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Dedicated to the memory of Giulio Elter and Carlo Sturani who taught us to read the rock record of the Canavese

The Canavese zone (internal Western Alps): a distal margin of Adria

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Abstract

The Canavese zone is situated in the westernmost Southern Alps bordering the Austroalpine Sesia zone along the internal Western Alps. It represents the southwestern (in present-day coordinates) continuation of the northwestern distal continental margin of Adria whose relics are exposed in the Austroalpine-South Pennine boundary zone (Err nappe) of Graubünden (eastern Switzerland). Although the stratigraphic successions of the Canavese zone are badly exposed and have been dismembered by Alpine ductile shear zones and brittle faults, the signatures of Early to Middle Jurassic rifting are still preserved in the rock record.

Two types of basement, separated by tectonic contacts, can be distinguished: (1) a migmatic basement of gneisses associated with anatectic leucogranites and inclusions of mafic granulites similar to those of the nearby Ivrea zone; (2) an amphibolite-grade basement, composed of amphibolites, gneisses and micaschists with shallow intrusions of Permian granitoids, obviously representing a higher crustal level comparable to the Strona-Ceneri zone of the Southern Alps. A first phase of rifting is testified by tectono-sedimentary breccias (Macchia Vecchia) and neptunian dykes of Liassic age cutting across the Triassic pre-rift carbonate platform sediments. Further rifting during the Toarcian (?) to Middle Jurassic exposed Variscan basement rocks and Permian granitoids at the seafloor, providing clasts for matrix-poor or -free, non-fossiliferous, polymictic debris-flow breccias and for sandstone turbidites interbedded with black shales (late syn-rift sediments). The polymictic breccias are dominated by granite clasts; however, they contain also fragments derived not only from the upper but also from the lower crust, and clasts of fault-rocks (phyllonites and cataclasites) most probably derived from exposed Jurassic fault planes. The occurrence of breccias and sandstone turbidites in the Radiolarite (Middle to Upper Jurassic) and Maiolica Formations (Lower Cretaceous) yielding clasts from the continental basement indicate the persistence of a submarine relief along the margin.

The Middle Jurassic late syn-rift sediments of the Canavese zone are conspicuously similar in terms of facies association, sedimentary structures and clastic content to the analogous syn-rift sediments (Saluver Formation) of the lower Austroalpine Err nappe (Graubünden). The occurrence of clasts of upper and lower crustal rocks in the polymictic breccias shows that the two types of basement of the Canavese zone were juxtaposed and exposed to the sea floor already in Middle Jurassic times, most probably along low-angle extensional detachment faults as observed today along the present-day west-Iberian margin. This scenario would match those developed for the ocean-continent transitions along the Austroalpine-South Pennine boundary zone of Graubünden, the southern prolongation of the Canavese zone in the external Apennines, and – last not least – the Cretaceous west-Iberian margin.

Keywords: Canavese zone, Southern Alps, Western Alps, Mesozoic rifting, low-angle detachment faults, lower crust, syn-rift sediments, sedimentary breccias.

1. Introduction

At the beginning of the last century, Gustav Steinmann (1905) recognised that in eastern Switzerland and western Austria the ophiolitic rocks always occurred in the same tectonic unit which he called the Rhetic nappe and which, together with their outliers in the Prealpine nappes of central and western Switzerland (Iberg klippen and nappe des Gets, Caron, 1972), he included into the south-Pennine units. With this concept, Steinmann anticipated the notion of a Liguria-Piemonte ocean separating the middle Pennine from the Austroalpine realm. However, the term Rhetic nappe did not survive, and eventually, in the Prealpine nappes of western Switzerland and Savoy, was replaced by the Simme nappe (Heim, 1922, p. 638). In the transect of western Switzerland, the "root" of the Rhetic nappe was still unknown at Steinmann's time, and between 1905 and 1907, Emile Argand searched for it in the internal parts of the Western Alps.

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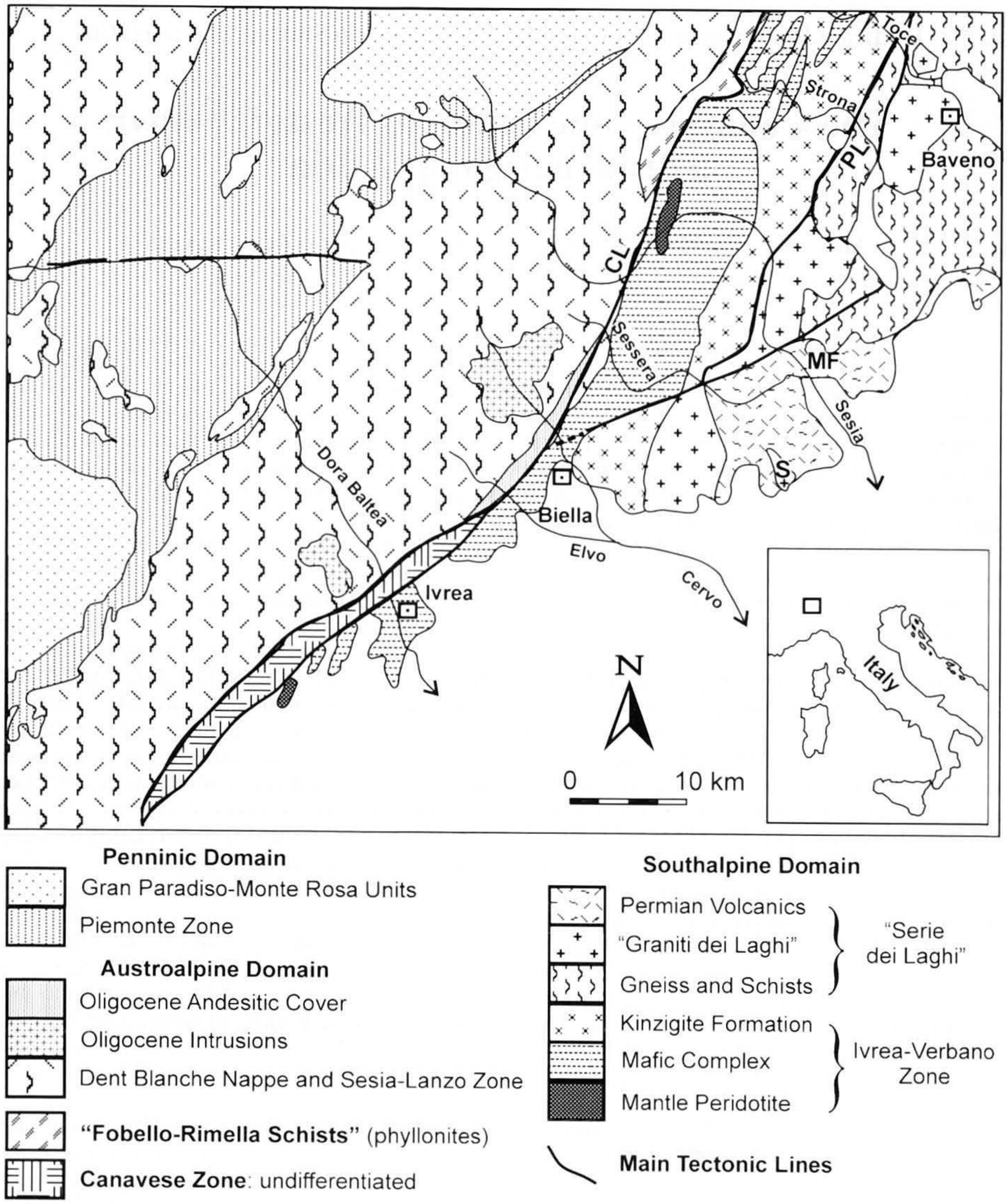

Fig. 1 Tectonic sketch-map of the Western Alps showing the major tectonic units and the location of the Canavese zone (from the 1:500.000 Structural Model of Italy by Bigi et al., 1990, modified). MF—Monte Fenera; S—Sostegno; CL—Canavese line; PL—Pogallo line.

Argand (1909a) thought that he had found the "root zone" of the Rhetic nappe in the Canavese region north of Torino where he recognised "a complex zone, however, with a tectonic individuality [extending] over long distances" and which he called the Canavese zone (Argand 1909b, his Fig. 3, our Fig. 1). He based his correlation with the Rhetic (Simme) nappe of the Prealps mainly on the identity in both units of the pelagic deep-sea sediments, namely the radiolarites, the Lower Cretaceous *Aptychus* limestones (= Maiolica), and dark shales with limestones (the present "Argille a Palombini"). Interestingly, Argand did not mention the occurrence of ophiolites within the Canavese zone, but he noticed them along its northwestern boundary towards the (in his view Pennine) Sesia zone. These ophiolitic rocks along the northwestern border of the Canavese zone do not belong to this zone but are tectonically separated from it (Novarese, 1929; Sturani, 1973; Pognante, 1989) and were always considered to be derived from the Piemonte ocean (or its ocean-continent transition).

The original palaeogeographic and tectonic position of the Canavese zone has been discussed for almost a century. On the one hand, the similarity of pelagic syn- and post-rift sediments and of clasts in the Cretaceous flysch formations of the Simme nappe (Simme nappe *s.s.* Caron, 1972) and in the Monte Cassio Flysch of the Ligurids of the Apennines with the Canavese rocks led Elter et al. (1966) to postulate a close relationship between the Simme nappe, the Canavese and the external Ligurids. These authors considered the "ophiolites" (serpentinites and subordinate "gabbros"), occurring within the area of the Canavese zone (Pesmonte), as part of the Canavese zone what seemed to support a correlation with (part of) the Simme nappe (i.e. the nappe des Gets with its ophiolites). On the other hand, the similarities of the crystalline basement and of the sedimentary succession of the Canavese zone with those of the western Southern Alps and of parts of the lower Austroalpine nappes led many authors to compare the sequences of the Canavese with these units (Spitz, 1919; Staub, 1924; Baggio, 1963b, 1965a, 1965b; Bernoulli, 1964; Sturani, 1973). In particular, Biino and Compagnoni (1989) and Borghi et al. (1996) documented the close analogies between the Canavese basement and the *upper* crust of the Southern Alps.

In the context of modern geology, a pre-Alpine co-occurrence of continental basement rocks and Triassic sediments with mantle rocks (serpentinite), emplaced during the Jurassic at the sea floor or in a spreading ridge, would be difficult to explain. This led Sturani (1973) to reconsider the palaeotectonic significance of the Canavese zone. He now regarded the ultramafics and gabbros of the Canavese area (Pesmonte) as tectonic slivers derived from the Ivrea zone, but still maintained the correlation with the external Ligurids and the Simme nappe for which he now assumed a thinned continental basement. Nevertheless, slivers of mantle rocks and continental basement may be present within the same Alpine-tectonic unit. Indeed, the relationships between the ultramafic rocks within the Canavese (Pesmonte) and the surrounding rocks are not clear. We do not know whether these ultramafics were tectonically introduced during the Alpine orogeny into the Canavese zone, or whether they are serpentinised mantle rocks exhumed during Tethyan rifting to form – together with the thinned continental crust – a Jurassic ocean-continent transition like in the Err-Platta system (cf. Froitzheim and Manatschal, 1996; Manatschal and Nievergelt, 1997; Manatschal and Bernoulli, 1999). In any case, it seems clear that the Canavese sediments are underlain by (thinned) continental crust of the South-Alpine margin with the possible occurrence of exhumed mantle rocks.

In our paper, we shall substantiate the hypothesis that the Canavese zone is part of the distal margin of Adria (Bertotti et al., 1993, Manatschal and Bernoulli, 1999). In particular, we demonstrate the similarities between the Canavese zone and the Austroalpine Err nappe. We base our argumentation on the similarity of the syn-rift and post-rift sediments and associated fault rocks of these units, and on the analogies between the continental upper and lower crustal rocks of the Canavese and those of the neighbouring Southern Alps. To this aim we petrographically studied the Canavese basement where it is most complete, i.e., in the area between Issiglio and S. Anna Boschi. Because until now the basement rocks were not described adequately, we shall document them as far as necessary for our purpose. We further review the syn- and post-rift sediments in the same area and north of Levone where the outcrops are most complete.

We shall not discuss the relationships of the Canavese to the Sesia zone: whether the Sesia basement was part of an extensional allochthon separated from the Canavese by a window of subcontinental mantle (Froitzheim and Manatschal, 1996), an integral part of the Adriatic margin (Sturani, 1973; Dal Piaz, 1999) or part of Europe (Aubouin et al., 1977; Fudral and Deville, 1986) is not part of our considerations. In our view there is no satisfying scenario available at present to explain the juxtaposition of the Sesia zone with its Alpine high-pressure metamorphism and the low-grade metamorphic Canavese zone; indeed, the Canavese and the Sesia zones might have been located quite distant from each other before subduction and subsequent exhumation of the latter.

2. Geological setting

The Canavese zone, as defined by Argand (1909b), is a tectonic unit about 2 km wide and about 40 km long, exposed in the internal Western Alps between Levone and Ceresito (Figs. 1–2). The tectonic complexity of the zone is mirrored by a confusing nomenclature, and often the tectonic unit has been confused with the geographical area. Several authors extended the Canavese zone of Argand (1909a,b) areally and included the higher metamorphic Mesozoic sediments occurring along the Insubric (external Canavese) line west of Lago Maggiore into it (e.g. Schmid et al., 1987, 1989); however, we shall restrict our considerations to the Canavese *s.s.* as defined by Argand. Until now, the Canavese basement did not receive much attention, and most of the older literature focussed on the sedimentary cover (Sismonda, 1845; Gastaldi, 1871; Baretti, 1877; Argand, 1909a; Spitz, 1919; Elter et al., 1966).

The Canavese zone is bounded by two tectonic lines (Figs. 1–3), the internal (ICL) and external (ECL) Canavese lines (Biino and Compagnoni, 1989), which have different ages and a different tectonic significance. The ECL, or the Canavese line *s.s.*, is the southwestern branch of the Insubric line, which is the main tectonic lineament separating the Southern Alps from the Austroalpine and Penninic domains (Schmid et al., 1987, 1989). In the Western Alps, the ECL is a brittle fault zone, which separates the Canavese zone from the Alpine metamorphic rocks of the Sesia zone and its Tertiary volcano-sedimentary cover which at times has been erroneously placed to the south of the Insubric line and therefore attributed to the Canavese zone (e.g. Ahrendt, 1972). The ICL, which separates the Canavese from the granulite-facies Ivrea zone, is a ductile fault zone, which is marked by the presence of mylonites with a very low-grade Alpine metamorphism, similar to that overprinting the Canavese rocks: consequently the ICL was considered as part of an older shear zone with fault rocks exhumed from greater depth (Biino and Compagnoni, 1989). During the Alpine orogeny the Canavese rocks suffered polyphase ductile to cataclastic deformation. These features, together with deep weathering and an extensive Quaternary cover, make the Canavese rocks difficult to be characterised without careful petrographic examination.

The Canavese zone, as defined by previous authors, consists of a number of tectonic slices including either basement and/or sedimentary cover rocks. The pre-Permian crystalline basement is intruded by post-Variscan Permian granitoids. The sedimentary sequence reflects the palaeotectonic evolution of the Adriatic margin with pre-rift Permian volcanics and continental clastics and a Triassic carbonate platform, a syn-rift sequence of tectono-sedimentary breccias and deep-water clastics, and a post-rift sequence of pelagic and hemipelagic radiolarites, limestones and shales.

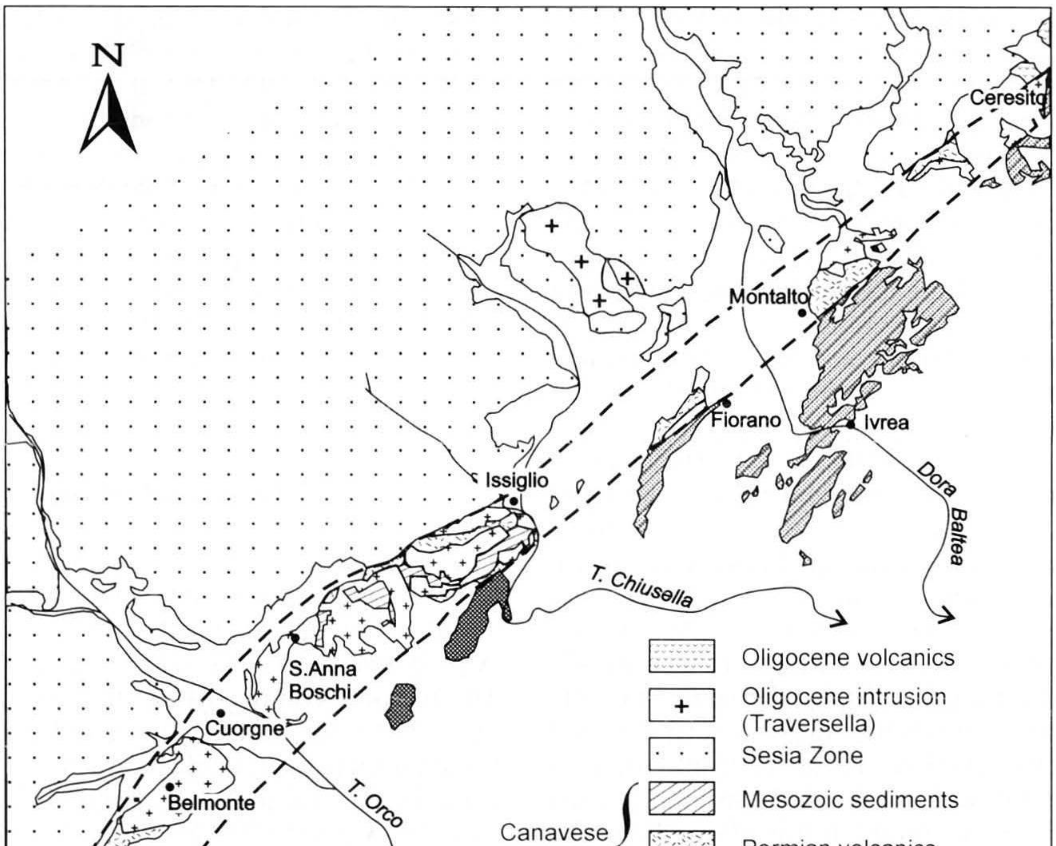

Fig. 2 Simplified geological map of the Canavese zone.

3. The metamorphic basement

In the area between Issiglio and S. Anna Boschi, two types of pre-Alpine metamorphic rock associations can be distinguished (Fig. 3): (1) a "*migmatic basement*" composed of migmatites with anatectic leucogranite, and (2) a "*gneiss-amphibolite basement*" composed of a heterogeneous assemblage of amphibolite-facies rocks, intruded by a wide spectrum of post-Variscan igneous rocks of probable Permian age. The two basement types are areally distinct and their mutual contacts are always tectonic.

The rocks of the *migmatic basement* underwent an upper amphibolite-facies metamorphism and include fragments of granulite-facies rocks, whereas those of the *gneiss-amphibolite basement* show a lower- to middle-amphibolite facies meta-

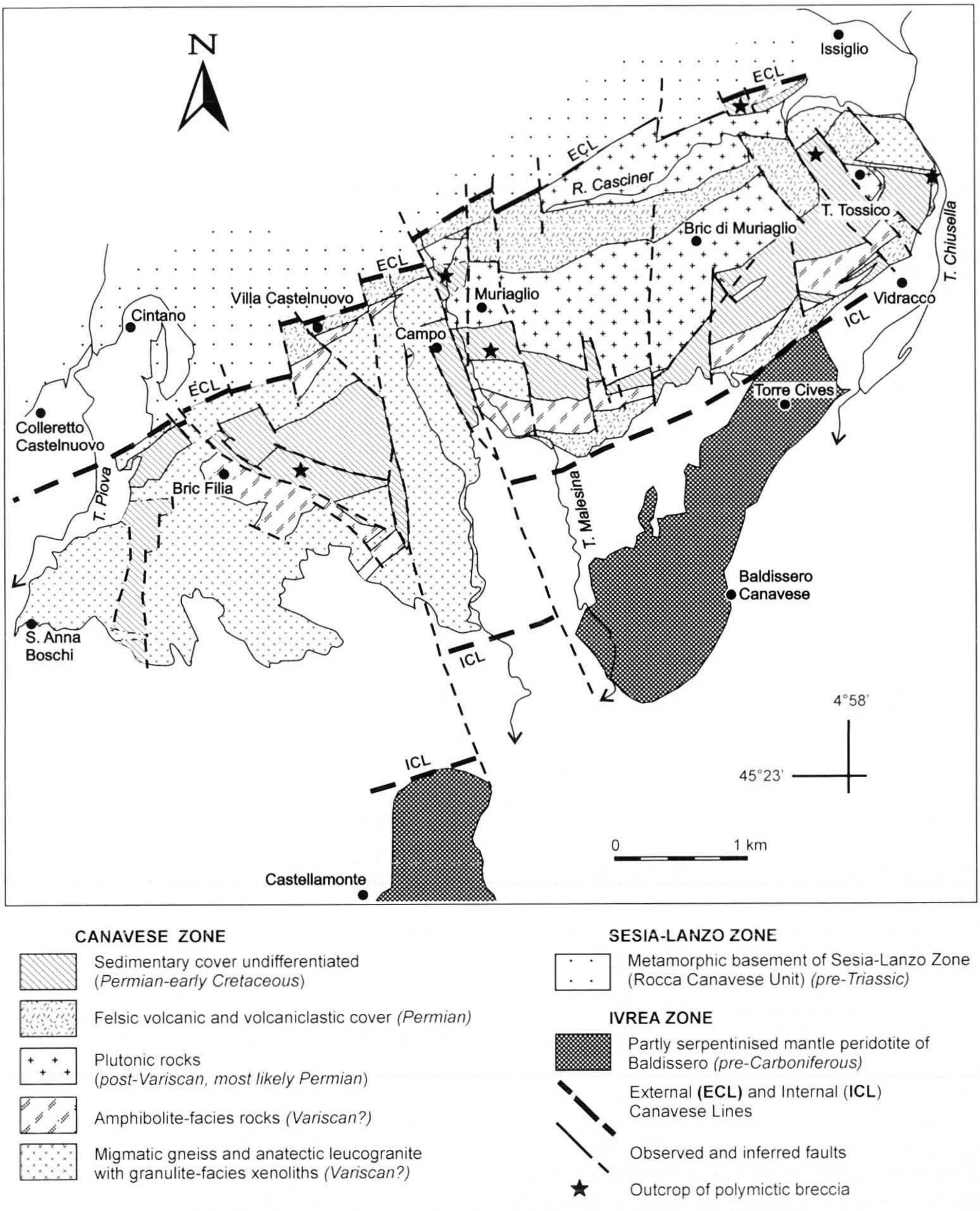

Fig. 3 Geologic map of the area between Issiglio and S. Anna Boschi.

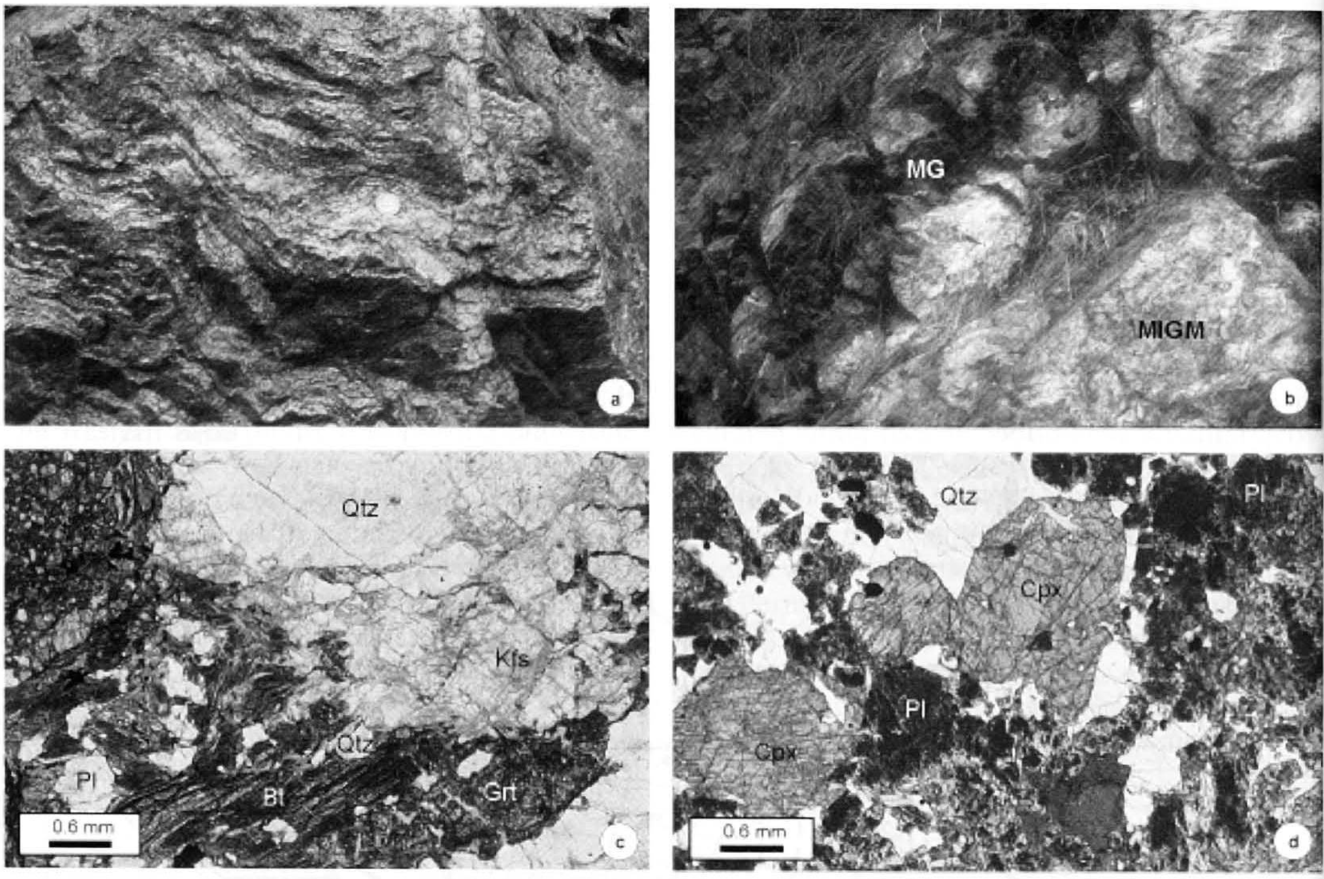

Fig. 4 Migmatic basement. (a) Outcrop of migmatic gneiss showing dm-thick quartz-feldspathic metatects. Road-cut between Vidracco and Issiglio. (b) Migmatic gneiss (MIGM) which includes a "fragment" of mafic granulite (MG) of Ivrea affinity. Road-cut between Vidracco and Issiglio. (c) Photomicrograph of a quartz-feldspathic metatect in a migmatic gneiss that consists of plagioclase, quartz, biotite, and garnet. Road-cut between Vidracco and Issiglio. Sample ZC 663, plane-polarised light (PPL). Abbreviations after Kretz (1983). (d) Photomicrograph of mafic granulite showing relics of igneous microstructure. Euhedral clinopyroxene (Cpx) and saussuritised plagioclase are included in late quartz. Road-cut between Vidracco and Issiglio. Sample ZC 664, PPL.

morphic overprint. However, both basements are characterised by an older F_{V1} foliation transposed into the main F_{V2} foliation. This indicates that, in spite of the different metamorphic conditions, the metamorphic rocks of both basements underwent the same ductile deformation. The preservation of primary intrusive contacts of the post-Variscan, most likely Permian, plutonic rocks and dykes with the amphibolite facies rocks indicate that these phases of metamorphism and deformation are pre-Permian in age, i.e. Variscan, or even older.

3.1. The migmatic basement

The migmatic basement is mainly exposed in the western part of the area, whereas in the eastern part, it is found only along the road-cut between Vidracco and Issiglio, and north of Vidracco (Fig. 3). This basement consists of a migmatic gneiss, showing nebulitic, schlieren, folded or phlebitic structures (in the terminology of Mehnert, 1968; Fig. 4a), intimately associated with anatectic leucogranite: the latter occurs as centimetre- to hectometre-sized bodies, characterised by transitional contacts with the enclosing migmatic gneiss. In the field, the anatectic leucogranite can be easily distinguished from the homogeneous post-Variscan granitoids by its variability in both muscovite content and mineral grain size. Along the road-cut between Vidracco and Issiglio, this leucogranite includes layers or "fragments", a few dm thick and a few m long, of mafic granulites (Fig. 4b). In the past, they were recognised only by Baggio (1963b) and Wozniak (1977). In particular, Wozniak (1977) compared them in terms of composition, microstructure and petrologic evolution, to the mafic granulites of the adjacent Ivrea zone, in which he seems to include them. The leucogranites were described by Issel (1893), Novarese (1929) and Fenoglio (1930) as part of the post-Variscan, mostly Permian, granitoid intrusive complex.

In thin section, the *migmatic gneiss* shows domains with a metamorphic structure and lens-shaped domains with a magmatic structure (metatects; Fig. 4c). The domains with a metamorphic structure are characterised by aggregates of plagioclase + quartz + cordierite (now replaced by "pinite") + porphyroblastic garnet, and by a transposition foliation defined by biotite + fibrous sillimanite (now altered to sericitic white mica) + K-feldspar. In contrast, the mineral assemblage of the domains with a magmatic structure only consist of quartz + plagioclase + K-feldspar + biotite + white mica. The migmatic gneiss locally shows a very low-grade metamorphic overprint, with the growth of sericite, prehnite, pumpellyite, opaque ores, epidote *s.l.*, and is cut by mm-thick discordant veins filled with either prehnite or chlorite + quartz + carbonate.

The fine- to coarse-grained *anatectic leucogranite* locally shows pegmatitic grain size and consists of variable amounts of K-feldspar, quartz, plagioclase, and minor white mica and biotite. Sometimes relics of garnet and cordierite are also observed. The anatectic leucogranite is cut by a network of cm- to mm-thick aplitic to quartzolithic dykes, whereas late veins of quartz + pumpellyite + prehnite + chlorite are locally found.

The inclusions of *mafic granulite*, which consist of metadiorite, metanorite, metagabbro, and rarer metaplagioclasite, have a medium fine- to coarse-grained granoblastic microstructure (Fig. 4d). They consist of variable amounts of plagioclase (mostly altered to saussurite, sericite, albite and/or carbonate), an amphibole zoned from dark green with Schiller inclusions in the core, through green-brown and green in the intermediate part to colourless in the rim, biotite, orthopyroxene, clinopyroxene (altered to chlorite and zeolites), and minor quartz. The rocks show a very low-grade metamorphic overprint characterised by chlorite + epidote *s.l.* + prehnite + zeolite + titanite + pumpellyite, and are cut by several generations of late mm-thick mono-mineralic (zoisite or prehnite) or bi-mineralic (i.e., chlorite + carbonate or prehnite + carbonate) metamorphic veins. Locally, relics of a former igneous microstructure occur, in which the crystallisation sequence and a mineralogical banding are preserved.

3.2. The gneiss-amphibolite basement

This basement type, mainly exposed in the eastern part of the area, crops out in the western zone only near Bric Filia and near Villa Castelnuovo (Fig. 3). It consists of amphibolite-facies rocks intruded by plutonic rocks and dykes.

Six different kinds of metamorphic rocks have been recognised: amphibolite (medium- and fine-grained; Fig. 5a) associated to minor leucocratic orthogneiss and garnet-bearing plagioclase-biotite orthogneiss, garnet–two mica schist locally converted to phyllonite, two-mica gneissic micaschist with fibrolitic sillimanite and garnet, and two feldspar-two mica augengneiss (the latter two lithologies are here described for the first time). In many outcrops, these rocks are cataclastic, mylonitic, or strongly sheared.

Under the microscope, the medium-grained *amphibolite* locally grades into amphibole ± biotite gneiss. Both amphibolite and gneiss show a planar foliation, defined by alternating layers rich in green amphibole and in plagioclase + epidote ± biotite, respectively. The fine-grained amphibolite consists of green amphibole, plagioclase, biotite, epidote, and quartz which define a well developed foliation wrapped around porphyroclasts of green amphibole (Fig. 5b) and plagioclase. A late growth of chlorite, albite, carbonate, and pumpellyite is locally observed. Discordant veins of chlorite, quartz + opaque ores + chlorite, and apatite ± quartz are also present.

The *leucocratic orthogneiss* shows a mylonitic fabric, characterised by the presence of K-feldspar and plagioclase porphyroclasts with foliated aggregates of quartz, plagioclase, biotite, minor garnet, and rare white mica wrapped around them. A late development of albite, chlorite and quartz is locally found.

The *garnet-bearing plagioclase-biotite orthogneiss* consists of plagioclase, biotite, quartz, epidote, and local garnet. Relics of the igneous protolith, consisting of

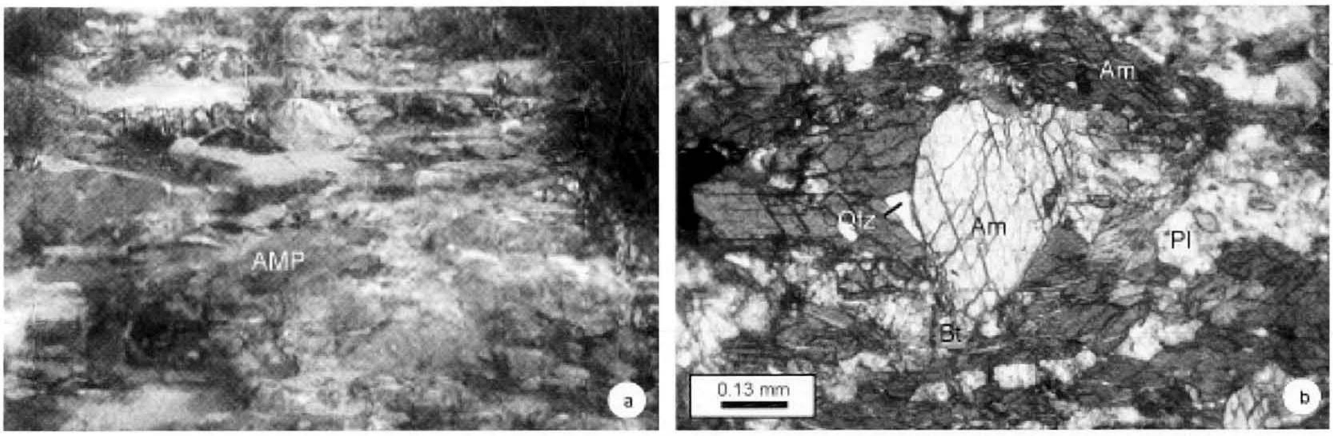

Fig. 5 Gneiss-amphibolite basement. (a) Outcrop of cataclastic fine-grained amphibolite (AMP). South of Muriaglio. (b) Photomicrograph of amphibolite characterised by a fine-grained matrix of amphibole (Am), plagioclase, biotite, and quartz wrapped around an amphibole porphyroclast. Bric Filia. Sample ZC 696, PPL.

plagioclase, quartz, and apatite, are locally preserved. The presence of isoclinally folded quartz veins indicates that the main foliation is a transposition foliation. Late discordant veins of chlorite + quartz, quartz + prehnite, and quartz + pumpellyite are also present.

The *garnet-two mica schist* consists of medium-grained white mica + biotite + plagioclase + garnet. The garnet usually contains a S_i, discordant to S_e, which is defined by the preferred dimensional orientation of small quartz inclusions. In the phyllonites, a younger mineral assemblage consisting of albite + white mica + green biotite + chlorite + Fe-rich epidote + carbonate + green tourmaline + ankerite is also present. Rarely, deformed mm-thick quartz + baryte veins are observed.

The *two-mica gneissic micaschist with fibrolitic sillimanite and garnet* shows a foliation defined by white mica, biotite, and minor fibrous sillimanite (partly replaced by white mica), which is wrapped around porphyroclasts of garnet and quartz. Late discordant veins of chlorite are locally present. A sample of this gneissic micaschist also includes coarse-grained biotite and andalusite, partly retrogressed to coarse white mica.

The *two feldspar-two mica augengneiss* exhibits an augen fabric with porphyroclasts of plagioclase and K-feldspar, with a fine-grained foliated matrix of quartz + white mica + biotite + plagioclase wrapped around them. A late growth of chlorite, carbonate, and pumpellyite is evident. Locally, the mylonitic fabric is accompanied by the development of Fe-rich epidote.

4. The post-Variscan igneous rocks

4.1. Intrusives

Both plutonic rocks and dykes crop out in the area between Issiglio and S. Anna Boschi (Fig. 3). The plutonic rocks, locally very weathered, are medium-grained and consist of quartzdiorite, quartz-bearing diorite, tonalite, granodiorite, and a locally porphyritic pink granite. The dykes, from a few dm to a metre thick, consist of lamprophyre, dolerite, porphyritic diorite, porphyritic quartzdiorite, quartzdiorite, and aplite. Of special interest is the quartzdiorite whose groundmass is often granophyric, suggesting a shallow intrusion level (Fig. 6). A very low-grade metamorphic overprint with prehnite, pumpellyite, epidote, sericite, chlorite, and carbonate is recognised in all lithotypes. In agreement with the previous authors, who described the pink granite (e.g. Fenoglio, 1930; Baggio, 1963b, 1965a) and the aplite dykes (Baggio, 1963b), a post-Variscan, most likely Permian age is suggested for both plutonic rocks and dykes. The Permian igneous rocks occur only within the amphibolite-facies rocks, but nowhere within the migmatic basement, that obviously represents a different level of the crust.

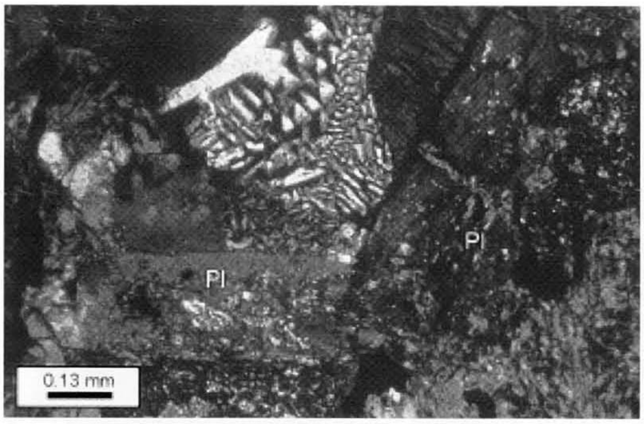

Fig. 6 Permian intrusives. Photomicrograph of a quartz-dioritic dyke with idiomorphic plagioclase crystals and granophyric groundmass. Southeast of Bric Filia. Sample ZC 738, crossed polarisers (CP).

4.2. Volcanics and volcaniclastics

Greyish, purple, or greenish volcanic and volcaniclastic rocks are mainly exposed in the eastern part of the area, but occur also near Villa Castelnuovo (Fig. 3). The volcaniclastics consist of mm- to cm-sized subangular fragments of rhyolites, and minor gneiss, quartz and feldspar clasts, set in a very fine-grained matrix now mainly altered to sericite. The microporphyritic rhyolites show a banded groundmass with flow microstructures. All the lithologies are usually cataclastic and may be cut by late veins filled with epidote + quartz + chlorite. In agreement with the previous authors (e.g. Fenoglio, 1931) these rocks are considered Permian in age.

5. Pre-rift sediments (Permian and Triassic)

Most sedimentary formations of the Canavese zone are in tectonic contact with their original basement and are also separated from each other by tectonic contacts.

5.1. "Verrucano"

Red and green conglomerates at the base of the Mesozoic sequence have been compared to the Alpine "Verrucano" of the Bergamasc Alps and the Austroalpine realm. These sediments contain mainly clasts of Permian volcanics and lesser fragments of crystalline basement rocks. Baggio (1965b) mentions intercalations of tuffs or tuffites and allocates these sediments to the Upper Permian. Upward, the conglomerates give way to lithic and feldspatic sandstones with intercalated shales. No fossils have been found in this continental formation, the age of which must be between the Early Permian and the Early Anisian Bellano Formation that preceded the transgression of the Middle Triassic sea.

5.2. Triassic dolomites

Near Montalto, grey, massive, non-fossiliferous dolomites without apparent bedding overlie the clastic sediments of the "Verrucano" (Baggio, 1965b). Along their top, they grade into tectono-sedimentary breccias of Macchia Vecchia-type (Baggio, 1965b). The dolomites could be either Middle and/or Late Triassic in age. Because in the Canavese zone, the terrigenous and evaporitic interval of the Carnian Raibl Beds (Marne di Pizzella) is not known, and because in the Southern Alps west of Lago Maggiore Liassic strata rest directly on Middle Triassic dolomites (Sostegno-Villa del Bosco, Franchi, 1903; Monte Fenera, Rasetti, 1897; Farabegoli and De Zanche, 1984), we favour a Middle Triassic age like earlier authors (Parona, 1924, p. 382; Novarese, 1929; Baggio, 1965a; Elter et al., 1966).

6. Syn-rift sediments (Lower and Middle Jurassic)

6.1. Macchia Vecchia and associated sediments

In the area of Montalto Dora and Vidracco, the upper part of the (Middle) Triassic dolomites is characterised by an intense tectonic brecciation and the occurrence of neptunian dykes (Macchia Vecchia-type), which document extensional faulting after deposition and diagenesis of the dolomites (Baggio, 1965b). The cataclastic dolomites grade laterally and upward into polyphase tectono-sedimentary breccias with cm- to dm-sized clasts of dolomite cemented by sparry calcite and/or embedded in a sedimentary matrix of older carbonate and younger arenaceous sediments (Baggio, 1965b). These sediments, red and pink crinoidal lime grainstones and compact limestones (Broccatello), red and green arenaceous limestones with phosphatic and/or ferromanganese nodules also overlie the Triassic dolomites, forming a condensed sequence (Elter et al., 1966). The red sandstone consists of sand-sized mineral grains and rock fragments included in a calcitic cement. The mineral grains are quartz, plagioclase, white mica, K-feldspar, and biotite, and the rock fragments are derived from the underlying crystalline basement (including, e.g., two feldspar-two mica augengneiss, quartzdiorite with granophyric groundmass) and from both the Permian volcanic and the Mesozoic sedimentary cover (e.g.: rhyolites, volcaniclastics, dolomitic and micritic limestones).

The limestones are dated as Early Liassic based on a fauna including *Spiriferina* and belemnites (Spitz, 1919), by an Early Sinemurian ammonite (Sturani, 1964), and by benthic foraminifera (*Involutina liassica* [= *"Spirillina" ticinensis*] Elter et al., 1966). Because limestones with pelagic bivalves are reported from the breccias at Montalto (Baggio, 1965b, Plate 1, Fig. 4), the youngest elements of the Macchia Vecchia breccia could be Late Liassic in age. In addition, Baggio (1965b) reports marly limestones, marls, and shales from Montalto to which he allocates a Middle Liassic age.

The tectono-sedimentary breccias present many analogies to syn-rift breccias described from the central part of the Southern Alps (Macchia Vecchia; Wiedenmayer, 1963; Bernoulli et al., 1990) and from the lower Austroalpine nappes (Alv Breccia; Schüpbach, 1973; Furrer, 1985) where a polyphase system of sedimentary (neptunian) dykes cuts across the Triassic host rocks and across marine scarp breccias. The red sandstones are similar to sandstones at the base of the Liassic sequence of Monte Fenera (lower Val Sesia; Bernoulli, 1964).

6.2. Polymictic breccias

From the area of Bric Filia, Ahrendt (1972) mentioned "areally occurring breccias" which he thought to be younger than the Lower Cretaceous formations and of Tertiary age. The outcrops of these breccias are everywhere bounded by faults, and the breccias themselves were affected by Alpine deformation. We have studied these breccias in the area of Bric Filia, along the Malesina river, along the road-cut between Vidracco and Issiglio, to the northwest of Truc del Tossico (Fig. 3), and to the northwest of Levone. Although we obviously deal with the same breccia formation, our observations and interpretations are markedly different from those of Ahrendt (1972) and Wozniak (1977).

The bedding of the breccias is very crude and often only defined by the long axis of clasts. The clasts of the breccias are up to a few dm across, very heterogeneous in size and composition, and typically of angular or subangular shape (Fig. 7a). They are embedded in a sparse, coarse-grained sandstone matrix, red-purple to green-greyish in colour, consisting of small lithic fragments from the same volcanic and basement lithologies wrapped by limonite. We have studied the clasts in detail: they are derived from the Canavese zone and include, beside clasts derived from the Permian intrusive and volcanic rocks, clasts from both types of the Canavese basement. Clasts from the gneiss-amphibolite basement include: garnet-bearing plagioclase-biotite orthogneiss, leucocratic orthogneiss, garnet-two mica schist, amphibolite, two feldspar-two mica augengneiss, two-mica gneissic micaschist with fibrolitic sillimanite and garnet. Migmatic gneisses, mafic granulites, and anatectic leucogranites similar to those observed in the migmatic basement are also found. Clasts derived from the intrusive rocks include quartzdiorite with a granophyric intergrowth (Fig. 7b), porphyritic quartzdiorite, dolerite, different granitoids, porphyritic diorite, aplite, and deeply altered lamprophyres. Only one single pebble of a Triassic dolomitic limestone has been found (Fig. 7c), whereas clasts of other sediments are lacking.

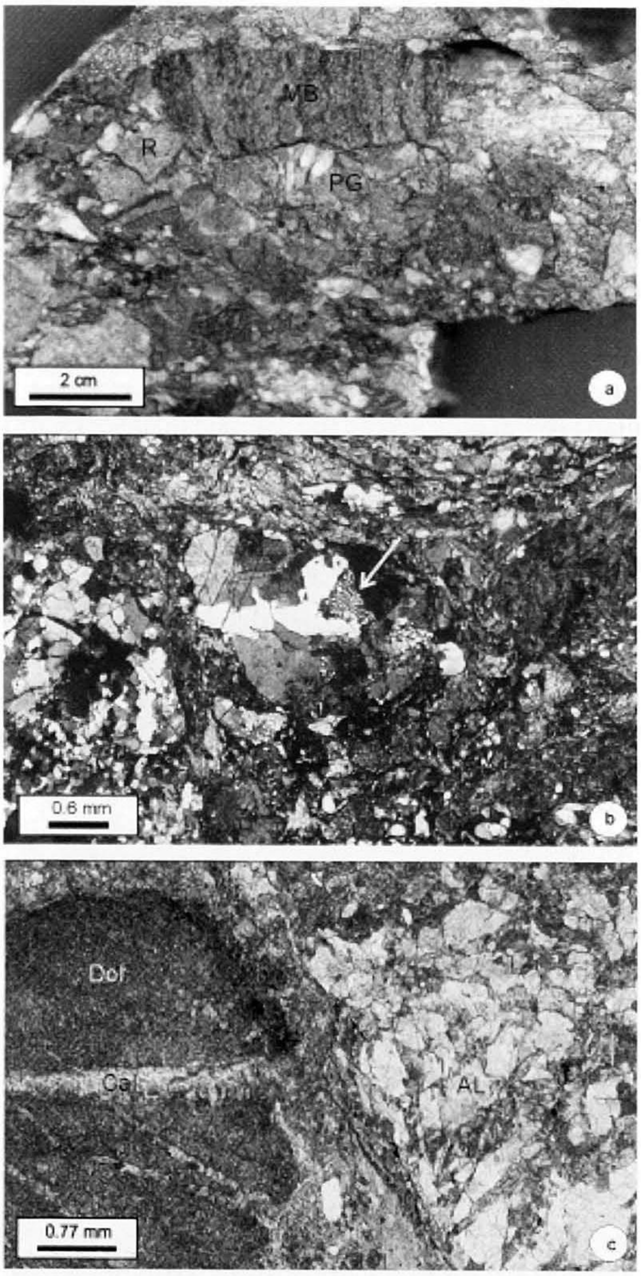

Fig. 7 Polymictic breccias. (a) Unsorted polymictic breccia with angular clasts of metamorphic basement (MB), Permian granitoids (PG), and rhyolites (R). Bric Filia, locality La Vigna. Polished sample. (b) Photomicrograph of polymictic breccia. In the centre, a clast of quartzdiorite with a granophyric intergrowth (white arrow). Bric Filia, locality La Vigna. Sample ZC 725, CP. (c) Photomicrograph of polymictic breccia showing a dolomite pebble with calcitic (Cal) veins and a pebble of anatectic leucogranite (AL). South of Muriaglio. Sample ZC 759, PPL.

Clasts of phyllonite, characterised by a mylonitic foliation defined by fine-grained green biotite, white mica, and chlorite, are derived from deformed garnet–two mica schists. Clasts of cataclastic granites and of cataclasites are equally present. These clasts testify to retrograde deformation of the basement rocks prior to the deposition of the breccias. Veins, filled by chlorite, chlorite + sericite, quartz and/or carbonate, are observed in some of the pebbles. Veins of quartz + baryte, a few mm thick, cut the breccias exposed along the road-cut between Vidracco and Issiglio. They suggest that the breccias have undergone Alpine deformation and low-grade alteration.

Because of the absence of fossils and because there are no stratigraphic relations to other formations, the polymictic breccias are hard to date. Accordingly, different ages have been ascribed to these sediments. The breccias exposed near Rio Casciner, that are characterised by pebbles of vein quartz in a red matrix, were considered Liassic by Novarese (1929) and Permian by Baggio (1963a, 1973). Ahrendt (1972) and Wozniak (1977) distinguished part of our polymictic breccias cropping out along the Vidracco-Issiglio road as “Permian Verrucano-type” conglomerates from the coarse breccias near Bric Filia which they considered Tertiary (Ahrendt, 1972) or Oligocene (Wozniak, 1977) in age. Although our six outcrop areas, including the Vidracco-Issiglio road outcrop, are separated from each other by faults, we consider them to belong to the same formation because they are identical in terms of lithology and clast content.

In the absence of fossils and relevant stratigraphic relationships, dating of the formation must rely on circumstantial evidence. A clast of dolomitic limestone, obviously derived from the Triassic, defines a lower time bracket for its deposition; younger clasts, in particular from the weathering-resistant radiolarites which are widely occurring in the area, are missing. Deformation of the rocks and the occurrence of mineral veins suggest a pre-Tertiary age for the formation. Based on the, admittedly scarce, occurrence of a Triassic clast and the absence of clasts from post-Triassic formations we suggest a post-Triassic, pre-late Jurassic age for the formation. This age is supported by the analogies with the ?Toarcian to Early-Middle Jurassic Saluver Formation (Members A and B) of the lower Austroalpine Err nappe which is characterised by thick submarine breccias and sandstones, deposited by mass-flow and turbidity currents (Finger, 1978).

The subangular shape and extremely poor sorting of most clasts suggest rapid transport, presumably by mass-flow, an accentuated relief and active tectonics. The occurrence of clasts from both basement areas of the Canavese indicates that both basement types were adjacent to each other already in mid-Mesozoic time.

6.3. Levone Series

Northwest of the village of Levone, a strongly cataclastic granite is, without a sharp boundary, overlain by sedimentary breccias, sandstones and black shales. The breccias are clast-supported with a scarce sandstone matrix (Fig. 8a) or matrix-supported with a black shale matrix. The clast-

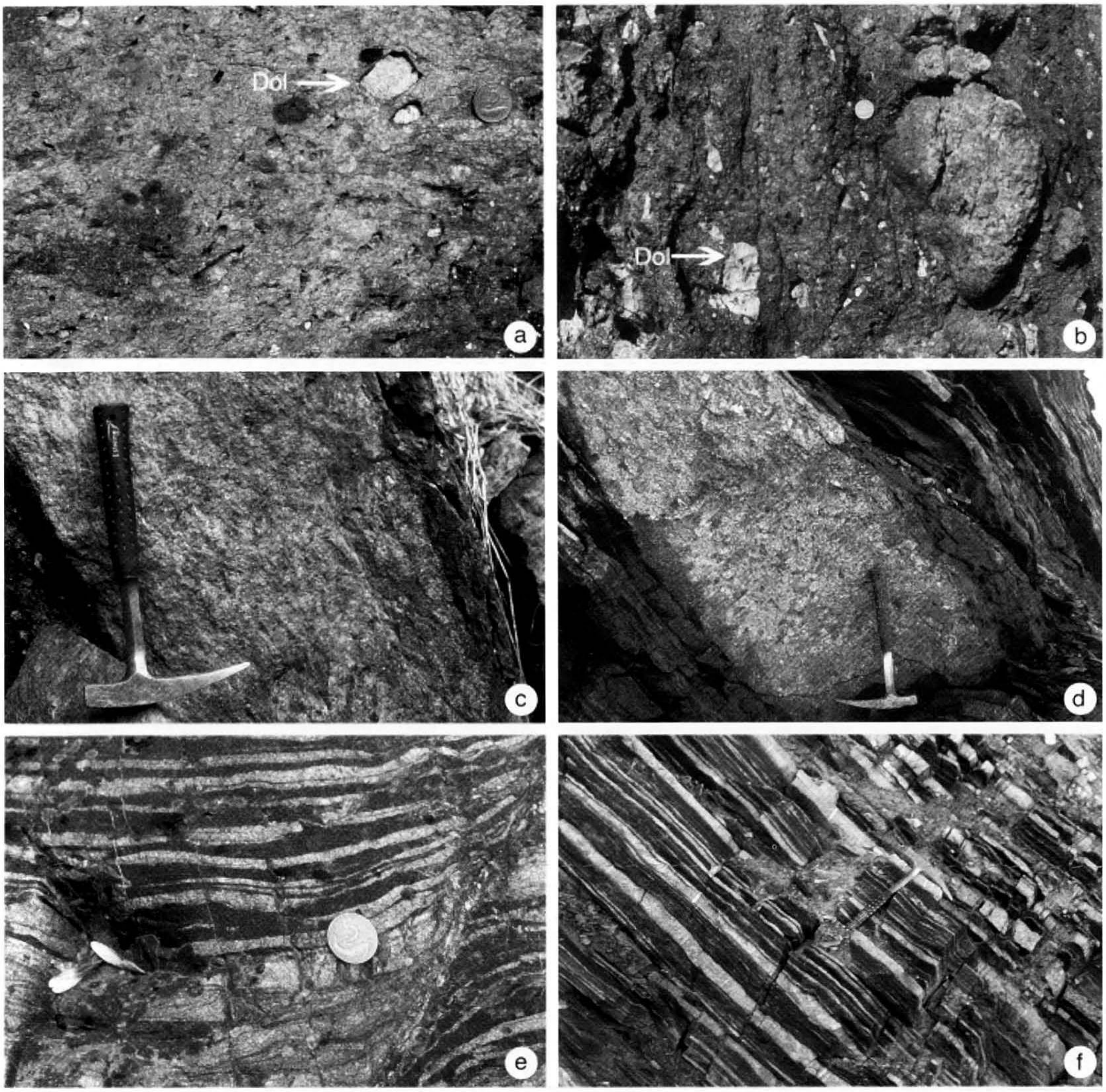

Fig. 8 Levone Series and Saluver Formation (lower Austroalpine Samedan zone, Graubünden, eastern Switzerland). (a–b) Unsorted breccias with coarse sandstone matrix, angular basement and sparse dolomite clasts: (a) Levone Series, Levone; (b) Saluver Formation, south–southwest of Muot Cotschen. (c–d) Crudely graded fine breccia to coarse sandstone with granitic and other basement clasts (both beds are tectonically overturned): (c) Levone Series, Levone; (d) Saluver Formation, Piz Nair (St. Moritz). (e–f) Thin-bedded sandstone turbidites and black shales: (e) Levone Series, Levone; (f) Saluver Formation, Piz Nair (St. Moritz).

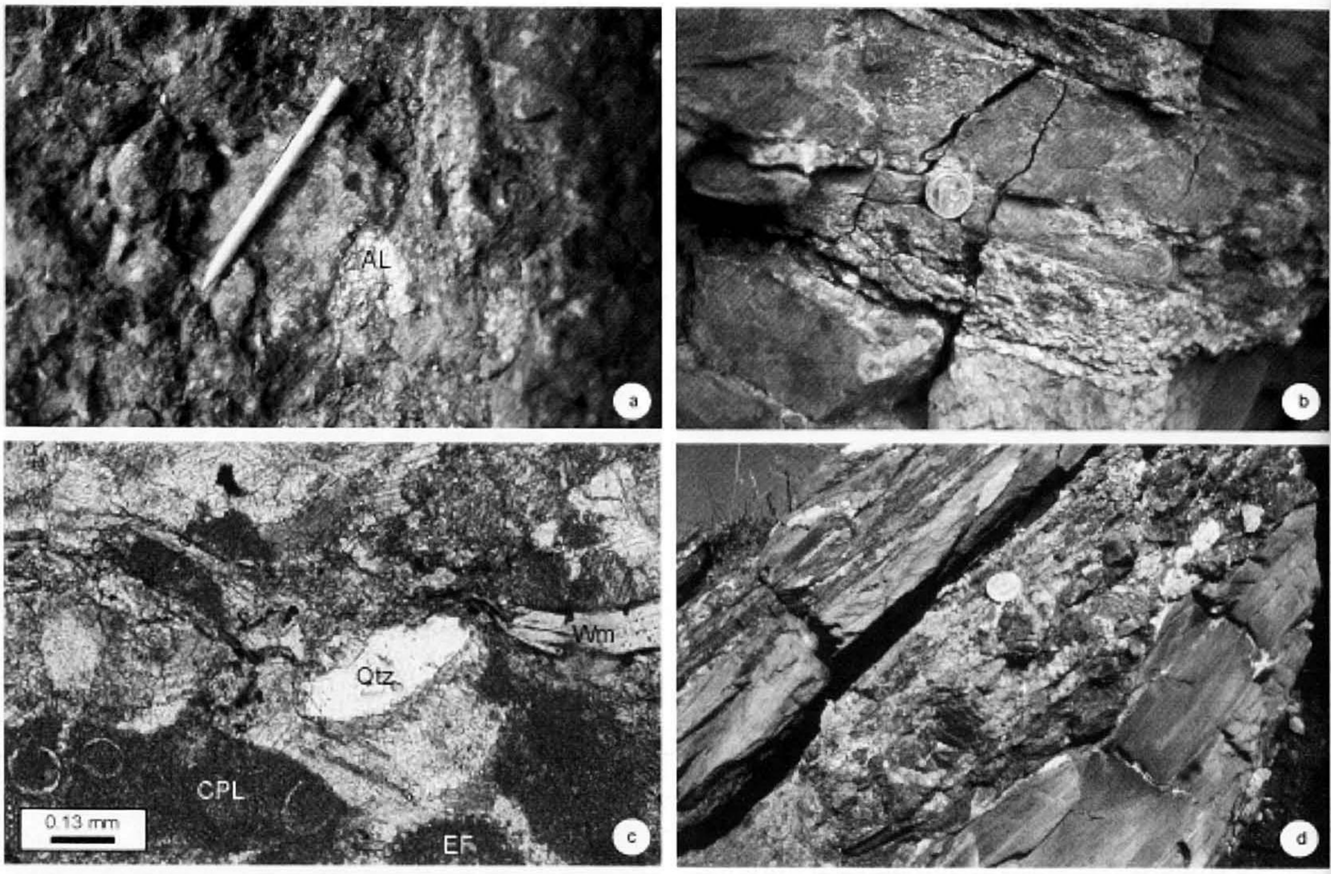

Fig. 9 Post-rift sediments. (a) Breccia with pebbles of anatectic leucogranite (AL) at the base of the Radiolarite Formation. West of Bric Filia. (b) Graded and laminated turbiditic sandstone interlayered with micritic limestones with *Calpionella* ("Maiolica"). West of Bric Filia, Forchetta dei Boschi quarry. (c) Photomicrograph of calcarenite with a clast of calpionellid-bearing pelagic limestone (CPL), an echinoderm fragment (EF), flakes of white mica (Wm), and fragments of quartz. West of Bric Filia, Forchetta dei Boschi quarry. Sample ZC 845, PPL. (d) Coarse breccia with cataclastic continental basement clasts, intercalated in Calpionella Limestone (= Maiolica). Lower Cretaceous. South-Pennine Totalp nappe, Parsenn, Davos, Graubünden, eastern Switzerland.

supported breccias are dominated by clasts of cataclastic granite and other basement clasts (gneiss, micaschist and phyllonite) with lesser clasts of Permian rhyolites and Triassic dolomites; some of the matrix-supported breccias are particularly rich in dolomite clasts. The sandstones are lithic and feldspathic arenites, and in general thick-bedded and crudely graded (Fig. 8c). Thin-bedded graded sandstones alternate with the black shales (Fig. 8e). The polarity of the beds indicates a narrow syncline with a relic of Triassic dolomites in the northwest limb which by 1966 had already nearly disappeared (cf. Elter et al., 1966). Further outcrops to the northwest and beyond another outcrop of granite include the same breccias, graded sandstones, black shales and argillaceous limestones. To the northwest, the Levone Series is separated from the ophiolites and Sesia mylonites by a major tectonic contact.

Like the polymictic breccias, the breccias at Levone are dominated by basement clasts; however, they are richer in dolomite fragments. They appear to overlie directly their major source rocks, the granites which along the ill-defined boundary zone appear to be strongly cataclastic. Like the polymictic breccias, the Levone breccias include fragments of Triassic dolomites, but no younger lithologies. For this reason, Elter et al. (1966) allocated a post-Triassic age to the Levone Series and compared it to the Liassic Allgäu Formation of the Austroalpine nappes. By contrast, Baggio (1965a) had correlated the Levone Series with the Maiolica Formation near Bric Filia; likewise he allocated the breccias he observed near Muriaglio (our polymictic breccias) to the Cretaceous. Because of the marked similarity of the Levone Series with the Saluver Formation of the Austroalpine nappes (Fig. 8b, d, f) we suggest a correlation with this formation and a ?Toarcian to Middle Jurassic age for the Levone Series. This correlation has already been suggested by Sturani (in Carraro and Sturani, 1972; Sturani, 1975).

Elter et al. (1966) noted that granitic breccias occur also within the cataclastic granites and allocated them to the formation of small grabens developing during Jurassic rifting. In our interpretation, the Levone Series rests unconformably on cataclasites related to the exhumation of the granite during Jurassic rifting. Outcrops of exhumed basement must have existed throughout the Jurassic to earliest Cretaceous interval as testified by the occurrence of basement clasts in the breccias and sandstones of the Radiolarite and the Maiolica Formation. A similar onlap of syn-rift breccias (Saluver Formation) on exhumed basement and related fault rocks is observed in the Austroalpine Err nappe (Manatschal and Nievergelt, 1997, their Fig. 10b). Because of its stratigraphic position and its probable palaeotectonic significance (exhumation of continental basement during rifting) we correlate the Levone Series with the polymictic breccias, described above.

7. Post-rift sediments (Middle Jurassic to Lower Cretaceous)

7.1. Radiolarite Formation

The Radiolarite Formation consists of an alternation of cm-bedded chert and shales. The alternating cherts and shales occur in packages several metres thick. The bedded cherts are reddish to greenish in colour, and in thin-section the quartz-filled molds of radiolarians are recognised. The fine-grained and radiolarian-rich granular cherts often show a sharp base, grading upward from white chert into red shale, testifying to the action of dilute turbidity or bottom currents. The cherts are locally recrystallised to glassy cherts which form lens-shaped concretions within the beds. In thin section, the concretions appear to be monomineralic quartz aggregates with a plumose microstructure. Locally, both the chert matrix and the quartz concretions are permeated by baryte veins and cut by a polyphase network of quartz veins.

Locally, the radiolarian chert includes, in the stratigraphically lower part, turbidite beds, a few dm-thick, consisting of lithic sandstone with a siliceous cement. The sandstone contains sorted, mostly subangular, clasts of minerals and rocks. The mineral grains include quartz, plagioclase, white mica, oxidised biotite, and rare zircon; the lithoclasts a variety of aphyric and porphyritic volcanic rocks with a glassy or microcrystalline groundmass, deeply weathered subvolcanics with a granophyric groundmass, and quartzites. Indeed, at Bric Filia, the radiolarites stratigraphically overlie the migmatic basement (Fig. 9a).

A Middle to Late Jurassic age is usually ascribed to the Radiolarite Formation in analogy to the Radiolarite Formation ("Selcifero Lombardo") of the Southern Alps (Bill et al., 2001) and because it is stratigraphically overlain by the Tithonian-Berriasian Maiolica (Baggio, 1963a).

7.2. Maiolica Formation

The Maiolica Formation, exposed near Bric Filia and Issiglio (Fig. 3), consists of well-bedded, light-brown to light grey micritic limestones, which locally include lenses and bands of diagenetic replacement chert (now polycrystalline quartz). Cm- to dm-thick beds of graded and laminated turbiditic sandstone are intercalated at irregular intervals (Fig. 9b). The lithic sandstones contain mineral grains, and rock fragments. The mineral grains are white mica, quartz, feldspar, biotite, zircon, tourmaline, apatite, garnet, whereas the lithoclasts include micritic limestone, chert, sandstone, and relatively abundant metamorphic rocks from the crystalline basement, i.e.: garnet-two mica schist, leucocratic orthogneiss, porphyritic quartzdiorite, two-mica gneissic micaschist with fibrolitic sillimanite and garnet, and phyllonite derived from garnet-two mica schist. Redeposited calcarenites contain besides sparse silicoclastic detritus clasts of micrite, including intraformational clasts of calpionellid-bearing pelagic limestone (Fig. 9c). Admixed fossils include agglutinated benthic foraminifera and echinoderm fragments, but no particles derived from a shallow-water carbonate platform were found.

Calpionellids date the Maiolica Formation to the late Tithonian-Berriasian (Baggio, 1963a). The Maiolica Formation grades upward through an interval of dark argillaceous limestones into the shales and limestones of the Argille a Palombini Formation.

7.3. Argille a Palombini

The Argille a Palombini Formation, exposed near Bric Filia and near Muriaglio, consists of dark grey shales with intercalated grey-brown weathering, dark grey argillaceous limestones with silicified lower and upper surfaces of the limestone beds – a feature typical for the limestones of the Argille a Palombini of the Ligurian nappes of the northern Apennines (e.g. Elter et al., 1966). In the Canavese zone the formation is not dated but considered to be of Early Cretaceous age, because it overlies the Tithonian-Berriasian Maiolica Formation and because of the analogies with the Argille a Palombini of the northern Apennines (Baggio, 1965a; Elter et al., 1966) and of the Gets nappe (cf. Caron, 1972).

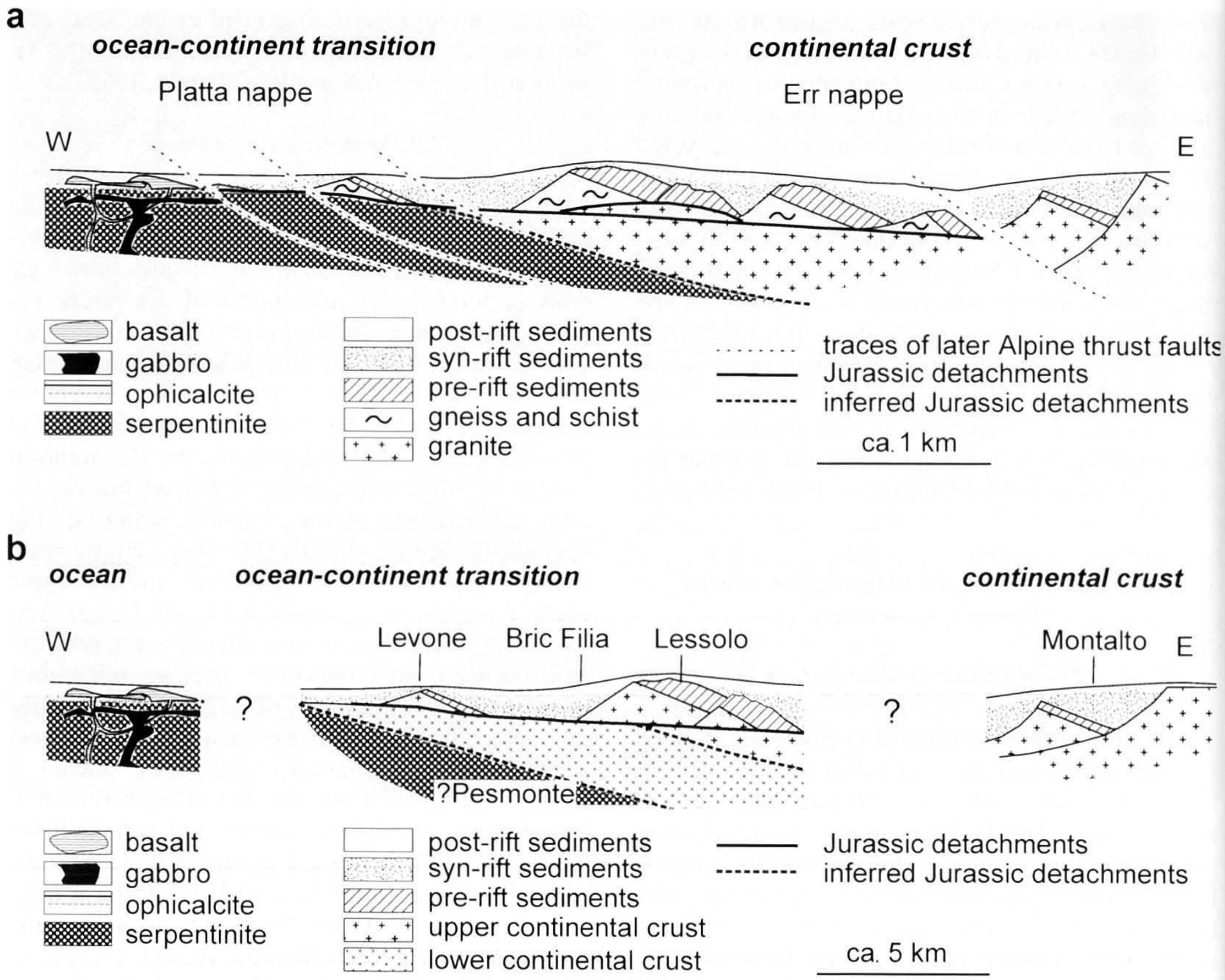

Fig. 10 (a) Palinspastic reconstruction of the Err-Platte ocean-continent transition (after Manatschal and Nievergelt, 1997). (b) A possible Jurassic scenario for the Canavese zone.

8. Alpine metamorphic and tectonic evolution of the Canavese rocks

Our petrographic observations allow us to constrain the Alpine metamorphic and tectonic evolution of the Canavese zone. A very low-grade tectono-metamorphic overprint can be recognised in all lithologies. It is characterised by the growth of quartz, albite, white mica, chlorite, carbonate, prehnite, pumpellyite, epidote *s.l.*, opaque ores, titanite and zeolites, and is associated with a mylonitic to cataclastic deformation. Because also the Mesozoic sediments show this overprint and because it is largely developed along the two major Alpine fault systems, an older one oriented NE–SW, and a younger one oriented approximately NNW–SSE (Fig. 3), it must be of Alpine age. Our observations and conclusions are in agreement with those of Zingg et al. (1976).

There is evidence that, between the Variscan and the Alpine tectono-metamorphic events, another tectono-metamorphic overprint took place along ductile shear zones. This phase of deformation is inferred from the presence of phyllonites with a mylonitic foliation defined by green biotite, i.e. a mineral incompatible with the metamorphic conditions of both the Variscan and Alpine events. Although this tectono-metamorphic event is difficult to constrain chronologically, it is most probably connected with the rifting of the continental crust leading to the opening of the Piemonte-Liguria ocean (see below).

9. Palaeotectonic evolution of the Canavese zone

The basement rocks and the Mesozoic sedimentary succession of the Canavese obviously have much in common with those of the western Southern Alps (Bernoulli, 1964; Baggio, 1965a, 1965b) and with the lower Austroalpine nappes (Spitz, 1919; Bernoulli, 1964; Sturani, 1973). An original proximity between the Canavese and the Ivrea zone is suggested by the presence of mafic granulite "fragments" within the migmatites. With the upper-Penninic Platta nappe of Graubünden, the Canavese zone shares the admittedly sparse occurrence of minor serpentinite bodies (Pesmonte). The serpentinite bodies are everywhere bounded by faults, and it is not clear whether they are fragments derived from the south-Pennine Piemonte zone, imbricated with the Canavese rocks during Alpine orogeny (e.g. Sturani, 1973), or are part of the Canavese basement (Baggio, 1965a). In our view, the palaeotectonic evolution places the Canavese zone at the thinned distal margin of the Adriatic plate, facing the Piemonte-Liguria ocean. Relics of this ocean are preserved in the thin serpentinite slices exposed along the tectonic contact with the adjacent Sesia Zone; however, within the Canavese a "real" ophiolite sequence (Elter et al., 1966) including also mafic volcanics is conspicuously missing.

9. 1. Lower and upper crustal rocks

Two clearly distinct types of basement assemblages are present in the Canavese zone, characterised by different metamorphic grade and lithological associations. The migmatic basement consists of migmatic gneisses, associated with anatectic leucogranite locally including relics of mafic granulites. Migmatites, kinzigitic gneisses and gabbros have been reported also by Wozniak (1977) from northwest of Belmonte and the Levone area. The mafic granulites are very similar, with respect to composition, microstructure and evolution, to the mafic granulites of the adjacent Ivrea zone (Wozniak, 1977), and the entire association presents analogies to the lower crustal rocks of the Ivrea zone. By contrast, the gneiss-amphibolite basement consists of various amphibolite-grade gneisses and schists, which were intruded by Permian granitoids. This basement does not include migmatites or enclaves of granulite-facies rocks and corresponds to a shallower crustal level.

The two basement assemblages, which now occur in neighbouring outcrops but represent different depth sections of the crust, could have been juxtaposed during the Alpine orogeny or during Mesozoic rifting and crustal thinning. Evidence that the two basement sections were juxtaposed already during the Jurassic comes from the clast content of the Middle Jurassic polymictic breccias. These breccias, besides clasts from the gneiss-amphibolite basement, locally include clasts of all the lithologies observed in the migmatic basement. These clasts show that the lower crustal rocks were exhumed to the surface already in Jurassic times. Indeed, the radiolarites stratigraphically overlie the migmatic basement at Bric Filia. In addition, the breccias yield clasts of (1) black cataclasites, similar to those described from low-angle detachments, active during rifting in the Err-Platta ocean-continent transition (Froitzheim and Eberli, 1990; Manatschal, 1999), and (2) phyllonites that otherwise occur in the Canavese basement. These phyllonites show a mylonitic foliation defined by green biotite, a metamorphic mineral indicating a temperature higher than that reached during the very low-grade prehnite-pumpellyite-facies overprint of the Alpine orogeny, usually shown by the Canavese rocks.

9.2. Exhumation of lower crust and mantle

The poor outcrops of the Canavese zone and the extreme tectonic imbrication of its stratigraphic succession does not allow for a palinspastic reconstruction of the pre-Alpine situation. However, a scenario for the exhumation of lower crustal and mantle rocks has been developed in the transect of the Err and Platta nappes in Graubünden (Froitzheim and Manatschal, 1996; Manatschal and Nievergelt, 1997), and been compared to the evolution of the distal continental margin west of Iberia (Manatschal and Bernoulli, 1998, 1999). Along the transect of Graubünden, the anatomy of the former distal margin and the ocean-continent transition can be reconstructed (Fig. 10a).

In the transect of the Austroalpine nappes of Graubünden and of the western Southern Alps (Fig. 11), two major phases of rifting can be distinguished. An earlier one, lasting from the late Norian into the Pliensbachian, was characterised by listric faults soling within the continental crust (Bertotti, 1991; Manatschal and Bernoulli, 1999, their Fig. 10b). This phase of rifting thinned the crust to about 10 km (Handy et al., 1999; Manatschal, 2004) and generated asymmetric sedimentary basins, between 20 and 30 km wide and filled by km-thick syn-rift sediments (Bernoulli, 1964; Eberli, 1988, Bertotti et al., 1993). During a second phase, lasting from the Toarcian (?) into the early Middle Jurassic, the area which was to become the distal margin of the Liguria-Piemonte ocean (Err nappe), was dissected by low-angle detachment faults. These faults form break-aways in the continental crust and cut oceanwards into the subcontinental mantle lithosphere. Pre-rift lower crustal rocks are generally not exposed along this detachment system but occur along the same margin in the Malenco area and in the Ivrea zone, where they are separated from the upper crust by crustal-scale, continentward-dipping faults (Margna fault, Malenco, Müntener and Hermann,

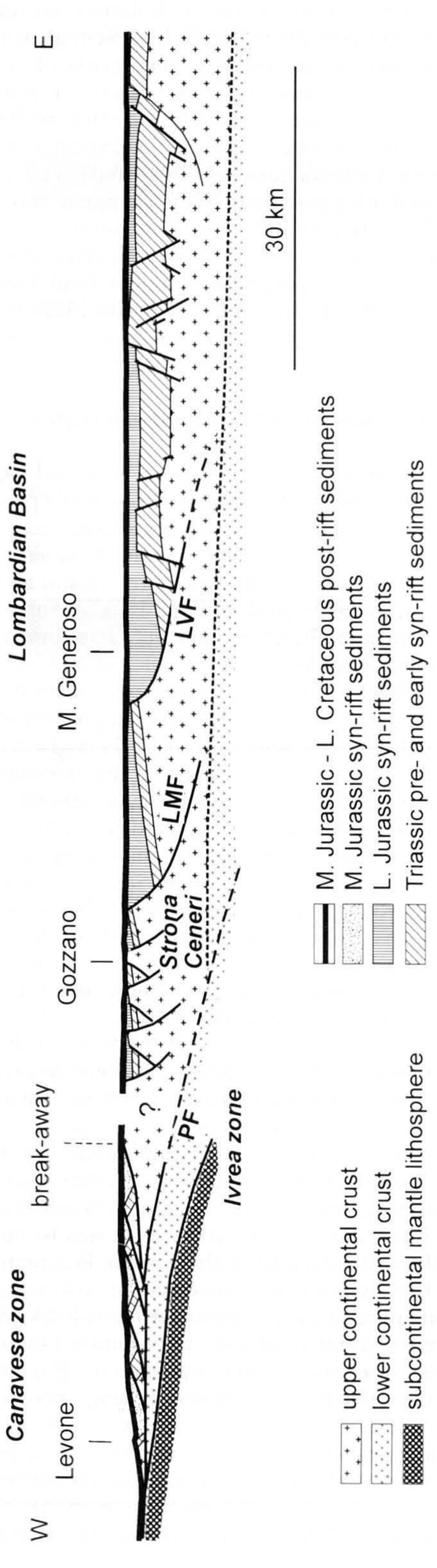

Fig. 11 Architecture of the South-Alpine continental margin during the Jurassic. Lombardian Basin after Bertotti et al. (1993). PF—Pogallo Fault; LMF—Lago Maggiore Fault; LVF—Lugano-Val Grande Fault.

2001; Pogallo fault, Ivrea zone, Handy and Zingg, 1991; Handy et al., 1999). By contrast, lower crustal rocks form clasts in the polymictic breccias (Middle Jurassic) of the Canavese. It is therefore possible that the Pogallo fault, that was active before 180 Ma, came to the surface in the Canavese zone.

Along the Austroalpine distal margin, extensional allochthons of upper crust were emplaced on the exhumed mantle along the system of low-angle detachment faults (Platta nappe, Fig. 10a). The fault rocks accompanying the detachment faults were exhumed to the sea floor and today occur as clasts in the syn-rift sediments of the Saluver Formation. These late syn-rift sediments include "matrix-free, chaotic breccias, formed by submarine, catastrophic mass-flow events at the base of a major fault scarp" (Froitzheim and Manatschal, 1996, p. 1126) and can be compared to the polymictic breccias of the Canavese Zone. Likewise, coarse mass-flow breccias, massive sandstones deposited from concentrated turbidity flow and thin-bedded turbidites interbedded with black shales (Finger, 1978), which accompany the extensional allochthons, closely resemble the breccias, sandstones and shales at Levone, both in terms of sedimentary structures and clast content (Fig. 8). We therefore correlate the polymictic breccias and the Levone series with the Saluver Formation.

In the Canavese zone, we can recognise the essential elements of the distal Austroalpine-South Alpine margin although we cannot reconstruct the distal margin palinspastically (Figs. 10b and 11). In the east, in the area of Montalto and Vidracco, Liassic rifting is documented by tectono-sedimentary breccias and neptunian dykes (Macchia Vecchia). Further west, west of Vidracco, the polymictic breccias (of presumably Toarcian to early Middle Jurassic age) include fragments of black cataclasites, phyllonites and lower crustal rocks. These clasts show that the fault rocks in question are pre-Alpine and that lower crustal rocks, similar to those of the Ivrea zone, were exhumed to the sea floor. The cataclastic granite of Levone, mantled by Saluver-type breccias and turbidites, may be interpreted as a fault block, emplaced in the hanging-wall of a low-angle detachment. The persistence of a submarine relief, related to the emplacement of fault blocks, throughout the Jurassic is further demonstrated by the occurrence of granitic and gneissic clasts in debris-flow deposits and turbidites intercalated in the Radiolarite and the Maiolica Formations, both in the Canavese Zone (Baggio, 1963b) and in Graubünden (Fig. 9d). This situation is similar to the one observed along the distal Armorican margin where outcrops of granites are observed still today, some 100 my after rifting (Pautot et al., 1976).

The isolated occurrence of serpentinised peridotites within the Canavese zone (Pesmonte) could suggest mantle exhumation during the Jurassic. In contrast to the peridotites of the Ivrea zone (including the peridotites of Baldissero) or of the Malenco unit, which were exhumed during the Jurassic (see Handy and Zingg, 1991 for the Ivrea zone; Hermann et al., 1997, and Müntener et al., 2000 for Malenco) but not exposed on the seafloor, the peridotites imbricated within the Canavese zone were completely serpentinised. This could indicate that they were uplifted to shallow depth (< 6 km, *cf.* Chian et al., 1999) during the Jurassic but not necessarily to the bottom of the sea because ophicalcites, which typically mark the trace of the low-angle detachment faults (Bernoulli et al., 2003) on the seafloor, are not known from Pesmonte.

9.3. The Canavese zone in the Alpine context

The close affinities of the Canavese zone with the Austroalpine Err nappe of Graubünden leave little doubt that the Canavese zone was, during the Jurassic, part of the distal margin of Adria facing the evolving Liguria-Piemonte ocean. A correlation of the western Southern Alps with the lower Austroalpine nappes was already proposed by De Sitter (1947) long ago. However, although the lower Austroalpine realm and the Canavese were part of the very same distal continental margin, they had a different fate during Cretaceous–Early Tertiary Alpine orogeny (De Sitter, 1947; Laubscher, 1991, his Fig. 11). During the Late Cretaceous, the Austroalpine and South-Pennine units of Graubünden were involved into a west-vergent (in present-day coordinates) pile of nappes (Froitzheim et al., 1994), whereas in the Southern Alps pre-mid-Eocene, possibly Late Cretaceous south-vergent thrusts towards a southern foreland are found at the surface (Schumacher et al., 1997). This does not exclude Late Cretaceous or Early Tertiary thrusting of the Ivrea zone onto the Canavese.

Elter et al. (1966) and Sturani (1973) correlated the Canavese zone across the presumed basement of the Monferrato with the external Liguride units of the Northern Apennines. In this area, the original Mesozoic substrate of the thrust nappes is only locally preserved, and the composition of the original basement has to be deduced from the components of sedimentary and tectonic melanges. For the internal (originally oceanward) part an ocean-continent transition with subcontinental mantle exhumed to the sea floor, gabbroic intrusions and extensional allochthons of continental crust – a situation similar to that of the Platta nappe (see Desmurs et al., 2001) – is suggested (Marroni et al., 2001). For the external part, a thinned continental basement, similar to that of the Err nappe may be assumed. Like in the Canavese, blocks of mafic granulites comparable to Permian gabbro-derived granulites of the Ivrea zone occurring in Cretaceous melanges (Marroni and Tribuzio, 1996) show that lower crustal rocks must have been exhumed under decreasing temperatures, with all certainty during Jurassic rifting (Marroni et al., 1998). The new data from the external Apennines confirm the previous correlation of Elter et al. (1966) and document the prolongation of the Adriatic rifted margin from the Eastern Alps and the Canavese zone into the Northern Apennines.

10. Conclusions

Although the stratigraphic successions of the Canavese zone are badly exposed and have been dismembered by late Alpine ductile shear zones and brittle faults, the signatures of Early to Middle Jurassic rifting are still preserved in the rock record. What can be deduced from these geological documents is a rifting history that is analogous to that reconstructed along the Australpine-South Pennine boundary zone in Graubünden (Manatschal and Nievergelt, 1997; Desmurs et al., 2001; Manatschal, 2004), the internal Apennines (Marroni et al., 2001), and along the early Cretaceous west-Iberian margin (Manatschal and Bernoulli, 1998, 1999; Manatschal, 2004). In particular, the Middle Jurassic late syn-rift sediments (polymictic breccias) of the Canavese zone are conspicuously similar to the analogous late syn-rift sediments of the lower Austroalpine Err nappe (Saluver Formation).

The occurrence of clasts of upper and lower crustal rocks in the polymictic conglomerates and breccias shows that the two types of basement occurring in the Canavese zone were juxtaposed and exposed to the sea floor already in Middle Jurassic times, most probably along low-angle extensional detachment faults as observed today along the Cretaceous west-Iberian margin. The occurrence of black cataclasites, associated in the Err nappe with the low-angle detachment zone (Manatschal, 1999), as clasts in the late syn-rift sediments of the Canavese underlines these analogies. We therefore interpret the Canavese zone as the distal continental margin of Adria, facing the Liguria-Piemonte ocean to the west. There is as yet no proof for the exhumation of mantle rocks to the seafloor in the Canavese zone, but to the west such rocks appear to have been exhumed along an ocean-continent transition like in the South-Pennine Platta nappe.

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References

Ahrendt, H. (1972): Zur Stratigraphie, Petrographie und zum tektonischen Aufbau der Canavese-Zone und ihrer Lage zur Insubrischen Linie zwischen Biella und Cuorgné (Norditalien). *Göttinger Arb. Geol. Paläont.* **11**, 1–89.

Argand, E. (1909a): Sur la racine de la nappe rhétique. *Mitt. Schweiz. Geol. Komm.* **1**, 1–7.

Argand, E. (1909b): L'exploration géologique des Alpes Pennines Centrales. *Bull. Soc. Vaud. Sci. Nat.* **45/166**, 5–64.

Aubouin, J., Blanchet, R., Labesse, B. and Wozniak, J. (1977): Alpes occidentales et Alpes orientales: la zone du Canavese existe-t-elle? *C. R. Somm. Soc. Géol. France* **3**, 155–158.

Baggio, P. (1963a): Sulla presenza di una serie titonico-cretacea nel Canavese s.s. (Prealpi Piemontesi). *Atti Ist. Veneto Sci. Lett. Arti* **121**, 215–234.

Baggio, P. (1963b): Osservazioni geologiche sulla zona del Canavese s.s., nel tratto Cuorgné-Issiglio (Prealpi Piemontesi). *Atti Accad. Sci. Torino* **97**, 1–22.

Baggio, P. (1965a): Geologia della zona del Canavese nel settore occidentale Levone-Cuorgné (Prealpi Piemontesi). *Mem. Accad. Patavina Sci. Lett. Arti* **77**, 41–71.

Baggio, P. (1965b): Caratteri stratigrafici e strutturali del Canavese s.s. nella zona di Montalto Dora. *Mem. Ist. Geol. Mineral. Univ. Padova* **25**, 1–25.

Baggio, P. (1973): Appunti su di un recente lavoro di H. Ahrendt riguardante la zona del Canavese, con note di chiarimento sulla linea insubrica. *Boll. Soc. Geol. It.* **92**, 767–775.

Baretti, M. (1877): Studi geologici sul gruppo del Gran Paradiso. *Atti R. Accad. Lincei* **1**, 195 pp.

Bernoulli, D. (1964): Zur Geologie des Monte Generoso (Lombardische Alpen). Ein Beitrag zur Kenntnis der südalpinen Sedimente. *Beitr. Geol. Karte Schweiz*, **N.F. 118**, 134 pp.

Bernoulli, D., Bertotti, G. and Froitzheim, N. (1990): Mesozoic faults and associated sediments in the Austroalpine-South Alpine passive continental margin. *Mem. Soc. Geol. It.* **45**, 25–38.

Bernoulli, D., Manatschal, G., Desmurs, L. and Müntener, O. (2003): Where did Gustav Steinmann see the Trinity? Back to the roots of an Alpine ophiolite concept. In: Dilek, Y. and Newcombe, S. (eds.): Ophiolite Concept and the Evolution of Geological Thought. *Geol. Soc. Am. Spec. Publ.* **373**, 93–110.

Bertotti, G. (1991): Early Mesozoic extension and Alpine shortening in the western Southern Alps: the geology of the area between Lugano and Menaggio (Lombardy, northern Italy). *Mem. Sci. Geol. (Padova)* **43**, 17–123.

Bertotti, G., Picotti, V., Bernoulli, D. and Castellarin, A. (1993): From rifting to drifting: Triassic evolution of the south-Alpine upper crust from the Triassic to the Early Cretaceous. *Sediment. Geol.* **86**, 53–76.

Bigi, G., Castellarin, A., Coli, M., Dal Piaz, G.V., Sartori, R., Scandone, P. and Vai, G.B. (1990): Structural model of Italy 1:500.000, sheet 1. C.N.R., Progetto Finalizzato Geodinamica, S.EL.CA., Firenze.

Biino, G. and Compagnoni, R. (1989): The Canavese Zone between the Serra d'Ivrea and the Dora Baltea River (Western Alps). *Eclogae geol. Helv.* **82**, 413–427.

Bill, M., O'Dogherty, L.O., Guex, J., Baumgartner, P.O. and Masson, H. (2001): Radiolarite ages in Alpine-Mediterranean ophiolites: Constraints on the oceanic spreading and the Tethys-Atlantic connection. *Geol. Soc. Am. Bull.* **113**, 129–143.

Borghi, A., Compagnoni, R. and Naldi, M. (1996): The crystalline basement of the Canavese Zone (Internal Western Alps): new data from the area west of Ivrea (Northern Italy). *Géol. Alpine* **72**, 23–34.

Caron, C. (1972): La Nappe Supérieure des Préalpes: subdivisions et principaux caractères du sommet de l'édifice préalpin. *Eclogae geol. Helv.* **65**, 57–73.

Carraro, F. and Sturani, C. (1972): Segnalazione di Toarciano fossilifero in facies Austroalpina ("Fleckenmergeln") nel lembo sedimentario di Sostegno (Biellese). *Boll. Soc. Geol. It.* **91**, 407–417.

Chian, D., Loudon, E.K., Minshull, T.A. and Whitmarsh, R.B. (1999): Deep structure of the ocean-continent transition in the southern Iberia Abyssal Plain from seismic refraction profiles: Ocean Drilling Program (Legs 149 and 173) transect. *J. Geophys. Res.* **104**, 7443–7462.

Dal Piaz, G.V. (1999): The Austroalpine-Piedmont nappe stack and the puzzle of Alpine Tethys: *Mem. Sci. Geol. (Padova)* **51**, 155–176.

De Sitter, L.U. (1947): Antithesis Alps-Dinarids. *Geol. Mijnbouw* **9**, 1–13.

Desmurs, L., Manatschal, G. and Bernoulli, D. (2001): The Steinmann trinity revisited: mantle exhumation and magmatism along an ocean-continent transition: the Platta nappe, eastern Switzerland. In: Wilson, R.C.L., Whitmarsh, R.B., Taylor, B. and Froitzheim, N. (eds.): Non-volcanic Rifting of Continental Margins: Evidence from Land and Sea. *Geol. Soc. (London) Spec. Publ.* **187**, 235–266.

Eberli, G. (1988): The evolution of the southern continental margin of the Jurassic Tethys Ocean as recorded in the Allgäu Formation of the Austroalpine nappes of Graubünden. *Eclogae geol. Helv.* **81**, 175–214.

Elter, G., Elter, P., Sturani, C. and Weidmann, M. (1966): Sur la prolongation du domaine ligure de l'Apennin dans le Monferrat et les Alpes et sur l'origine de la Nappe de la Simme s.l. des Préalpes romandes et chablaisiennes. *Arch. Sci. (Genève)* **19**, 279–377.

Farabegoli, E. and De Zanche, V. (1984): A revision of the Anisian stratigraphy in the western Southern Alps west of Lake Como. *Mem. Sci. Geol. (Padova)* **36**, 391–401.

Fenoglio, M. (1930): Studi petrografici sulla Zona del Canavese. Il granito di Belmonte. *Period. Mineral.* **2**, 61 pp.

Fenoglio, M. (1931): Studi petrografici sulla Zona del Canavese. Porfidi e Tufi. *Period. Mineral.* **3**, 213–258.

Finger, W. (1978): Die Zone von Samaden (unterostalpine Decken, Graubünden) und ihre jurassischen Brekzien. *Mitt. Geol. Inst. ETH. Univ. Zürich* **N.F. 224**, 140 pp.

Franchi, S. (1903): Affioramenti di Trias e di Lias in Valsesia e nel Biellese. *Boll. R. Com. Geol. It.* **35**, 1–20.

Froitzheim, N. and Eberli, G. (1990): Extensional detachment faulting in the evolution of a Tethys passive continental margin, eastern Alps, Switzerland. *Geol. Soc. Am. Bull.* **102**, 1297–1308.

Froitzheim, N. and Manatschal, G. (1996): Kinematics of Jurassic rifting, mantle exhumation, and passive-margin formation in the Austroalpine and Penninic nappes (eastern Switzerland). *Geol. Soc. Am. Bull.* **108**, 1120–1133.

Froitzheim, N., Schmid, S. and Conti, P. (1994): Repeated change from crustal shortening to orogen-parallel extension in the Austroalpine units of Graubünden. *Eclogae geol. Helv.* **87**, 559–612.

Fudral, S. and Deville, E. (1986): La zone Sesia existe-t-elle? Nouvelles observations sur les enveloppes métasédimentaires du massif cristallin pré-triasique de Sesia au Nord du Mont Ciucrin (Alpes occidentales-Région de Lanzo-Italie). *C.R. Acad. Sci. Paris* **302**, sér. 2, 1021–1026.

Furrer, H. (1985): Field workshop on Triassic and Jurassic sediments in the Eastern Alps of Switzerland. *Mitt. Geol. Inst. ETH. Univ. Zürich* **N.F. 248**, 81 pp.

Gastaldi, B. (1871): Studi geologici sulle Alpi Occidentali, Parte I. *Mem. R. Com. Geol.* **1**, 1–47.

Handy, M. and Zingg, A. (1991): The tectonic and rheological evolution of an attenuated cross-section of the continental crust: Ivrea crustal section, southern Alps, northwestern Italy and southern Switzerland. *Geol. Soc. Am. Bull.* **103**, 236–253.

Handy, M.R., Franz, L., Heller, F., Janett, B. and Zurbriggen, R. (1999): Multistage accretion and exhumation of the continental crust (Ivrea crustal section, Italy and Switzerland). *Tectonics* **18**, 1154–1177.

Heim, A. (1922): Geologie der Schweiz, Band II, Die Schweizer Alpen. Tauchnitz, Leipzig, 1018 pp.

Hermann J., Müntener, O., Trommsdorff, V., Hansmann, W. and Piccardo, G.B. (1997): Fossil crust-to-mantle transition, Val Malenco (Italian Alps). *J. Geophys. Res.* **102**, 123–132.

Issel, A. (1893): Appunti geologici sui colli di Baldissero (Canavese). *Boll. Soc. Geol. It.* **12**, 255 pp.

Kretz, R. (1983): Symbols for rock-forming minerals. *Am. Mineral.* **68**, 277–279.

Laubscher, H. (1991): The arc of the Western Alps today. *Eclogae geol. Helv.* **84**, 631–659.

Manatschal, G. (1999): Fluid- and reaction-assisted low-angle faulting: Evidence from rift-related brittle fault rocks in the Alps (Err nappe, Switzerland). *J. Struct. Geol.* **21**, 777–793.

Manatschal, G. (2004): New models for evolution of magma-poor rifted margins based on a review of data and concepts from West Iberia and the Alps. *Int. J. Earth Sci.* **93**, 432–466.

Manatschal, G. and Bernoulli, D. (1998): Rifting and early evolution of ancient ocean basins: the record of the Mesozoic Tethys and of the Galicia-Newfoundland margins. *Mar. Geophys. Res.* **20**, 371–381.

Manatschal, G. and Bernoulli, D. (1999): Architecture and tectonic evolution of nonvolcanic margins: present-day Galicia and ancient Adria. *Tectonics* **18**, 1099–1119.

Manatschal, G. and Nievergelt, P. (1997): A continent-ocean transition recorded in the Err and Platta nappes (Eastern Switzerland). *Eclogae geol. Helv.* **90**, 3–27.

Marroni, M. and Tribuzio, R. (1996): Gabbro-derived granulites from External Liguride units (northern Apennines, Italy): implications for the rifting process in the western Tethys. *Geol. Rundsch.* **85**, 239–249.

Marroni, M., Molli, G., Montanini, A. and Tribuzio, R. (1998): The association of continental crust rocks with ophiolites in the Northern Apennines (Italy): implications for the ocean-continent transition in the western Tethys. *Tectonophysics* **292**, 43–66.

Marroni, M., Molli, G., Ottria, G. and Pandolfi, L. (2001): Tectono-sedimentary evolution of the External Liguride units (Northern Apennines, Italy): insights in the pre-collisional history of a fossil ocean-continent transition zone. *Geodin. Acta* **14**, 307–320.

Mehnert, K.R. (1968): Migmatites and origin of granites. Elsevier, Amsterdam, 393 pp.

Müntener, O. and Hermann, J. (2001): The role of lower crust and upper mantle during formation of non-volcanic passive margins. In: Wilson, R.C.L., Whitmarsh, R.B., Taylor, B. and Froitzheim, N. (eds.): Non-volcanic Rifting of Continental Margins: Evidence from Land and Sea. *Geol. Soc (London) Spec. Publ.* **187**, 267–288.

Müntener, O., Hermann, J. and Trommsdorff, V. (2000): Cooling history and exhumation of lower crustal granulite and upper mantle (Malenco, eastern central Alps). *J. Petrol.* **41**, 175–200.

Novarese, V. (1929): La Zona del Canavese e le formazioni adiacenti. *Mem. Descr. Carta Geol. It.* **22**, 65–212.

Parona, C.F. (1924): Trattato di geologia. F. Vallardi, Milano, 648 pp.

Pautot, G., Renard, V., Auffret, G. and Pastouret, L. (1976): A granite cliff deep in the North Atlantic. *Nature* **263**, 669–672.

Pognante, U. (1989): Lawsonite, blueschist and eclogite formation in the southern Sesia zone (western Alps, Italy). *Eur. J. Mineral.* **1**, 89–104.

Rasetti, E. (1897): Il Monte Fenera di Valsesia. *Boll. Soc. Geol. It.* **16**, 141–175.

Schmid, S.M., Zingg, A. and Handy, M. (1987): The kinematics of movements along the Insubric Line and the emplacement of the Ivrea Body. *Tectonophysics* **135**, 47–66.

Schmid, S.M., Aebli, H.R., Heller, F. and Zingg, A. (1989): The role of the Periadriatic line in the tectonic evolution of the Alps. In: Coward, M.P., Dietrich, D. and Park, R.G. (eds.): Alpine Tectonics. *Geol. Soc. (London) Spec. Publ.* **45**, 153–171.

Schumacher, M.E., Schönborn, G., Bernoulli, D. and Laubscher, H. (1997): Rifting and collision in the Southern Alps: In: Pfiffner, O.A., Lehner, P., Heitzmann, P., Müller, St. and Steck, A. (eds.): Deep Structure of the Swiss Alps – Results from National Research Program 20 (NRP 20), Birkhäuser, Basel, 186–204,

Schüpbach, M. (1973): Comparison of slope and basinal sediments of a marginal cratonic basin (Pedregosa Basin, New Mexico) and a marginal geosynclinal basin (southern border of Piemontais Geosyncline, Bernina nappe, Switzerland). Ph.D. Thesis, Rice University, Houston, 126 pp.

Sismonda, A. (1845): Notizie e schiarimenti sulla costituzione delle Alpi Piemontesi. *Mem. Accad. Sci. Torino* **2**, 34–40.

Spitz, A. (1919): Liasfossilien aus dem Canavese. *Verh. Geol. Reichsanst.* **11**, 317–325.

Steinmann, G. (1905): Geologische Beobachtungen in den Alpen, II. Die Schardtsche Ueberfaltungstheorie und die geologische Bedeutung der Tiefseeabsätze und der ophiolithischen Massengesteine. *Ber. Natf. Ges. Freiburg im Breisgau* **16**, 18–67.

Staub, R. (1924): Der Bau der Alpen. *Beitr. Geol. Karte Schweiz* **NF 52**, 272 pp.
Sturani, C. (1964): Prima segnalazione di Ammoniti nel Lias del Canavese. *Rend. Accad. Lincei* **37**, 482–483.
Sturani, C. (1973): Considerazioni sui rapporti tra Appennino settentrionale ed Alpi occidentali. In: Moderne vedute sulla geologia dell'Appennino. *Accad. Naz. Lincei Quad.* **183**, 119–142.
Sturani, C. (1975): Explanatory notes on the western Alps (from the Sestri-Voltaggio line to the Val d'Ossola. In: Ogniben, L., Parotto, M. and Praturlon, A. (eds.): Structural model of Italy, Maps and explanatory notes. *CNR, Quaderni de La Ricerca Scientifica* **Chapter 6**, 149–174.
Wiedenmayer, F. (1963): Obere Trias bis mittlerer Lias zwischen Saltrio und Tremona (Lombardische Alpen). Die Wechselbeziehungen zwischen Stratigraphie, Sedimentologie und syngenetischer Tektonik. *Eclogae geol. Helv.* **56**, 529–640.
Wozniak, J. (1977): Contribution à l'étude géologique des Alpes Occidentales internes: la region du Canavese. Ph.D. Thesis, Univ. Pierre et Marie Curie, Paris, 146 pp.
Zingg, A., Hunziker, J.C., Frey, M. and Ahrendt, H. (1976): Age and degree of metamorphism of the Canavese Zone and of the sedimentary cover of the Sesia Zone. *Schweiz. Mineral. Petrogr. Mitt.* **56**, 361–365.

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