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Volcanic products from the Early Permian Collio Basin (southern Alps) and their geodynamic implications

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Abstract. — The typical Early Permian Collio Basin, in the central Southern Alps between eastern Lombardy and western Trentino, developed in a widespread transtensional regime, likewise all the Permian continental basins of this region, and was associated with the emplacement of volcanic products.

The basal plateau, up to about 130 m thick, is made up of calc-alkaline rhyolitic ignimbrites interpreted as early anatectic magmas from the lower crust, thickened after the Variscan collision. However, andesite lithic inclusions suggest that a volcanic phase with intermediate composition occurred prior to the conspicuous silica rich-volcanism. The source area of these subaerial igneous flows, also known as "Lower Quartz Porphyries" in the literature, was probably between the southwestern margin of the basin and the present lower Camonica Valley. A pile, less than 100 m thick of vitric and crystal tuffs, marked at the top by diffuse accretionary lapilli, follows above.

Later, the overlying alluvial-to-lacustrine Collio Formation was interfingered with several subaqueous thin volcaniclastic key-beds, suitable for correlation. They normally consist of (1) a lower, amalgamated coarse-sandy to gravelly crystal-rich massive turbiditic subunit, 10–20 and more metres thick, which displays isolated outsize clasts of the underlying Collio Formation, as well as of volcanic and metamorphic rocks; and (2) an upper, well-bedded sandy-pelitic subunit, generally less than 3 m thick and rich in outsize porphyritic fragments, which suggest deposition from fine-grained turbidity currents. These so-called "Dasdana Beds" originated from one or more igneous centres at the eastern part of the Collio Basin beyond the Caffaro Valley, near the Brescia-Trento border, rapidly thinning westwards. In particular, the main areas feeding the igneous activity were located along the ENE Val Trompia lineament, north of the Bagolino-Riccomassimo "knee-fold". Here, the subvolcanic bodies cut the crystalline basement and part of the overlying Lower Permian succession and flowed into the basin floor from the Dosso del Bue lava dome (up to about 200 m thick). Eastwards, from Riccomassimo to Darzo (upper Val Sabbia), close to the intersection between the Val Trompia and the Lower Giudicarie lines, the Early Permian igneous activity is more developed and shows textural heterogeneities probably related to the subvolcanic occurrence of the bodies.

The last igneous event of the basin is represented by further Early Permian rhyolite/rhyodacite massive ignimbrites ("Auccia Volcanics"), which filled up the Collio Basin. The top of this upper volcaniclastic plateau, probably exposed for more than 20 Ma,

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displays clear erosional surfaces and palaeosols in many parts of the basin, before deposition of the fluvial Verrucano Lombardo-Val Gardena red beds, which mark the end of the Late Variscan igneous activity all over the Southern Alps.

Riassunto. — Il Bacino di Collio si sviluppa nel Sudalpino centrale, tra la Lombardia orientale e il Trentino occidentale, e ha avuto origine nel Permiano inferiore durante un regime tettonico transtensile, che ha generato tutti i bacini continentali permiani della regione, e si è accompagnato alla messa in posto di una notevole quantità di prodotti vulcanici.

Il *plateau* vulcanico alla base della successione ha uno spessore massimo di circa 130 m ed è costituito da ignimbriti riolitiche calc-alcaline, interpretate come magmi anatettici precoci prodotti nella crosta inferiore ispessita dopo la collisione Varisica. Tuttavia, *enclaves* di andesiti suggeriscono che una fase vulcanica con composizione intermedia si sia sviluppata prima del vulcanismo acido. L'area sorgente dei flussi vulcanici subaerei era probabilmente collocata tra il margine sud-occidentale del bacino e l'attuale Val Camonica inferiore. L'orizzonte ignimbritico basale, noto in letteratura anche sotto il nome di "Porfidi Quarziferi Inferiori", culmina con un'unità di più di 100 m di spessore di tufi vetrosi ed a cristalli, caratterizzata alla sommità da lapilli accrezionari.

La soprastante Formazione di Collio contiene numerose intercalazioni di livelli vulcanoclastici, utili per le correlazioni laterali. Questi livelli sono, di regola, costituiti da: (1) una sub-unità inferiore, massiva, torbiditica, ricca in cristalli di granulometria variabile da sabbie grossolane a ghiaie, di spessore compreso tra 10 e più di 20 metri, che contiene clasti isolati di dimensioni cospicue della sottostante Formazione di Collio e di rocce vulcaniche e metamorfiche; (2) una sub-unità superiore, ben stratificata, arenaceo – pelitica, generalmente di spessore inferiore a 3 m, ricca in frammenti grossolani di rocce porfiriche che è stata probabilmente deposta da correnti di torbida. Tali livelli (i cosiddetti "Dasdana Beds") si sono originati da uno o più centri di attività magmatica situati nella parte orientale del bacino di Collio, oltre la Val Caffaro, vicino al limite tra le provincie di Brescia – Trento, e si assottigliano rapidamente verso ovest. In particolare, la principale zona di alimentazione magmatica era collocata lungo il lineamento ENE della Val Trompia, a N della piega a ginocchio di Bagolino-Riccomassimo. In quest'area i corpi subvulcanici tagliano il basamento e parte della soprastante successione del Permiano inferiore, e fluiscono sul fondo dell'antico bacino lacustre dal duomo di Dosso del Bue (potente fino a 200 m). Verso E, da Riccomassimo a Darzo (Val Sabbia superiore), vicino all'intersezione tra la linea della Val Trompia e la linea delle Giudicarie, l'attività magmatica attribuita al Permiano inferiore è più sviluppata e mostra eterogeneità nei caratteri tessiturali, soprattutto dovute alla messa in posto di corpi subvulcanici.

La formazione vulcanica più recente dell'area è costituita da una seconda ignimbrite massiva del Permiano inferiore (Vulcaniti di Auccia), che colmò il Bacino di Collio. Il livello superiore dell'ignimbrite è stato a lungo (probabilmente più di 20 Ma) in condizioni sub-aeree e mostra numerose evidenze di erosione e paleosuoli precedenti alla deposizione dei "red beds" fluviali del Verrucano Lombardo – Arenarie della Val Gardena. Questi ultimi depositi segnano il termine della attività vulcanica tardo Varisica in tutto il Sudalpino.

Key Words: *Post-Variscan geodynamics, Collio Basin, calc-alkaline volcanism, tectonic control, fluvial-lacustrine sediments.*

Introduction

The Late-Variscan intramontane fault-bounded Collio Basin is located in the central Southern Alps, between eastern Lombardy and western Trentino (Fig. 1). It is infilled by acidic-to-intermediate calc-alkaline volcanic and alluvial-to-lacustrine siliciclastic deposits, attaining a maximum thickness of about 1500 m, which non-conformably rest on the Variscan crystalline basement. The sequence can be interpreted as the Lower Permian Tectono-Stratigraphic Unit (TSU 1) and is followed upwards, again after a marked angular unconformity sealing a gap of as-yet-unknown duration, by another Unit (TSU 2), which spans the Middle?–Upper Permian Verrucano Lombardo fluvial red beds, the Lower Triassic shallow-marine polychromous Servino Formation, and up to include part of the Lower Anisian, the carbonate and evaporitic yellowish Carniola di Bovegno (Fig. 2). These Units respectively correspond to the Lower (1) and Upper (2) Cycles defined in more recent literature (Italian IGCP 203 Group, 1986; Cassinis *et al.*, 1988; Cassinis and Perotti, 1997a, and others).

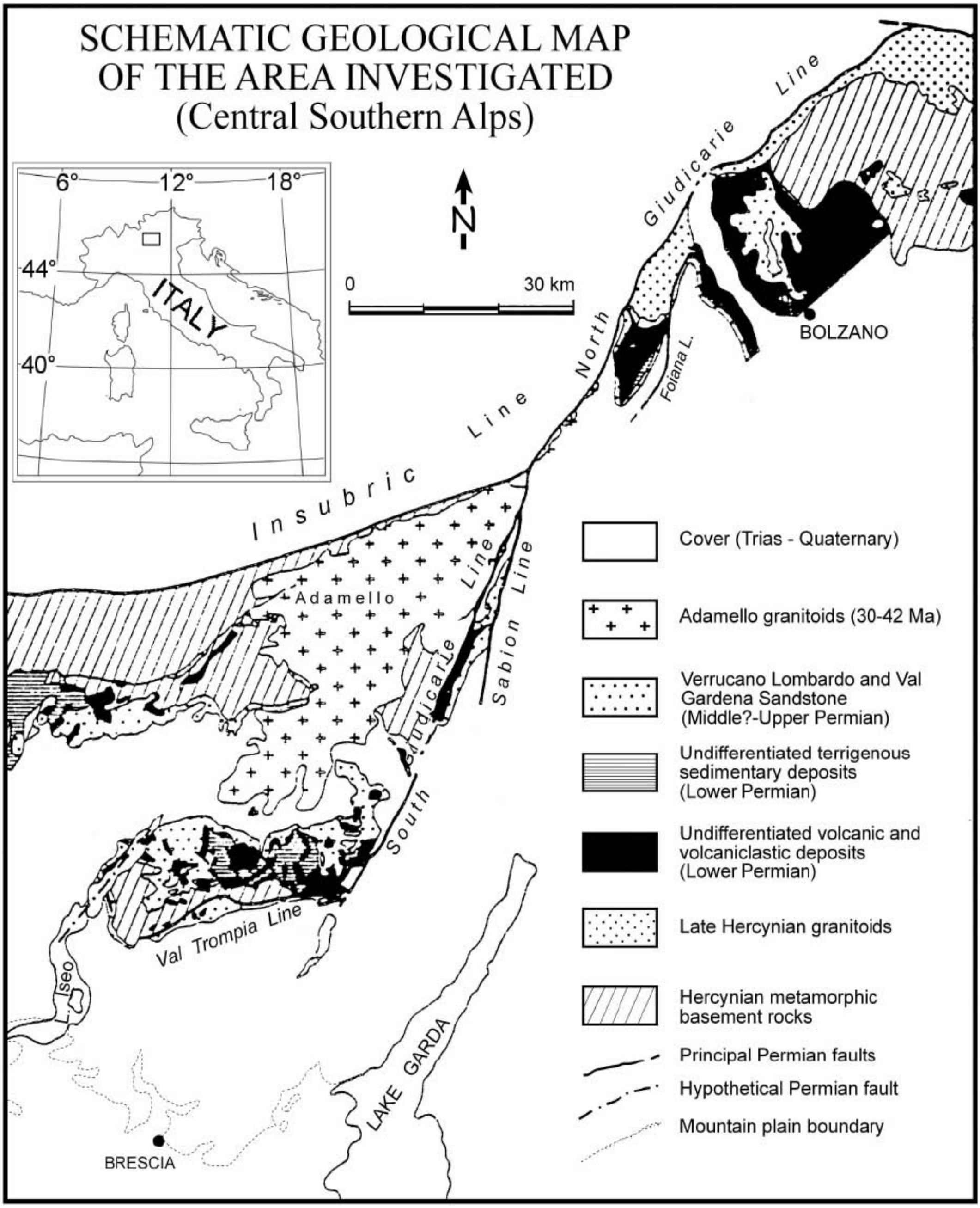

Fig. 1 – Schematic geological map of the central sector of the Southern Alps, including the main Permian continental basins (Tregiovo, Tione, Collio and Orobic Basins in a clockwise order) and neighbouring areas. (Adapted from Consiglio Nazionale delle Ricerche, 1992).

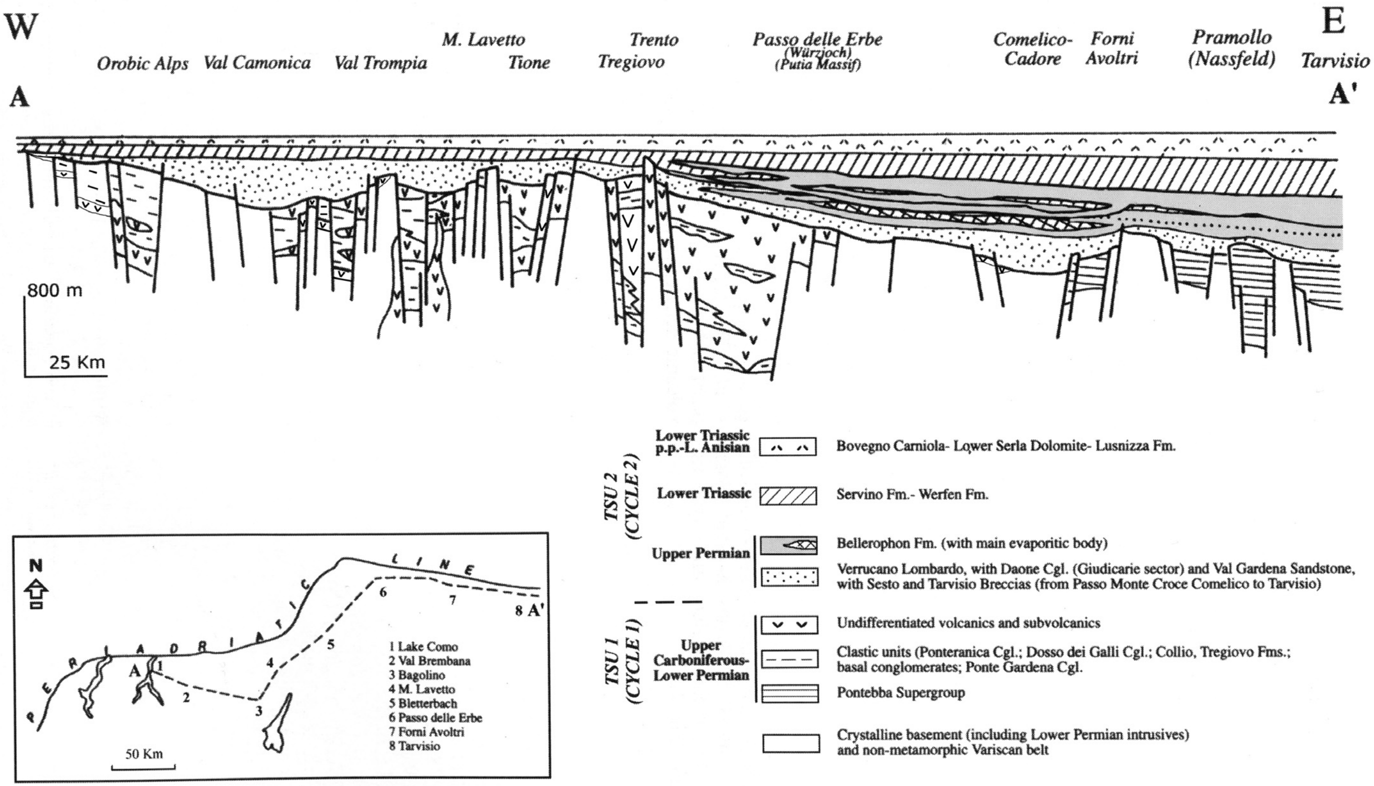

Fig. 2 – Schematic non-palinspastic cross-section (see *trace* on the *inset* map) through the Permian and the Lower Triassic of the central and eastern Southern Alps. *Datum line*: restored top of the Anisian succession, before the beginning of Middle Triassic tectonics (from Italian IGCP-203 Group, 1986 and Cassinis *et al*., 2000a, both slightly modified). TSU 1 and TSU 2: first and second "Tectono-stratigraphic units" of the South-Alpine succession, respectively.

Historical remarks

Early geological investigations on the Collio Basin date back to about the 1800s. These were drawn up by Giuseppe Ragazzoni, a very active and skilful naturalist of Brescia, whose observations gathered the interest of several researchers and shed light on the nearly unknown geology of the region. Cassinis (1966) discovered, in a field notebook of Ragazzoni, three interesting sketches of Mount Colombine (including the upper Val Trompia and surroundings), which represent the oldest stratigraphic sections, from the crystalline basement up to the Triassic rocks, carried out in the Collio Basin. Since then, a great number of Italian and foreign scientists have visited the basin, due to the well-preserved general setting, to detail its stratigraphy and to better understand its geological features. As it is not possible to report all their contributions here, we will point out only the most significant data, which have generally been published since the Second World War and are mainly related to the topic of this paper.

Tectonic setting

The Permian structural evolution of the Collio Basin can be divided into two main intervals. During the first stage, Early Permian in age, the Alpine Giudicarie and some associated lines (Sabion and Foiana), the Val Trompia and other lines were already active (Fig. 3). They can be interpreted, at least in part, as marginal segments of the Collio, Tione and Tregiovo basins and identified with fault scarps controlling sedimentation. Thus these boundary faults, now generally showing SSW–NNE and W–E trends, often coincide with long-lived features reactivated before and during the Alpine orogenesis.

The close connections of these faults with the evolution of the Permian basins in the region, the tectonic structures recognised within some areas, and the geological and sedimentary aspects of the basin successions (clearly influenced by tectonic movements) allowed to envisage that strike slip basins were associated with transtensional tectonics, regionally controlled by dextral-lateral movement of the Giudicarie Line (Cassinis and Perotti, 1994; Fig. 3). In particular the Collio Basin could be interpreted as a wrench-induced pull-apart basin. The Orobic extensional Basin, towards the NW, has probably a similar origin, connected with the transtensional activity of the E–W Insubric lineament (Cadel, 1986; Cassinis and Perotti, 1994).

This Early Permian tectonics, active in the Variscan areas since Carboniferous times, displays a geometry compatible with the structural framework subsequent to that orogeny, within a dextral megashear zone stretching from the Appalachians to the Urals (Arthaud and Matte, 1977; Blès *et al*., 1989; Fig. 3).

The palinspastic reconstructions deduced from palaeomagnetic data (Van Hilten, 1960; Zijderveld and De Yong, 1969; Vanderberg and Wonders, 1976; Westphal, 1976; Heiniger, 1979; Heller *et al*., 1989) indicate that the central South-Alpine areas underwent counterclockwise rotation of 50-60° with respect to stable Europe, probably during Mesozoic times. Rotating the present tectonic framework to its position during the Permian, the Giudicarie (Fig. 3) and associated lines assumed approximately E–W orientations consistent with the recorded tectonic setting of Late Variscan Europe.

The present asymmetrical sigmoid shape of the Collio Basin is probably due to this pristine geodynamic architecture. In fact, the basin exhibits two main structural sectors: i) the WSW–ENE-trending western area, more or less parallel to the Val Trompia Line, and ii) the NNE–SSW oriented eastern area, parallel to the Giudicarie Line.

The southern margin of the basin was bounded by the extensional ENE fault system of the Val Trompia paleo-line; south of it, the Upper Permian Verrucano Lombardo red beds step down directly onto the Variscan crystalline basement in the lack of the older Permian volcano-sedimentary deposits.

The Giudicarie Line currently marks the eastern margin of the basin. During Permian times, active tectonic scarps and an intense magmatic activity consistently influenced the sedimentation in adjacent areas along this ancestral major shear zone (Cassinis, 1988; Cassinis and Perotti, 1994, 1997a, b).

The western border of the basin is masked by younger deposits; only its SW corner crops out near the Val Rosello, where a number of Permian faults bound a south-western structural high (M. Muffetto), thereby separating the Collio Basin from the westernmost and smaller Boario Basin. However, the stratigraphic succession of these basins indicates that they were at least in part connected.

The northern margin is not visible as younger Permian and Triassic deposits cover it. The few and reduced pre-Verrucano Lombardo volcanic and sedimentary deposits (Cassinis, 1985), presently outcropping over and around the Alpine Adamello magmatic intrusion, suggest that the extension of the Collio Basin to the north was rather limited and that the Adamello region was generally dominated by a mountainous landscape during the Early Permian.

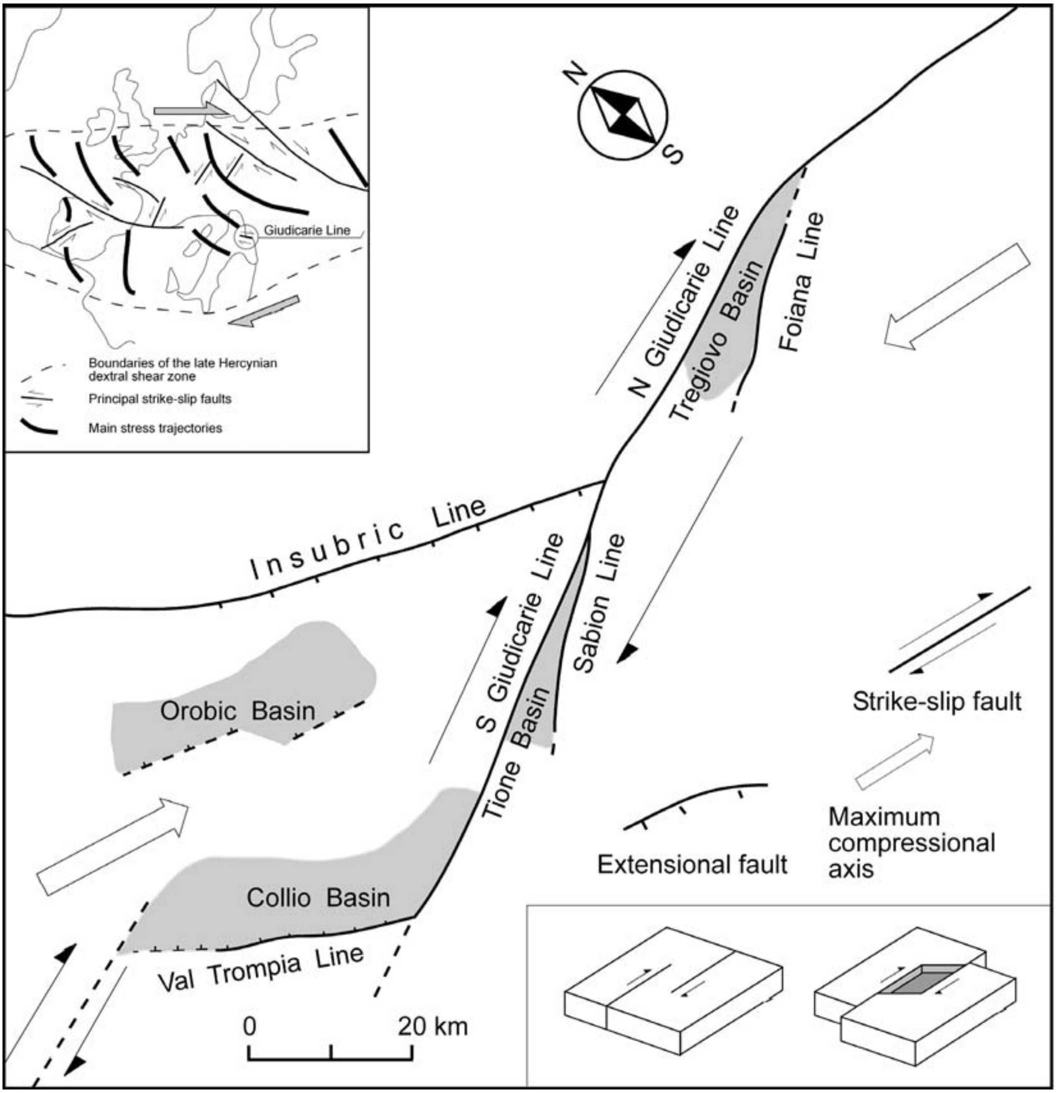

Fig. 3 – Interpretative schematic model of the Permian tectonic setting of the central Southern Alps, before deposition of the Upper Permian Verrucano Lombardo-Val Gardena Sandstone red beds. The north-south orientation of that tectonic framework during Permian times is also shown. (From Cassinis and Perotti, 1994, redrawn). On the inset map: tectonic late-Variscan framework of Europe (after Arthaud and Matte, 1977 and Blès *et al.*, 1995, modified and simplified), including the Giudicarie line.

Other NW-trending faults such as the Rosello, Poffe, Pofferatte, Persole and Vaia (from W to E; Fig. 4), which occur within the western basin's sector, probably indicate a change in the direction of the transtensional activity during the upper Collio deposition. They downthrew the eastern blocks with an extensional right-slip movement (Cassinis and Perotti, 1997a) and presumably mark the onset of a transpressional phase preceding the deposition of the Second Tectono-Stratigraphic Unit (TSU2). This Mid–Late Permian structural reorganisation was generally accompanied by a shifting of the depocentral areas (Cassinis and Perotti, 1997a).

The second tectonic stage subsequent to the Collio Basin, generally Late Permian in age, caused widespread erosion and was marked by cessation of volcanic activity. The faults active during the first stage were sutured by the red clastic deposits of the Verrucano Lombardo–Val Gardena Sandstone lithosome (Fig. 2), and show reactivation and tectonic inversion due essentially to Alpine movements (Cassinis, 1985). The main older transcurrent faults probably were reactivated as normal faults.

Stratigraphy and lithology

The volcanic and sedimentary record of the Collio Basin, object of continuous and detailed investigations, may be considered, also for its magnificent and almost undeformed exposures, as the best example of continental Permian in the Southern Alps. Stratigraphical, petrographical, palaeontological, and palaeogeographical data stand out from a large number of papers.

The current activity by the Italian Commission of Stratigraphy (ICS) and the Italian Geological Survey (APAT), with field mappings of new Geological Sheets of the Lombardy and Trentino areas at a scale 1:50.000, has also highlighted the Permian stratigraphy of some included intramontane basins, and firstly the Collio Basin.

Synthetically, the Permian succession of this basin (Fig. 5), along and near the Maniva-Croce Domini road, located in its western E–W trending sector (*i.e.* from the M. Muffetto area to the Caffaro Valley), comprises the following units (base to top): a jutting plateau of rhyolitic ignimbrites, overlain by a pile of tuffs with wedges of polygenic sandstones and conglomerates-breccias; the well-stratified and varicoloured Collio Formation, upwardly intercalated with thin volcaniclastic mass flow deposits ("Dasdana Beds"); the massive greenish to reddish Dosso dei Galli Conglomerate, including the thinly-bedded, bioturbated, medium-to-fine-grained clastics of the Pietra Simona Member; a second prominent rhyolitic ignimbrite flow. As already pointed out, the uppermost volcanics, at the end of Permian TSU 1, are unconformably capped, often through erosional surfaces and palaeosol profiles, by the pre-Lower Triassic Verrucano Lombardo.

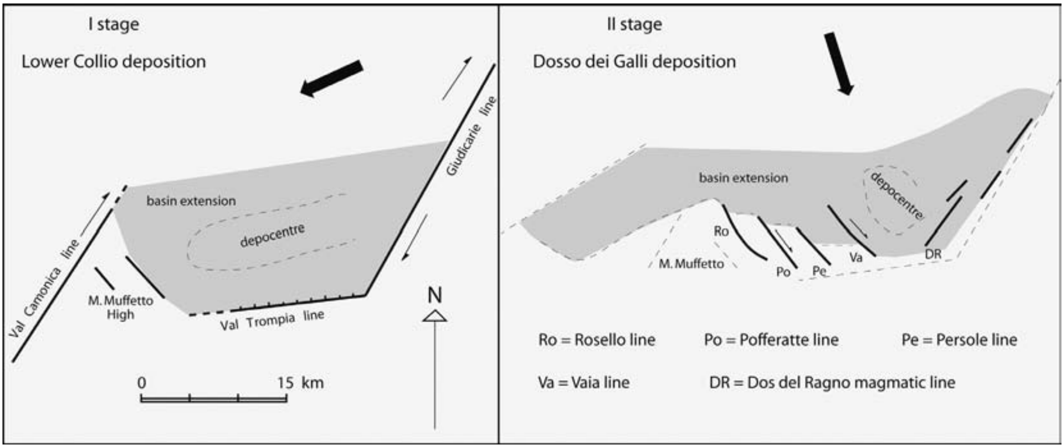

Fig. 4 – Tectonic interpretative scheme of the Collio pull-apart basin development during Permian times. (From Cassinis and Perotti, 1997a).

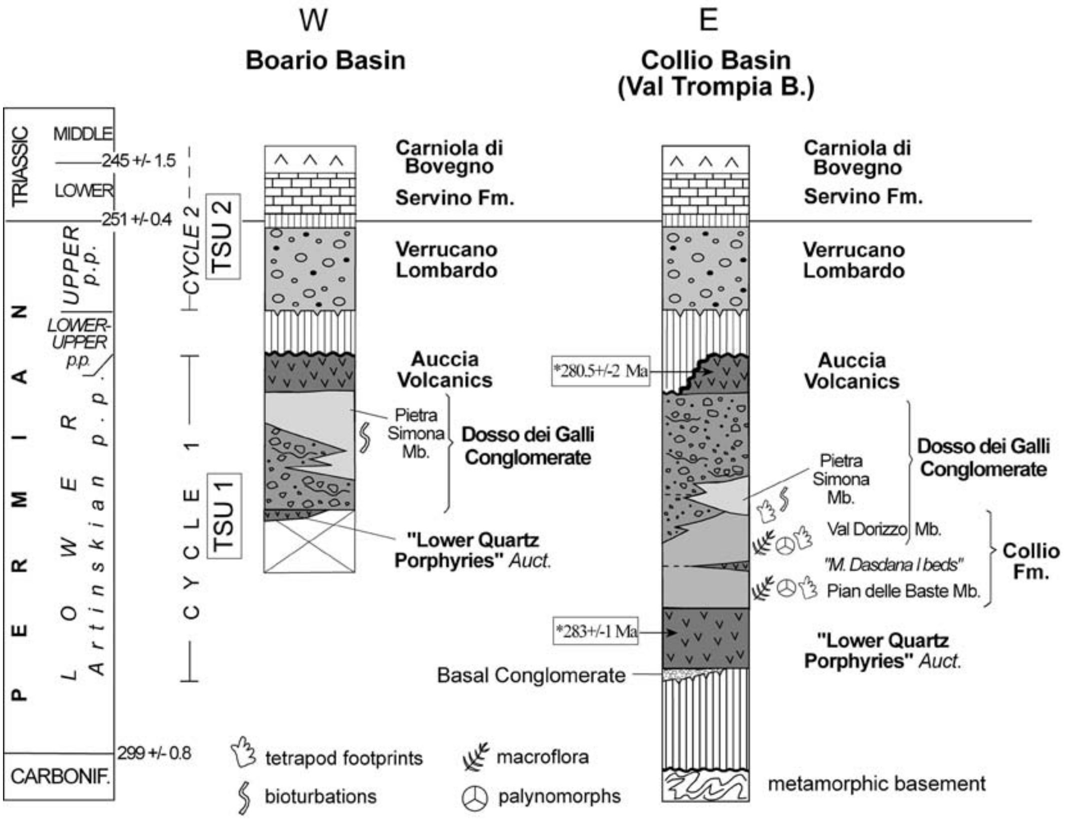

Fig. 5 – Synthetic stratigraphic columns (not in scale) in eastern Lombardy from the typical Early Permian Collio Basin (E) and its cover, along and near the Maniva-Passo di Croce Domini road, and from the lateral small Boario Basin (W) in the lower Val Camonica. Geologic timescale from Gradstein *et al.* (2004).

According to this subdivision, the detailed volcanic and sedimentary record of the Permian succession is as follows.

A) Lower Tectono-Stratigraphic Unit

The basal, red-violet and greyish, massive rhyolitic ignimbrites, associated with subordinate tuffs, originated as a subaerial plateau, from 20 to 130 m thick, and unconformably rests on the Variscan crystalline complex, in places affected by pedogenic alteration. They correspond to the "Lower Quartz Porphyries" *Auct*. and are calc-alkaline in composition. The source area of these volcaniclastic deposits is still doubtful, but their increase in thickness towards the southwestern margin of the upper Val Trompia and the eastern side of the lower Val Camonica suggests that they possibly originated from these areas (Fig. 6). A large intrusive xenolith found near Malga Luca, in proximity of the Trompia Valley and resembling the Val di Rango Diorite, intruded within the underlying crystalline basement, supports this interpretation. The Permian basal volcanics extend from the Camonica Valley as far as the Giudicarie line, for at least 25 km beyond the boundary of the future alluvial-lacustrine Collio Basin. Below the volcanic plateau (Fig. 6), at its western margin in Val Trompia, near Baita Prada (Val Bozzoline), a narrow band of red-brown fluvial clastics from 0 to about 20 m thick rests directly on the crystalline complex. The lithoclasts contain metamorphic and vein-quartz; volcanic fragments

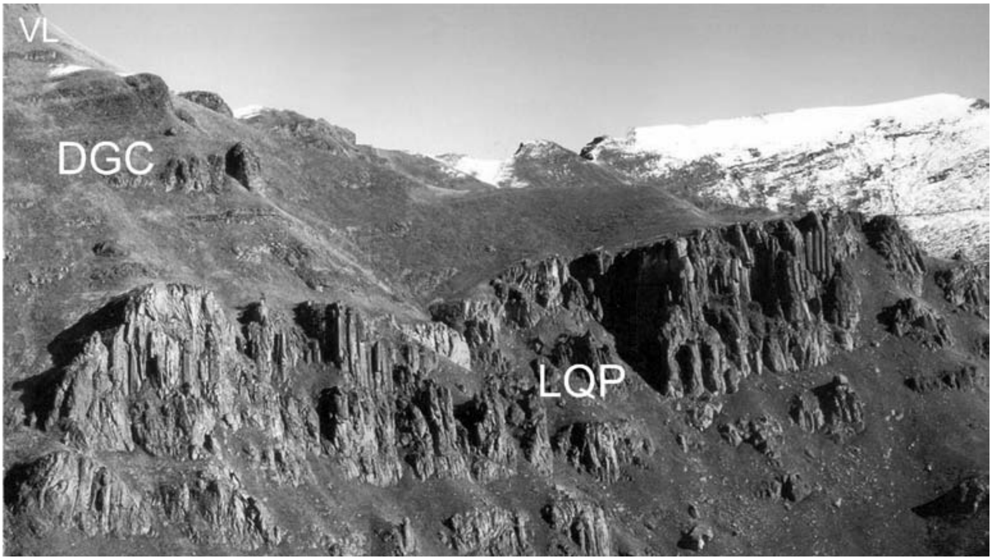

Fig. 6 – Basal rhyolitic ignimbrite plateau (LQP) in the south-westernmost Collio Basin, below Corni del Diavolo, upper Val Trompia. It is locally overlain, bottom upward, by tuffaceous deposits, the Dosso dei Galli Conglomerate (DGC) and the Verrucano Lombardo (VL).

are completely absent. This Basal Conglomerate marks in Val Trompia, as well as in the whole Brescian Alps, the first sedimentary body following the Variscan orogeny.

Varicoloured and well-bedded volcaniclastic products, about 30–90 m thick, interpreted as airfall rhyolitic deposits, generally consisting of vitric and crystal tuffs, lie on the subaerial ignimbritic plateau and below the alluvial-to-lacustrine Collio Formation (Fig. 5). In particular, at the top they are characterised by accretionary lapilli, generally widespread within a brick-red subunit diffusely cropping out in the basin (Cassinis 1966, 1967; Cassinis *et al*., 1975). The tuffs are irregularly interbedded with and covered by at least three medium- to coarse-grained clastic sedimentary alluvial bodies. The uppermost detrital band (10–13 m thick) is particularly significant for the evolutionary structural framework of the basin because of its lateral continuity immediately below the Collio Formation. All the detrital deposits are inferred as erosional products of Permian and pre-Permian rocks due to the stepwise tectonic subsidence of the Collio Basin.

As a matter of fact, this stratigraphical section includes the lithologic assemblage of a transitional unit built up between the disappearance of terrestrial conditions and the onset of more or less subaqueous environments. Consequently, this unit could be interpreted in the field either a member of the underlying volcanics or as a member of the “Collio” cover; however, the rank of a separate formation should also be taken into account.

The overlying traditional Collio Formation is represented by variegated and laminated sandy-shaley deposits (Fig. 5). It was analysed by Cassinis (1966); however new data suggest revision of its type-section established along and around the Maniva-Croce Domini road. Two lithostratigraphical portions, each affected by a different structural evolution, may be defined in the basin and easily delimited in the field. The “lower Collio”, recently renamed as “Pian delle Baste member” and overlain by a thin volcaniclastic body (Mt. Dasdana I Beds, according to Breitkreuz *et al*., 2001a), is made up of alluvial to lacustrine, varicoloured and graded sand to shale sediments, up to about 200 m thick. Generally these strata mark a cycle (from distal alluvial fan to sandflat, mudflat and lacustrine environments) towards deeper water conditions. However, the presence of plant debris and tetrapod footprints indicates that the basin was never very deep and was often exposed. Calcareous lenses and nodules occur locally.

This "lower Collio" sub-unit includes, at the top, black micaceous shales with layers and nodules of spherulitic danburite, ankeritic carbonates with minor dravite and trace gold. According to Cabella *et al.* (1987), these mineralizations are interpreted as precipitation from a hydrothermal activity in alkalinised, shallow-water closed basins, which in the Val Trompia Collio Basin could be associated with the emplacement of the overlying volcaniclastic mass-flow deposits (Dasdana Beds).

The "upper Collio", on the other hand, is characterised by a more irregular distribution of the deposits, probably due to a first activation of the basin marginal fans connected to volcano-tectonic movements. This sub-unit has been recently and informally named the "Val Dorizzo member", from a locality of the middle Val Caffaro, in the east. In general, preserved fossil plants, tetrapod footprints, ripple-marks and so on, imply that the basin, continuously awash with shallow-water and subjected to frequent emergence, was not affected by significant changes. However, several thin extrusive bodies (as in the Vaia and Caffaro valleys) issued from eastern sources suggest the development of significant tectono-magmatic activity essentially at the SE corner, between the Giudicarie and Trompia lines.

Already identified as calc-alkaline rhyolitic lavas (Peyronel-Pagliani, 1965), these extrusive products, used as key beds, are at least in part presently interpreted as sublacustrine volcaniclastic mass-flow deposits (Cassinis and Perotti, 1997a; Breitkreuz *et al*., 2001a, b). East of Mt. Dasdana, along the Maniva-Croce Domini road, a section of the Dasdana I Beds is represented (base to top) by (1) a light-grey, amalgamated coarse sandy to gravelly crystal-rich massive subunit, including black pelite (lacustrine Collio rip-ups) and minor volcanic and metamorphic clastics (Fig. 7), which resemble Bouma-a(b) divisions suggesting deposition from coarse-grained turbidity currents; and by (2) a greenish, well-bedded sandy-shaley more dilute turbiditic subunit with outsize porphyritic lava fragments (Breitkreuz *et al*., 2001b; Fig. 7). On the whole, this succession can locally reach up to ~ 20 m in thickness.

The overlying Dosso dei Galli Conglomerate (Fig. 5) was formally introduced by Cassinis (1969a). The type-section crops out along the upper Val Dasdana (near the divide between the Camonica and Caffaro valleys), whose base is characterised and widely substituted upwards to the west, in the lower Val Camonica, by stratified and bioturbated, red-brown, medium to fine-grained sandstones and shales (Fig. 5). In the Boario Terme sub-basin, the type-section of this so-called "Pietra Simona" Member is estimated at about 300 m in thickness (Assereto and Casati, 1965), whereas in the Dosso dei Galli reference section it is reduced to 120 m. This deposit is regarded as originated in either finer-grained clastic zones, lateral to the

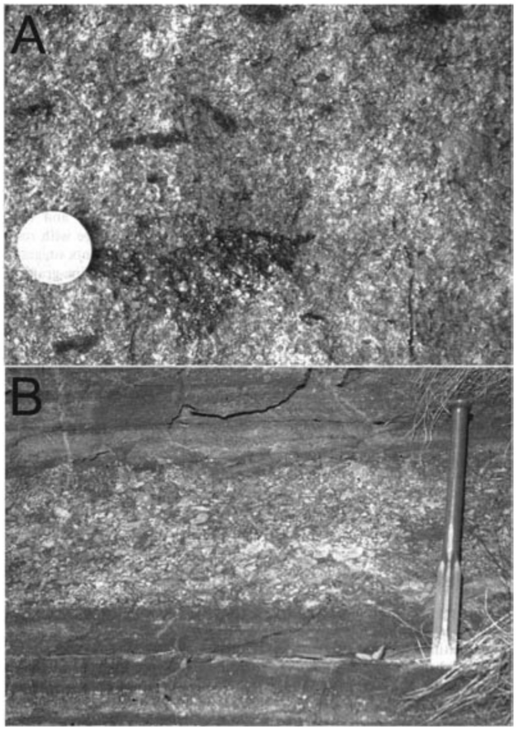

Fig. 7 – Details of the "Dasdana Beds" at the type-section, along the Maniva-Passo di Croce Domini road. (A) Clast-supported sandy to gravelly crystal-rich turbiditic subunit with outsize fragments (porphyritic andesite clasts and Collio Formation sediments) (the coin is 2.2 cm across). (B) Sandy-pelitic dilute turbiditic beds rich in silicic porphyritic fragments (chisel is 20 cm long). (After Breitkreuz *et al.*, 2001b).

main conglomeratic cones, or in non-active areas on the fans (Ori *et al.*, 1988). However, the lower part of the formation is again essentially made of polychrome conglomerates, locally intertongued with the sandy-shaley "Collio" sediments (*e.g.* above the small Dasdana lake), or stacked one on top of the other. At Mt. Colombine, overlooking the Lake Ravenole area, these basal clastic deposits, up to about 180 m thick, consist of three coarsening-upward sequences. According to Ori *et al.* (1988), the upper conglomerates of these cycles correspond to proximal debris-flow sediments that pass downstream into channelled deposits, characterised by traction and turbulent flow. Finally, in the most distal (lowermost) part, sheet-flow deposits merge with the lacustrine mudstones of the Collio Formation. These sequences indicate a progradation of alluvial fan bodies into the shallow-water Collio paleo-lake.

The "upper member" of the Dosso dei Galli Conglomerate, up to 200 m in thickness, is composed of red-brown, ill-defined, disorganised conglomerates and subordinate coarse sandstones, referable to debris-flow or mass-flow deposits (Fig. 5). Clast composition mostly includes metamorphic, quartzitic and extrusive igneous rocks, from the underlying volcanic units of the basin but also from distal, extra-basinal bodies. Palaeocurrent directions show that these lithics derived from a source area located to the south-southwest of the basin. Upwards, metamorphic pebbles generally replace volcanic detritus. Eastwards, between Caffaro Valley and the Lower Giudicarie, some conglomerates are monomict, composed of volcanic lithologies.

The overlying and last volcanic products of the Lower Permian Tectono-Stratigraphic Unit, are known as the "Auccia Volcanics" (Fig. 5). This formation, formally introduced by Cassinis (1968, 1969b), is essentially made up of calc-alkaline rhyolitic/rhyodacitic violet ignimbrites rich in *fiammae* (Peyronel-Pagliani and Clerici-Risari, 1973) with a maximum thickness of 130–140 m along its type-section, cropping out at the Dosso dei Galli-Giogo della Bala area, across and near the Maniva-Croce Domini road. These igneous products, occurring from the lower Val Camonica to the Giudicarie region, correspond to the definitive disappearance of the Collio Basin, as well as to the closing of the Lower Permian "cycle" or "group" *Auct.*

As first highlighted at the Giogo della Bala by Wopfner (1981), the upper boundary of this volcanic plateau, exposed for more than 20 Ma?, shows clear erosion surfaces and palaeosol profiles in many parts of the basin.

B) Upper Tectono-Stratigraphic Unit

During the Permian, the onset of this tectono-stratigraphic unit, extending to Anisian times (Massari *et al.*, 1994; Massari and Neri, 1997), was characterised by the Verrucano Lombardo Formation or Group (Figs. 2 and 5). This unit, ranging from

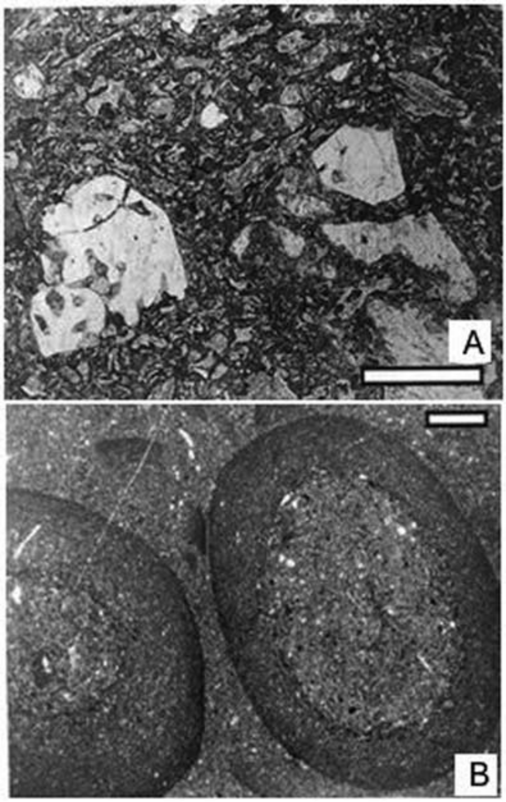

Fig. 8 – Thin section microphotographs, plane polarized light, scale bar: 1 mm. A) Basal ignimbrite: embayed and fractured quartz (centre, left) and K-feldspar phenoclast in a matrix of glass shards. B) Accretionary lapilli in tuffs below the sedimentary Collio Formation.

approximately 200 m to 500 m in thickness, in the Brescian province is essentially represented by reddish, fine- to coarse-grained, often micaceous sandstones, from medium- to very thick-bedded, up-section rich in dark red siltstones. Conglomerates with vein-quartz and volcanic rock fragments also occur. In particular, a sandy-conglomeratic lower part represents a braided sedimentation, and a sandy-silty upper part, corresponds to meandering conditions. Locally, the top of the Verrucano Lombardo is characterised by the presence of sheet-flow deposits, related to terminal fans (Ori *et al*., 1988). In conclusion, this fining-up sequence could be interpreted locally as including at least two informal members. The formation, first introduced in the literature by Assereto and Casati (1965, 1966), rests unconformably everywhere, within the Collio Basin and in the adjoining areas, on both the previous Lower Permian and pre-Permian rocks.

Some authors relate the Verrucano geological setting to marked extensional rift tectonics, in contrast with the older setting in which a transcurrent regime prevailed or pulsed; thickness variations fit well also with a shifting of its depocentres towards the east (Cassinis and Perotti, 1994; Perotti and Siletto, 1996; Cassinis *et al*., 1997).

Age interpretation

Due to the lack of direct stratigraphic tools, the age of the Verrucano Lombardo is generally inferred as Late Permian, mainly because of its position below the Lower Triassic marine Servino Formation and the correlation with the eastern fluviatile Val Gardena Sandstone of Dolomites.

The underlying Permian sequence was object of macro- microfloral and tetrapod footprint investigations, and of radiometric dating (Fig. 5). The floral assemblages (*Walchia piniformis*, *W. filiciformis*, *Hermitia geinitzii*, *Schizopteris fasciculata*, *Sphenopteris suessii*, etc.) of the Collio Formation suggest a poorly-defined Early Permian age (Geinitz, 1869; Tyroff 1962, *in* Cassinis, 1966; Remy and Remy, 1978; Visscher *et al*., 1999); the palynomorphs (*Cordaitina* sp., *Potoniesporites* sp., *Nuskoisporites* sp., *Lueckisporites granulatus*, *Vittatina foveolata*, *V. costabilis*, etc.) are generally ascribed to a late Artinskian, Kungurian or early Ufimian age (Clement-Westerhof *et al*., 1974; Cassinis and Doubinger, 1991; Pittau, 1999); while the ichnofaunas (*Batrachichnus* sp., *Amphisauropus latus*, *Ichniotherium cottae*, *Dromopus lacertoides*, etc.) broadly indicate an Early Permian interval (Haubold and Katzung, 1975; Ceoloni *et al*., 1987; Conti *et al*., 1991). Contrasting radiometric dates were obtained from the lowermost and the uppermost volcanics of the Permian section (Schaltegger and Brack, 1999). A mean $^{206}Pb/^{238}U$ age of 283±1 Ma was calculated from four concordant U-Pb zircon analyses of a sample from the “basal ignimbrites” exposed along the Maniva-Croce Domini road. An age of 280.5±2 Ma results from three concordant zircon analyses of the uppermost Auccia Volcanics, immediately northeast of the Goletto del Giogo della Bala. These age values imply a time span of about 3-5 Ma for the deposition of the volcanic and sedimentary succession in the Collio Basin, probably coeval to late or latest Sakmarian/early-middle Artinskian, with a depositional rate of about 0.3-0.5 mm/a. However, the radiometric ages are significantly older than the numeric values assigned to a corresponding interval in current time-scales (Menning, 1995, 2001; Jin *et al*., 1998, Wardlaw and Schiappa, 2001; Gradstein *et* al., 2004). The discrepancy may be, at least in part, due to uncertainties in age estimates based on palynomorphs from continental deposits.

From general considerations (Cassinis and Ronchi, 2001; Cassinis *et al*., 2002a, b), it follows that the gap between the Auccia Volcanics and the overlying Verrucano Lombardo, *i.e*. between the Lower and Upper Tectono-Stratigraphic Units (or the Lower/Upper Cycles or Groups) of the Permian System, could be estimated, in accordance with the Menning’s time-scales (1995, 2001), at more than 20 Ma.

Nature and composition of the main volcanic products

The volcanism within the Collio Basin was generally subdivided intro three main igneous events studied since the 1960s.

The basal volcanic rocks (Peyronel-Pagliani, 1965; Cassinis *et al*., 1975; Origoni-Giobbi *et al*., 1979; Cortesogno and Gaggero, 1999; Breitkreuz and Ronchi, 2004), which represent the first event, are attributed to calc-alkaline rhyolitic ignimbrites (Fig. 8) sedimented in a subaerial environment. The crystalline fraction, which forms 20–40% of the total rock, includes plagioclase, quartz, K-feldspar, minor biotite, flattened pumice lapilli, porphyritic and groundmass fragments of intermediate composition. The coarse plagioclase crystals are nearly pure albite ($An_{7\text{-}10}$). The included andesite clasts evidence bimodal volcanic activity prior to, and perhaps coeval with the voluminous silica rich-volcanism. Metamorphic and pyroclastic lithics, with a pseudo-trachytic structure, occur locally; microlithic elements probably originated in the volcanic conduits. Accessory minerals are zircon, rare apatite, and iron oxides. The matrix consists of ash and glass fragments. *Fiammae* are common, mainly concentrated in the lower part of the unit.

The chemical composition (Figs. 9 and 10) of the basal ignimbrites is rather uniform. According to Peyronel-Pagliani (1965) and Origoni-Giobbi *et al*. (1979), they show granitic to aplitic composition; however hydrothermal alteration produced alkali leaching and differential Si and Al enrichments.

The overlying, well-stratified volcanic products generally consist of vitric and crystal tuffs, deposited in subaerial conditions. Compared with the underlying ignimbrites, these lithofacies show different bulk and mineral composition for the crystal fraction (Peyronel-Pagliani, 1965). Large glomeroporphyric plagioclases have composition $An_{8\text{-}10}$. Quartz and K-feldspar (orthose and minor sanidine) are subordinate. Biotite is very rare. The lithoclasts generally include volcanites, pumices and pseudo-trachytic fragments as in the underlying ignimbrites. Sericite and chlorite are widespread in the cineritic matrix as secondary alteration. The bulk rock composition is peraluminous, although Na-enriched compared with the Permian basal volcanics (Peyronel-Pagliani, 1965).

The top of the lower volcaniclastic section is marked by a reddish layer of glassy tuffs with

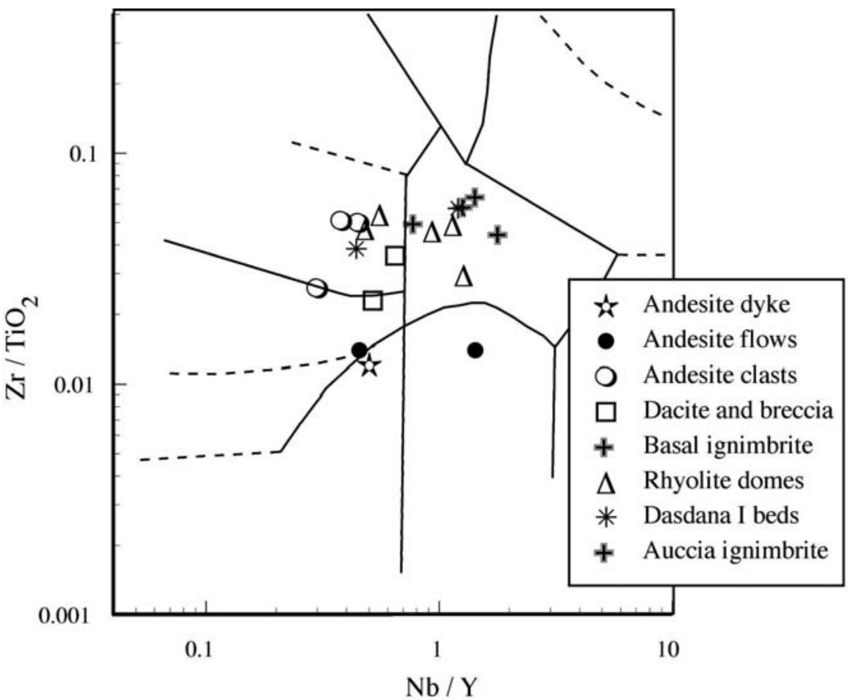

Fig. 9 – Zr/TiO_2–Nb/Y for volcanic rocks (Winchester and Floyd, 1977). The basal ignimbrite and the andesite products exhibit a prevalent calc-alkaline signature, whereas the main dacite-diorite activity and the Auccia ignimbrite show a transitional to high K character.

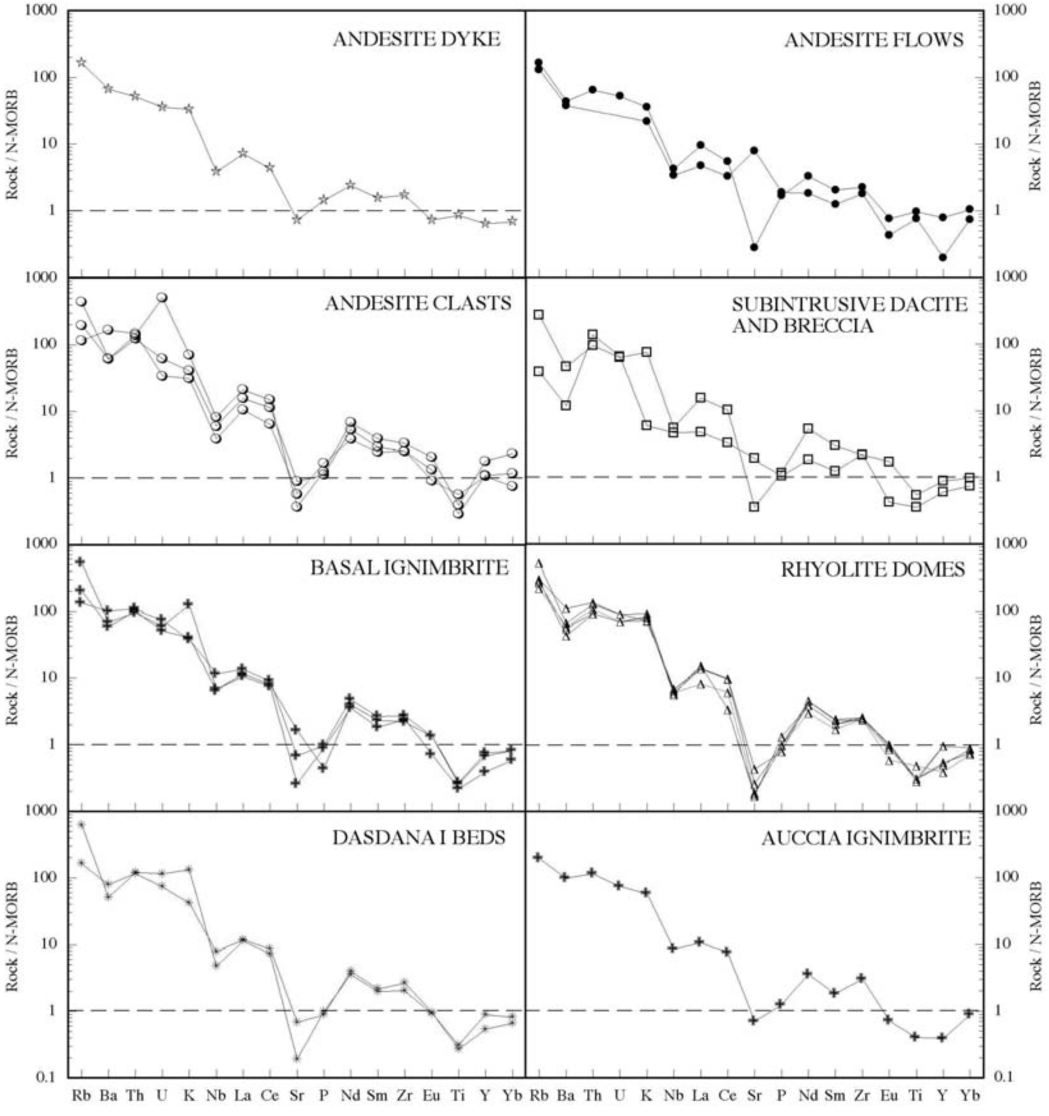

Fig. 10 – Rock / MORB diagrams normalized according to Pearce and Parkinson (1993) for the volcanic products of the Collio Basin.

accretionary lapilli, known as a "key bed" due to its lateral continuity in the Collio Basin (Fig. 8B). According to Peyronel-Pagliani (1965), the composition of the very scanty crystals is analogous to that of the underlying tuffs. Chips and flat whitish spots rich in neogenic albite, from ash fragments, often occur. The accretionary lapilli consist of a core with a very thin quartz-feldspathic aggregate and a microfelsitic rim rich in Fe oxides. Their presence suggests episodes of explosive (phreatomagmatic?) activity in a shallow-water to subaerial environment. The composition of the uppermost tuffs is quartz-latitic, with calc-alkaline serial affinity (Peyronel-Pagliani, 1965). As a

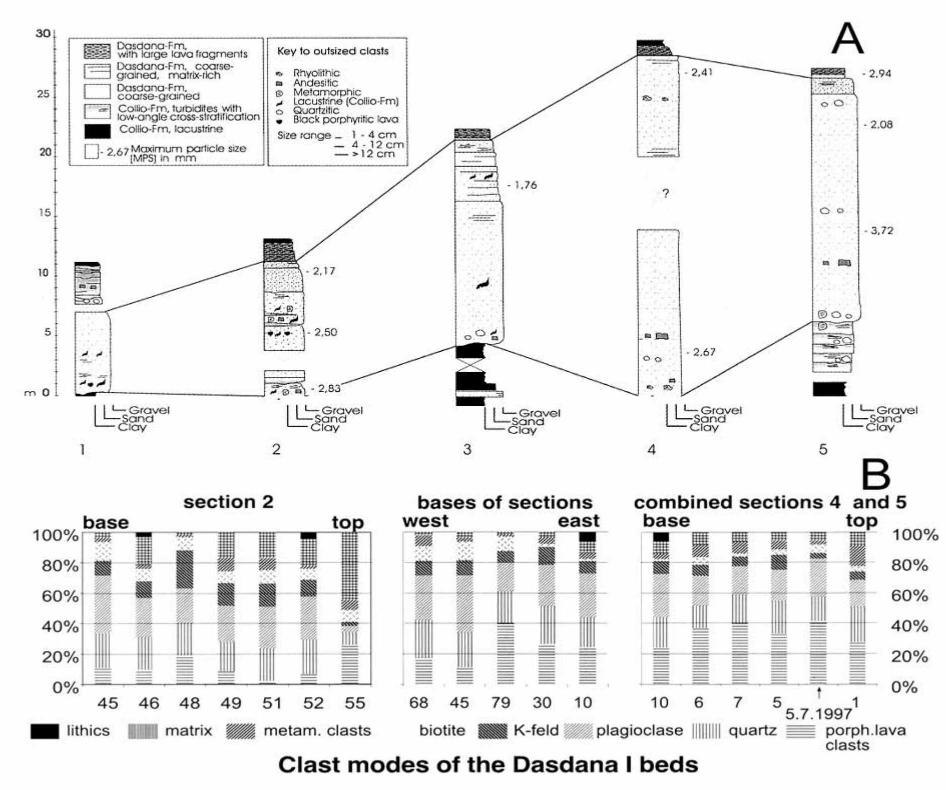

Fig. 11 – A) Sedimentary sections of the first "Dasdana Bed" (DB), from west (1: Passo delle Colombine, Val Trompia) to east, Val Caffaro (2: Monte Dasdana; 3: Valle di Vaia; 4: Fienili Frei Basso; 5: Dosso del Bue). B) Modal composition of the first DB, related to selected sections of A). (After Breitkreuz *et al*., 1999).

whole, all the pyroclastic products of this post-ignimbrite unit were grouped under the name of "plagioclase-bearing rhyolitic pyroclastites".

The second volcanic event was coeval with the "Collio" shallow-water alluvial to lacustrine sediments. Therefore, it can be interpreted, in large parts of the basin, as generally deposited within a subaqueous environment. Preliminary lithological, petrographical and geochemical characterisation are described in Peyronel-Pagliani (1965), Cassinis (1966, 1988), Cassinis *et al.* (1975), Origoni-Giobbi *et al.* (1979), Cassinis and Perotti (1997a).

Subsequently, the Dasdana Beds (DB) irregularly expanded as thin layers on the basin floor (Breitkreuz *et al.*, 1999, 2001a, b). Their source areas were located to the east of Val Caffaro, and correlated with the presence of some (crypto)domes (Dosso del Bue and Dosso dei Lupi, near Bagolino). The sedimentological, petrographical and geochemical data (Figs. 9-11) highlighted the turbiditic origin of the Dasdana reworked extrusives, and thus confirmed the preliminary interpretations (Cassinis *et al.*, 1975; Cassinis and Perotti, 1997a). Each layered body generally consists of two sub-units, showing abundant lithic elements: the lower massive and crystalline subunit, greyish in colour, was identified as due to volcaniclastic mass flow deposits; the upper subunit, thinner and greenish, is represented by well-bedded sandy-shaley sediments. According to Breitkreuz *et al.* (2001b), the clast composition of the DB lower subunit consists of crystal fragments of plagioclase (20-

30%), quartz (20%), K-feldspar (7%), biotite (3-10%), and clasts of rhyodacitic/rhyolitic porphyries (5-40%), metamorphic basement rocks (5%) and minor intermediate volcanics and pelites. Between these clasts, the matrix includes very fine-grained fragments of quartz, K-feldspar, biotite, white mica and subordinate zircon and epidote; chlorite aggregates with minor titanite replace volcanic glass and biotite. The lower Dasdana I Beds revealed some systematic proximal-distal trends such as a higher plagioclase and biotite content, together with decreasing unit thickness, maximum particle size and modal porphyritic lava fragments toward the west (Breitkreuz *et al*., 2001b). The phenocryst assemblage within the lava fragments of the upper subunit is similar to that in the lower subunit; however, here spindle shapes are dominant and the presumably glassy groundmass of the fragments was mainly replaced by illite and carbonate. On the whole, the emplacement dynamics envisaged by Cassinis *et al.* (1975) and Breitkreuz *et al*. (1999, 2001a, b; Fig. 12) is related with the inflation of a cryptodome within the lacustrine basin, along an active tectonic lineament.

In the lower Val Caffaro, between Bagolino and Riccomassimo, *i.e.* in the southeastern part of the basin, a large vertical feeder dyke follows the W–E Val Trompia lineament (Cassinis *et al*., 1975). It runs from the Rio Secco (W) to the Rio Riccomassimo (E) up to the border with the Trento region, resulting in the Dosso dei Lupi, Dos del Ragno, Ermos Basso and Corno della Tor domes (Fig. 13). Along the “Vie Rate”, in the Dos del Ragno sector, the subvolcanic column clearly cuts the crystalline basement, the basal Permian rhyolitic ignimbrites, the covering tuffs and the

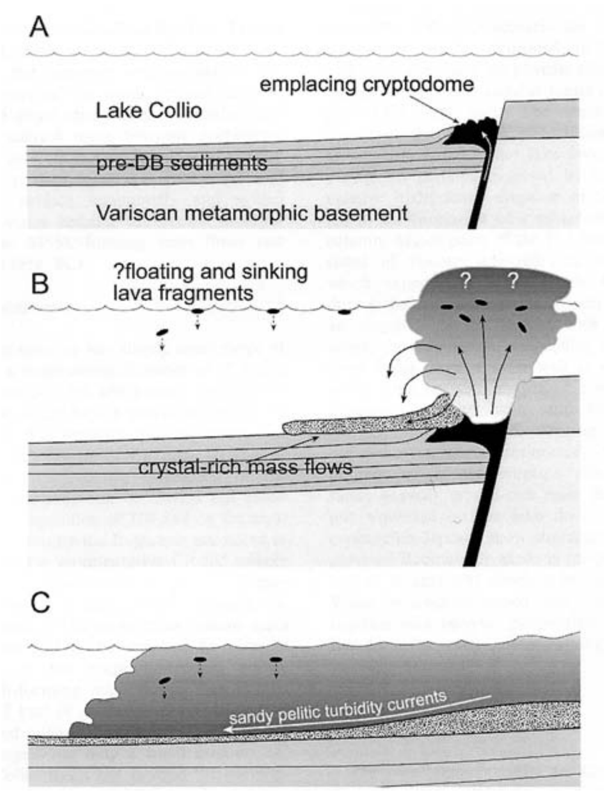

Fig. 12 – Schematic model for the formation of the “Dasdana Beds” and the related cryptodome eruption. A, B, C point out the main steps of this volcanic activity, which is coeval to the Early Permian Collio Formation. (Further details in Fig. 8 of Breitkreuz *et al*., 2001b).

lower Collio Formation. North of Rio Secco the magmatic vent produced the subaqueous and than subaerial Dosso del Bue dome (up to about 200 m thick; Fig. 14), which probably also assumed during its emplacement, at least temporarily, the shape of a laccolith.

The turbiditic mass-flows of the Dasdana Beds toward the west were certainly triggered by the marked elevation of this marginal zone of the Collio Basin, evaluated at about 300 m, on the basis of the difference in height of the basal ignimbrites between the lower part of Rio Secco (1050 m) and the Dos del Ragno area (1370 m).

The subvolcanic bodies intruded between Rio Secco and Rio Riccomassimo, also occurring to the east (Cassinis *et al*., 1975), show a greenish facies at the contact with the host rocks, with rare coarse pink K-feldspar phenocrysts (Origoni-Giobbi *et al*., 1979). The margins, from few centimetres to some metres thick, occur diffusely (Vie Rate, Dos Tupì, Ermos Basso, etc.); these facies (called "differenziati basici") are latites and latite-andesites showing intersertal structure. The prevalent crystal fraction consists mainly of oligoclase (An_{20}) and biotite. Quartz is absent or very rare; the accessory minerals are rutile, apatite and zircon. The plagioclases of the intersertal groundmass (rich in chlorite and Fe oxides) are more basic. Limited compositional variations occur in the greenish chilled margins. According to Origoni-Giobbi *et al.* (1979), the nature, composition and relative abundance of the phenocrysts account for the thin veneers of differentiated marginal rocks. The concentration would be caused by temperature gradients and by consequent differential magma viscosity.

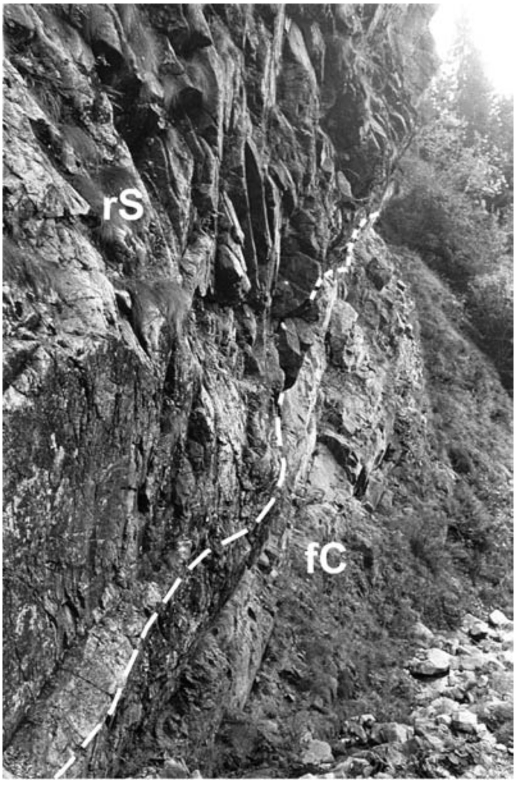

Fig. 13 – The discontinuous contact between the Rio Secco subvolcanic body (rS) and the basal Collio Formation (fC), due to the upwelling of the former unit in the lower Val Caffaro near Bagolino. (From Cassinis *et al*., 1975)

Eastwards, from Val Riccomassimo to Darzo in the upper Val Sabbia, close to the intersection between the Val Trompia and the Giudicarie Lines, the igneous activity assigned to the Early Permian is more abundant, producing subvolcanic bodies with different lithological features (Cassinis, 1982, 1988). Along the eastern SSW–NNE-trend of the Collio Basin, eruption centres have been interpreted in the upper Val Sorino, near Malga Serodine, and clearly documented to the north, in the Val Giulis-Val Aperta (M. Tanarone) area (Santi, 1986; Cassinis, 1988).

The third main igneous event in the area is represented by a well-developed subaerial plateau, made of rhyolitic/rhyodacitic ignimbrites which filled and sutured the Collio Basin. The uppermost Auccia Volcanics mark the end of the first Lower Permian TSU and, through an important unconformity, are capped by the Upper Permian Verrucano Lombardo fluvial red beds.

The Auccia Volcanics have porphyroclastic textures in a fine-to-very fine, violet matrix (Peyronel-Pagliani and Clerici-Risari, 1973). They include volcanic and metamorphic rock fragments; diorite xenoliths (up to a decimetre in size) are in places abundant. *Fiammae* occur in elliptical lenses (up to 50 cm and more), flattened on the stratification. They have light colour and larger crystals compared to the host rock. The abundant spherulites and the pervasive weathering of feldspars and biotite suggest pervasive fluid

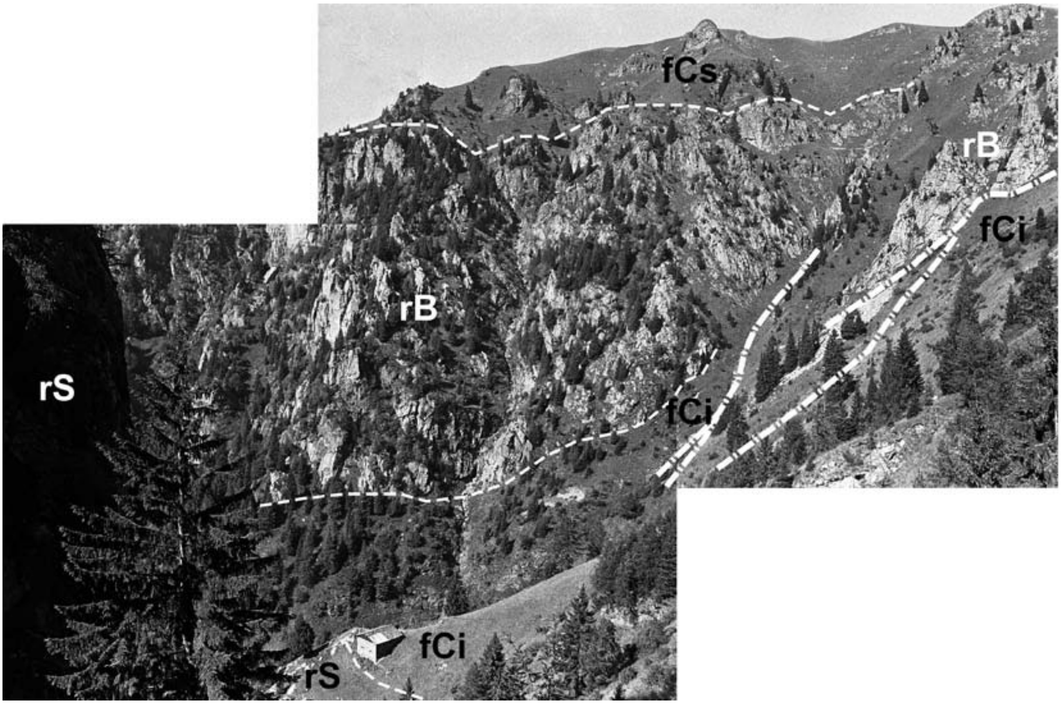

Fig. 14 – Geometrical relationships between the Collio Formation and the intermediate volcanic products in the upper Rio Secco, near Bagolino.In the foreground, the subvolcanic bodies of Rio Secco (on the left and around F.le Zoadel), in the background is clearly developed, for about 200 m in thickness, part of the Dosso del Bue dome, which discharged the sublacustrine "Dasdana Beds" toward the west, running separately on the basin floor.
At present, the transition band between the Rio Secco and Dosso del Bue bodies is marked by some Alpine tectonic lineaments, which can be interpreted as a reactivation of Permian deformations. Abbreviations: rS: Rio Secco igneous body; fCi and fCs: sediments of the lower and upper Collio Formation, respectively; rB: Dosso del Bue igneous body. Dashed-lines: approximate stratigraphic boundaries; dashed-dotted lines: faults. (From Cassinis *et al*., 1975).

circulation during diagenesis. The Auccia Volcanics are rich in vitroclastic and eutaxitic textures. The phenoclasts are quartz, plagioclase (oligoclase-andesine, An $_{25\text{-}35}$), biotite, K-feldspar and a chloritised femic phase, possibly pyroxene. At the top of the volcanic unit, a more acidic plagioclase (An_{10}) is associated with K-feldspar (sanidine) phenocrysts. However, K-feldspar generally occurs in the matrix of all the volcanic levels. Millimetre – sized biotite is widespread. Accessory minerals are apatite, zircon, iron oxides. Alteration is poor, and represented by minor chlorite, epidote, albite, K-feldspar and Fe oxides.

The Auccia ignimbrite is a very homogeneous calc-alkaline rhyolite body (Peyronel-Pagliani and Clerici-Risari, 1973; Origoni-Giobbi *et al*., 1979; Breitkreuz *et al*., 1999; Cortesogno and Gaggero, 1999; Figs. 9 and 10). Compared with the Permian basal ignimbrite it results more SiO_2 – rich (SiO_2 ~ 70 Wt.%) with higher potassic character (Fig. 9).

Basin history and geodynamic implications

The sedimentary and tectonic evolution of the Permian in the South-Alpine region is characterised by the two tectono-sedimentary units or cycles. The history began by a first stretching phase (Early Permian *p.p.* times) with abundant clastic sedimentation and volcanism inside a fault-bounded basin, and a second slower phase (Late Permian *p.p.*) corresponding to the expansion of the basin. Initially, crustal thinning was combined with increased heat flow, in a general transcurrent to transtensional regime. This cycle was associated with the onset of regional uplift, unroofing, collapse and stretching of the Variscan orogen, upwelling of the asthenosphere and intrusion of granitic melts into the crust.

In contrast, during the following unconformable deposition of Verrucano Lombardo (Fig. 15), the recovery of the isotherms occurred and a general minor subsidence took place in an enlarged sedimentary basin that buried the wrench-induced Collio pull-apart basin. During Late Permian times, stretching and extension were no longer concentrated in narrow or restricted areas, but influenced the entire Southern Alps. This tectonic phase is probably linked to a vigorous plate reorganisation related with the more or less simultaneous opening of the Neotethys ocean and the Meliata back-arc basin, and accelerated the progressive closure of Palaeotethys eastward, culminating in the Middle Triassic and slightly later times.

The reconstruction of the stepwise tectono-sedimentary Permian evolution in the Southern Alps potentially finds similarities with other Permian large basins in paleo-Europe, *e.g.* the Saale depression (Germany), from NE Spain to southern France, and in some sectors of Romania and Bulgaria. Recently, Ziegler and Stampfli (2001) also emphasised that the Upper Carboniferous to Lower Triassic sedimentary and volcanic series of the Variscan domain can be subdivided into several tectono-stratigraphic successions, however, only grossly correlative. In essence, in the Southern Alps, a latest Carboniferous to Early Permian "syn-to-late tectonic" cycle and a Late Permian-Early Triassic "post-tectonic" cycle can be recognised, in response to different geodynamic regimes, as in other sectors of the Southern Variscides (Cortesogno *et al*., 1998).

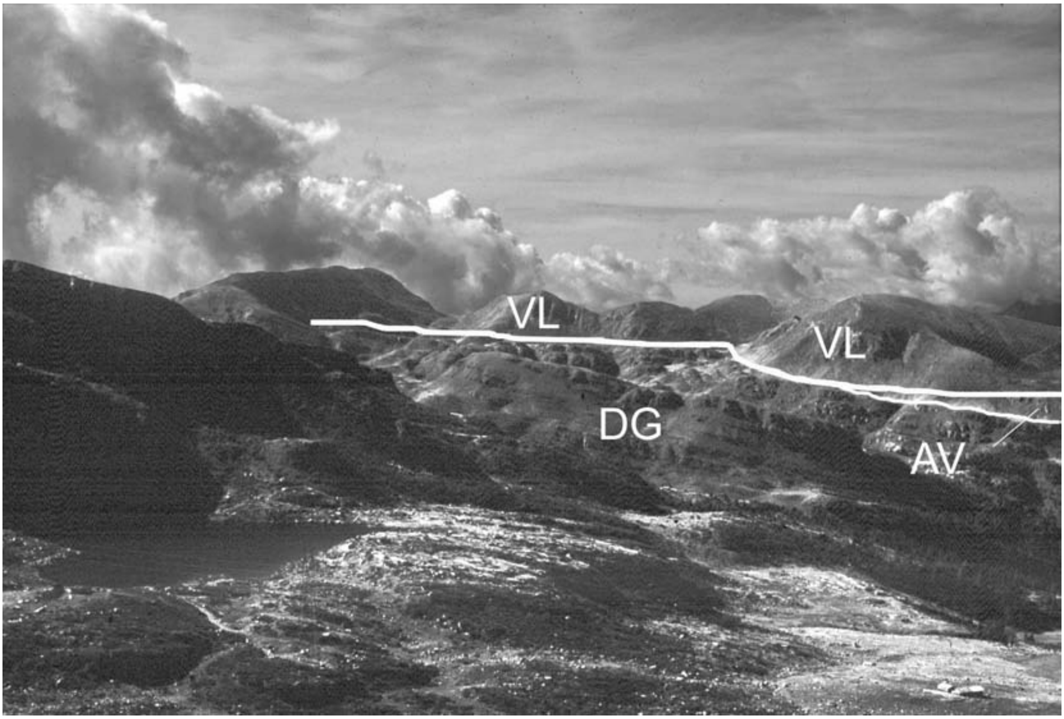

Fig. 15 – Angular unconformity (marked by a continuous line) between Cycle 1 (TSU1) and Cycle 2 (TSU2) at the Dosso Betti – Mount Crestoso area, on both sides of the Pofferatte line, crossing the uppermost Trompia and Camonica valleys. Abbreviations. DG: Dosso dei Galli Conglomerate; AV: Auccia Volcanics; VL: Verrucano Lombardo. The Verrucano unconformably overlies, for progressive erosion, both the older units.

CONCLUSIONS

The volcanic and tectono-stratigraphic evolution of the Collio Basin allows to remark the following main points:

- the Collio Basin development, during the Early Permian, was connected with a volcanic activity induced by transtensional tectonic movements;

- the fluvio-lacustrine and volcanic basin sequence is between two prominent plateaux of calc-alkaline, mainly rhyolitic ignimbrites;

- after the basal eruption, block faulting led to the formation of a half-graben structure, which was affected by an active tectonic subsidence (over 1200 m of deposits in about 3-5 Ma);

- the eastern sector of the basin (between the Val Trompia and Giudicarie Lines) was intruded by some cryptodomes, which discharged their products (the "Dasdana Beds"), as subaqueous conditions, toward the west; syn-sedimentary transtensive faults stemmed the distribution;

- the overlying calc-alkaline acidic ignimbrites (Auccia Volcanics), which close the first tectono-stratigraphic unit (TSU1), led to the disappearance of the Collio Basin;

- subsequently, a non-depositional and erosional period ("Mid-Permian Episode" of *e.g.* Deroin and Bonin, 2003) brought to the end of late-Variscan deformations. Over the gap, estimated in the Collio Basin area in about 20 Ma, the Verrucano Lombardo red beds mark the beginning of the second Permian TSU, within a wide structural reorganization (minor subsidence, tectonic inversion, cessation of the igneous activity, plate movements, etc.).

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This paper is dedicated to the memory of Luciano Cortesogno, who carried out extensive and remarkable research on the petrology and geology of several European areas. We also remember his talent, the large availability to collaborations and the generous and intense energy profused in the work. Dear "Lucio", thank again for your friendship and help!

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