundaries of sillimanite prisms; no fibrolite nucleates on andalusite (And) (Sassi *et al.*, 2004).

particular, the geochemical characters of metapelites coming from different units have been used to define the exact extension of the SC in that area (Peruzzo and Busà, 2001).

– Detailed SEM based studies (EBSD, OC, XRM) of different garnet porphyroblast types occurring within the micaschists of the western SC allowed to establish a new conceptual and numerical ***model of garnet porphyroblast formation***, implying multiple nucleation, coalescence and misorientation driven rotation of single garnet grains (Fig. 5c: Spiess *et al.*, 2001c; Dobbs *et al.*, 2003).

– All ***AA quartzphyllites*** and related clastic- and volcanic-rich sequences have been interpreted as the products of a single basin that evolved from a back-arc basin during the Ordovician through a rifting basin during the Silurian and the Early Devonian to a passive margin during the Middle to the Late Devonian. The closure of this basin occurred from the Visean to the Early Westphalian (Neubauer and Sassi, 1993).

– Pervasive mylonitic effects and contrasting mineral assemblages in the ***phyllonites of the Cima Dura/Durreck Complex*** were interpreted as the deformational-metamorphic Alpine overprint on a Variscan paragneissic basement covered by a sequence of phyllites. A later, water-controlled, retrograde alteration, irregularly distributed and localized along anastomosing bands, suggests a channelized fluid flow during Late-Alpine overprint (Mazzoli *et al.*, 1993, 1994).

– The ***Upper Ordovician acidic plutonism and volcanism*** have been considered the product of a unique magmatic cycle that produced a huge amount of acidic melts with calc-alkaline affinity. They include AA orthogneisses, sheet-like granitoids, augengneisses and «porphyroids», and SA «porphyroids». Petrographic, geochemical, isotopic and field data indicate that the most appropriate genetic process is crustal anatexis with some subcrustal contribution. The huge amount of melts within a large crustal volume indicates that the Ordovician crust was affected by an important heat flow increase, consistent with a crustal thickening process (Mazzoli and Sassi, 1992).

– Constraints on the interpretation of the seismic reflectors, such as those recognised and published by the TRANSALP Working Group (2002), have been provided by measuring the ***seismic properties of the volumetrically more relevant rock types*** of the eastern AA Basement of the EA (Mazzoli *et al.*, 2002). The location of the samples used for such petrophysical measurements is shown in Fig. 3.

– The ***abundance of 55 elements*** in volumetrically relevant rock types from the Aurina/Ahrntal-Pusteria/Pustertal valleys area, ***in combination with petrovolumetric estimates*** based on detailed N-S geological transects has been used for proposing a model for the average crust composition in the EA (Mazzoli *et al.*, 2003). This was a result of a National project which used specific standardized procedures (Burlini *et al.*, 2003).

– In the ***southern contact aureole of VR***, the metapelitic country rocks have been divided into six mineralogical zones (Cesare, 1992) that correspond to type 2*bii* of the facies series scheme of Pattison and Tracy (1991). Therefore, the pressure of contact metamorphism is in the range 3.5-4.5 kbar if the Al_2SiO_5 triple point of Pattison (1992) is adopted. The peak temperature conditions have been estimated at 600-620°C by Cesare (1994a).

– One of the peculiarities of the ***contact aureole of VR*** is the occurrence of andalusite-bearing veins. Based on their field, petrological and fluid inclusion characterization (Cesare, 1994b; Cesare and Hollister, 1995), the genesis of these veins has been explained via the «***synmetamorphic veining***» model, i.e., that veins formed by hydrofracturing during the progress of And-producing devolatilization reactions. Other studies performed on the contact aureole of VR include the TEM characterization of the topotactic replacement of kyanite by staurolite (Cesare and Grobety, 1995), the modelling of the reaction producing hercynite by the breakdown of staurolite (Cesare, 1994a), the microstructural and mass

balance modelling of the polymetamorphic evolution of a primary garnet site (Cesare, 1999a,b), and the study of myrmekite coronas around K-feldspar porphyroclasts in mylonitic orthogneisses (Fig. 5d: Cesare *et al.*, 2002b).

– Evidence of contact metamorphism, with And-St mineral assemblages identical to those observed at VR, has been found in the area of M. Sommo/Sambock, NW of Brunico/Bruneck. As Oligocene plutonic rocks do not outcrop in this area, these assemblages have been referred to the presence at shallow depth of a ***hypothetical buried intrusion*** (Moretti and Mazzoli, 2000).

THE SOUTHALPINE BASEMENT

Geological outlines and lithostratigraphy

The metamorphic SA-CB of the EA outcrops in three main areas: *(i)* a northern, approximately E-W trending belt, from the Sarentino/Sarntal Valley through Bressanone/Brixen-Pusteria/Pustertal to Comelico; *(ii)* an intermediate, approximately SW-NE trending belt, from Valsugana through Cima d'Asta to Agordo; *(iii)* a southern area, the Recoaro-Schio area. The SA-CB consists of thick phyllitic sequences, in which a lower pelitic complex (**LPC**), an intermediate volcano-sedimentary complex (**VSC**) and an upper pelitic complex (**UPC**) have been distinguished by Sassi and Zirpoli (1989). The LPC mainly consists of quartz-phyllites, in which mica-rich and quartz + albite-rich bands are repeatedly interlayered as effects of synkinematic metamorphic differentiation, which enhanced and transposed primary sedimentary banding. The VSC consists of a pelitic-psammitic sequence in which many intercalations characteristically occur. They are: a) acidic metavolcanics and metavolcaniclastics (the so-called «porphyroids»: Bellieni and Sassi, 1981; Meli, 1998; Meli and Kloetzli, 2001); b) a discontinuous horizon of basic metavolcanics and metavolcanoclastics, now represented by epidote-chlorite ± actinolite schists and albite-epidote amphibolites; c) Fe, Cu, (Zn, Pb) «*kieslager*» type mineralizations, mainly associated to the basic metavolcanics (Frizzo, 1983); d) ilmenite-rich phyllites; e) a discontinuous horizon of carbonate-bearing phyllites grading to carbonate schists; f) a discontinuous thin layer of white quartzites; g) black (carbonaceous) phyllites and quartzites. UPC and LPC display identical metamorphic and microstructural features (with some few exceptions, e.g. the local occurrence of carbonate layers in the former). Consequently, they can only be distinguished on the basis of their positions respectively below or above the VSC.

As regards sedimentation age, the available biostratigraphic data unfortunately refer to a single locality. An acritarch assemblage found at Col di Foglia (near Agordo), suggests a Late Cambrian to Tremadocian age (Sassi *et al.*, 1984; Kalvacheva *et al.*, 1986), that is the oldest sedimentation age recorded in the metamorphic SA-CB of the whole Alps. It is worth mentioning that Ordovician-Silurian palynomorphs were also found in the Central Southern Alps (Gansser and Pantić, 1988).

Metamorphism

The SA-CB was affected by the two-episode Variscan metamorphism (for geochronological details: see Sassi *et al.*, in this Volume; and Meli, 2004), which covers the whole temperature range of the greenschist-facies, and took place under low pressure conditions. A metamorphic thermal gradient of about 40°C/km was estimated (Mazzoli and Sassi, 1988; Arkai *et al.*, 1991; Sassi and Spiess, 1993), and a similar value was obtained in Carnia by means of basin modelling by Rantitsch (1997).

Eastwards, in Carnia, the metamorphic SA-CB sharply disappears, at the Val Bordaglia fault, to the east of which a subgreenschist-facies Palaeozoic sequence prevails (Sassi *et al.*, 1995; Läufer *et al.*, 2001; Brime *et al.*, 2003; Sassi *et al.*, in this Volume). It overlies the above mentioned acidic metavolcanic horizon, and mainly consists of Silurian and

Devonian sediments deformed by a poliphase, Variscan and Alpine, tectonics.

As concerns the regional metamorphic zoning, Sassi and Zirpoli (1968) and Sassi *et al.* (1974) pointed out an increase in metamorphic grade from the est (Comelico area: chlorite zone) to the west (Sarentino/Sarntal Alps: almandine zone), and from the south (Recoaro area: mainly chlorite zone) to the north (Sarentino Alps). However, such a pattern cannot be directly related to the palaeogeothermal gradient. In fact, unbelievably low values of the thermal gradient are obtained, due to the wide spacing of the mineral zones in map view, in sharp contrast with the relatively high thermal gradient which has been estimated (see above). Mazzoli and Sassi (1988) pointed out that the above mentioned regional pattern is a combined result of regional folding of the isothermal surfaces, and different depths of erosion (see Fig. 3 in Sassi *et al.*, this Volume).

It is worth pointing out here that the vanishing of the Variscan metamorphism towards the south is consistent with the lack of Variscan metamorphic effects in the Venice Llandelian granodiorite (Meli and Sassi, 2003a, b).

Two main Palaeozoic magmatic events are recorded in the SA-CB, respectively of Upper Ordovician and Permian age. During Upper Ordovician a very strong, prevailingly acidic, volcanic activity took place, mainly represented by thick levels of metarhyolites («porphyroids»), radiometrically dated on zircons (U/Pb: ca. 480 Ma; Meli and Kloetzli, 2001). Their geochemistry and petrology indicate a crustal anatectic origin through dehydration melting reactions, in a possible late to post-orogenic scenario (Meli, 1998).

During Permian (specifically ca. 280-260 Ma ago), numerous acidic plutonic bodies emplaced within the SA-CB, producing contact metamorphism (Cima d'Asta, Monte Croce/Kreuzjoch, Ivigna/Iffinger, Bressanone/Brixen-Chiusa/Klausen, etc.). These plutons display an EW elongate shape and are parallel or close to the IL. Such a situation evidences that their emplacement was tectonically controlled, and suggest the possible existence of a palaeo-IL at least since Permian (Sassi *et al.*, 1994). These intrusions make up a wide calc-alkaline association with the Atesino Volcanic District. Field, petrographical, geochemical and isotopic evidence supports a hybrid nature for this association, originating through complex interactions between mantle-derived magmas and crustal materials during a period of post-orogenic extensional/transtensional faulting which controlled the magma ascent and emplacement (Bonin *et al.* 1993; Rottura *et al.* 1997, 1998a, b; Bargossi *et al.*, 1999).

Some recent petrological highlights

Some recent results obtained by the team of Padova are shortly presented below.

– Recently Meli and Sassi (2003a,b) and Sassi *et al.* (2004) studied the ***granodiorite of Venice,*** i.e. samples of the SA basement buried under the Po Plain. This granodiorite body was reached by an oil exploratory well in northern Adriatic Sea (Assunta borehole). It stands 4711 m below the sea floor, directly overlain by Triassic dolostones. The drilled core represents a unique evidence of the SA-CB underneath the Po plain. A Llandeilian (461-463 Ma) emplacement age is inferred by U/Pb single grain conventional dating on zircon (Meli and Sassi, 2003b). Metapelitic xenoliths trapped within trachytes from the Euganean Hills District (northeastern Italy) preserve replacement microstructures that indicate a complex metamorphic history and also preserve microstructural and petrological evidence that may help to understand what drives fibrolite formation (Fig. 5e: Sassi *et al.*, 2004).

– A ***comparison between the AA and SA quartzphyllites*** has been attempted, in order to evaluate critically similarities and differences on the basis of lithostratigraphic correlations, metamorphic evolution and magmatic events. Similarities seem to prevail on differences, suggesting that AA and SA quartzphyllites shared a common Palaeozoic evolution, at least

since the Ordovician (Sassi *et al.*, 1994). Such an interpretation is not surprising if we keep in mind that AA and SA CBs both belonged to the northern margin of the Adria microplate.

CONCLUDING REMARKS

Although the Eastern Alps represent one of the most studied areas in the world, several important problems are still open: as a rule, the new results fill a specific lack of knowledge but open new problems often on a larger scale. With this review we aimed to highlight our recent results, and to show how, combining the petrological and microstructural approaches with detailed geochronological dating and extensive fieldwork, we gave numerous significant contributions to unravel several key aspects of the above still open problems concerning the evolution of the Eastern Alps since the Early Paleozoic.

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