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Structures along the Orobic thrust, Central Orobic Alps, Italy

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Abstract A series of regional deformation phases is described for the metamorphic basement and the Permian cover in an area in the central Orobic Alps, northern Italy. In the basement deformation under low-grade amphibolite metamorphic conditions is followed by a second phase during retrograde greenschist conditions. These two phases predate the deposition of the Permian cover and are of probable Variscan age. An extensional basin formed on the eroded basement during the Late Carboniferous, filled with fan conglomerates and sandstones, and rhyolitic volcanic rocks. Well-preserved brittle extensional faults bound these basins. Further extension deformed basement and cover before the onset of Alpine compressional tectonics. Cover and basement were deformed together during two phases of compressional deformation of post-Triassic age, the first giving rise to tectonic inversion of the older extensional faults, the second to new thrust faults, both associated with south-directed nappe emplacement and regional folding. Foliations develop in the cover only during the first phase of deformation as part of the activity on "shortening faults". Main activity on the Orobic thrust actually postdates the first phase of thrusting and foliation development in the cover.

Key words Orobic Alps · Orobic thrust · Inversion tectonics · Fault reactivation · Extensional basin · Alpine orogeny

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Introduction

Tectonic studies of the Alps have long focused on the western, central and eastern Alps, whereas the southern Alps were assumed to be a relatively undeformed foreland, composed of a metamorphic basement formed during the Variscan orogenesis and overlain by late Paleozoic and early Mesozoic sediments. Detailed mapping in the Orobic Alps between Lake Como and the Adamello massif (Fig. 1) was first undertaken between 1930 and 1940 by a Dutch research group who recognised the presence of series of Alpine nappes in both basement and cover and who interpreted these structures as a result of superficial gravity tectonics (De Sitter and De Sitter-Koomans 1949; de Jong 1979). Gaetani and Jadoul (1979) interpreted the nappes as thrust imbricates in a compressional setting, associated with crustal shortening. Laubscher (1985) applied the concept of thin-skinned tectonics to the western Orobic Alps and proposed a shortening of approximately 40 km for that area in a south-verging thrust system. Schönborn (1992) constructed balanced cross sections through the Central Orobic Alps (Fig. 1) and proposed a total shortening varying from 80 km in the western to 110 km in the eastern Orobic Alps.

Most of the literature concentrates on complex deformation in the southern part of the Orobic Alps where the sedimentary cover is deformed by a series of imbricate thrust faults (De Sitter and De Sitter-Koomans 1949; Rossi 1975; Gaetani and Jadoul 1979; de Jong 1979). The northernmost of these structures, along which metamorphic basement is thrust over cover, is called the Orobic thrust. This fault is generally represented as a simple thrust fault, locally also associated with duplex structures or more complicated imbricates (Schönborn 1992). In some areas this fault interferes with older structures in the basement. This study investigates such interference in an area along the Orobic thrust near Lago del Diavolo in the Central

Fig. 1 Simplified map of the Orobic alps. *Rectangle* indicates Lago del Diavolo area

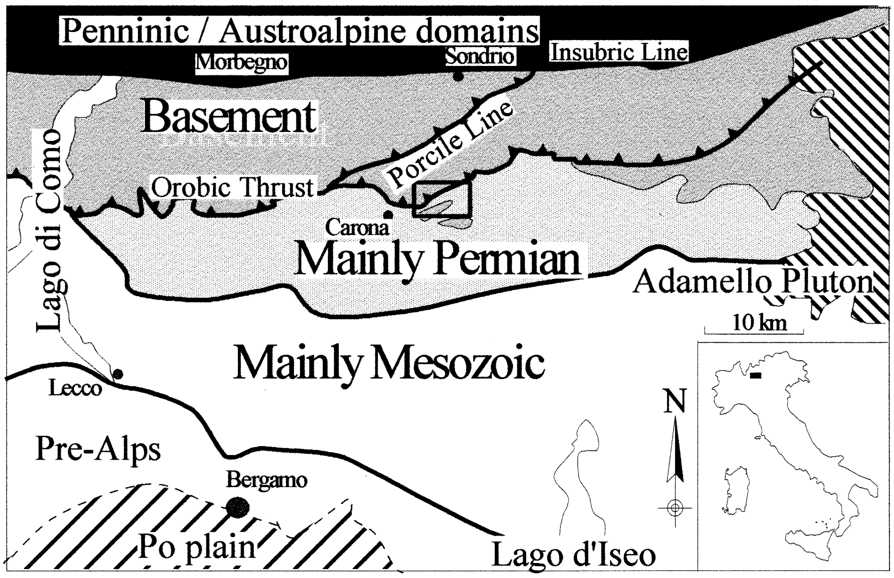
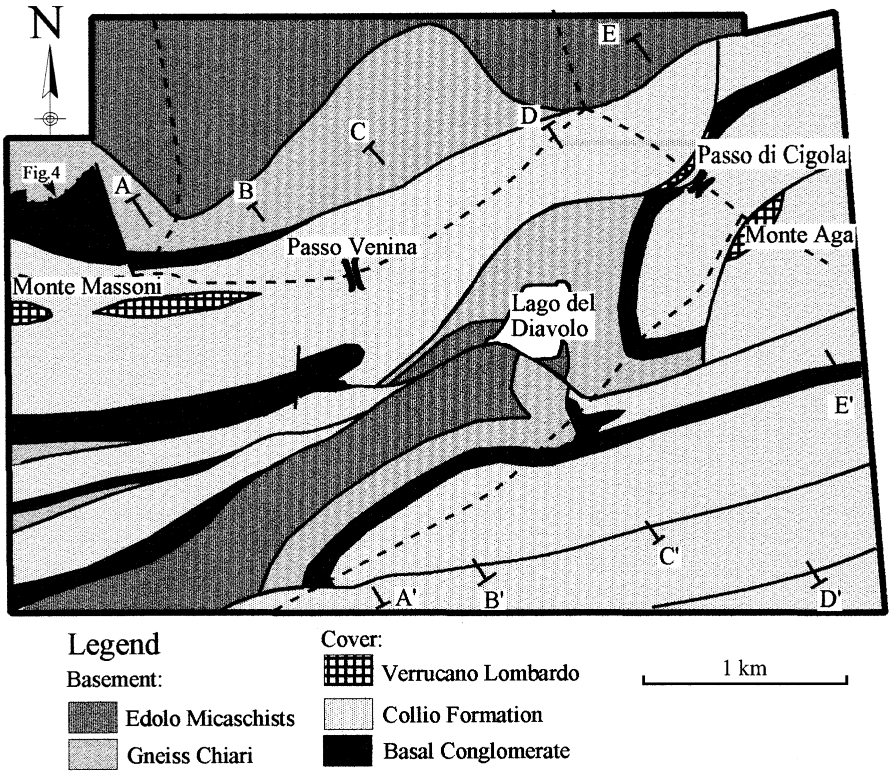


Fig. 2 Map of the Lago del Diavolo area. Indicated sections are shown in Fig. 6



Orobic Alps. The Lago del Diavolo area, outlined in Fig. 1, is situated in the upper Val Brembana, approximately 60 km NNE of Bergamo (Fig. 2).

Geological setting

The Orobic Alps are separated from the Austroalpine and Penninic domains of the central Alps by the Insubric line and are bounded by the Lombardic Pre-Alps and the Po-plain in the south. Variscan basement rocks outcrop dominantly in the north, and post-Variscan cover rocks in the central and southern parts (Fig. 1). In the studied area, two distinct units can be recognised in the basement (Fig. 2): a leucogranitic orthogneiss with a spaced white mica foliation, known as Gneiss Chiari (Dozy 1935) and metasediments, of probably Ordovician to Silurian age (Gansser and Pantic 1988).These metasediments are mainly muscovite schists, known as Edolo micaschists (Rossi 1975). A layering defined by alternating quartzitic and pelitic layers is well preserved. The rocks have low-grade amphibolite metamorphic assemblages of muscovite, biotite, orthoclase and almandine and a foliation defined by muscovite and biotite. The Gneiss Chiari locally shows clearly intrusive relations in the micaschists, and contains enclaves of this unit (De Sitter and De Sitter-Koomans 1949). However, nearly all presently exposed contacts with the metasediments are brittle faults which obscure the original geometry of the intrusions.

Post-Variscan development

After the Variscan deformation in the basement, the area was uplifted and eroded, bringing the presently exposed basement into near-surface position. During the Late Carboniferous, the region was a plateau, subdivided by structurally controlled, low-relief escarpments formed by left lateral movements along the proto-Insubric line (Cadel 1986). During the Late Carboniferous–Early Permian, elongate pull-apart basins were formed. The formation of these basins in the Orobic Alps at this time was probably related to a dextral transform zone between Africa and Europe of Stephanian–Autunian age (Arthaud and Matte 1977). However, Cadel (1986) interprets the basin as a calderic structure, albeit with a rectilinear configuration. Siletto et al. (1993) interpreted the extensional basins as the result of the post-collisional collapse of the Variscan chain.

The Lago del Diavolo area described in this paper is located on the extreme northern margin of one of the sedimentary basins. Normal faulting (D_3) caused the formation of an elongated pull-apart basin, filled with a Late Carboniferous–Early Permian conglomerate of basement erosion products and volcanic material, the Basal conglomerate. This formation forms a clastic wedge, declining in thickness to the south and reaching a maximum thickness of ca 120 m in the north. This geometry suggests a provenance from the north (Cadel 1986). This was followed by a large volume of rhyolitic volcanic rocks, which occur in sequences of at least 500 m to the south of the Lago del Diavolo area, near Monte Cabianca (Dozy 1935). Subsequently, the basin was filled with pile of approximately 1 km of sedimentary rocks, including alluvial fan sandstones and conglomerates along the basin margins, and lacustrine and braided stream deposits (sandstones and mudstones) in the centre of the basin, as well as some minor tuff beds (Cassinis et al.1986). These deposits are known as the Collio formation. In the later Permian, sedimentation stopped and part of the sequence was faulted, tilted and eroded (Cadel 1986). The tilted sequence was then unconformably covered by the Verrucano Lombardo formation, a coarse-grained oxidised braided fluviatile deposit (Casati and Gnaccolini 1967). The angle of unconformity between Collio and Verrucano varies and is of the order of 2–5 in the Lago del Diavolo area.

Results

Basement structures

In the basement two deformation phases (D_1 and D_2) can be recognised that predate the structures in the sedimentary cover and are therefore considered to be pre-Alpine in age.

D_1 is characterised by small tight to isoclinal, rootless similar folds of layering in the Edolo micaschist (S_0), with millimetre- to metre-scale fold amplitude. Milano et al. (1988) reported kilometre-scale D_1 folds along the Pizzo di Rodes–Pizzo Biorco ridge, a few kilometres NE of the Lago del Diavolo area. In the Edolo micaschist, D_1 folds develop an axial planar cleavage (S_1), subparallel to the bedding with a mean orientation of 360/40. D_1 fold axes plunge toward the north. S_1 is the regionally dominant foliation in the basement. Growth of biotite, muscovite, orthoclase, almandine and occasionally staurolite during D_1 suggest amphibolite facies metamorphism and P/T conditions of approximately 500–700°C and more than 1.5 kbar (Deer et al. 1992).

D_2 folds are open to isoclinal similar folds of both S_0 and S_1, with a millimetre- to metre-scale fold amplitude. Most D_2 folds lack an axial planar foliation, but in the micaschist, a N-dipping crenulation cleavage (S_2) was locally developed. D_2 occurred under retrograde greenschist facies metamorphic conditions, as indicated by the synkinematic growth of chlorite and sericite. Overprinting relationships of D_1 and D_2 folds form spectacular type-3 fold interference patterns (Ramsay 1967).

Mottana et al. (1985) describe two metamorphic events based on K–Ar ages on gneisses and schists in the basement. The earlier metamorphic event is interpreted to have occurred around 312 to 368 Ma, and this may be related to both D_1 and D_2. Their younger event is interpreted to be low-pressure reactivation related to the thick sedimentary pile on top of the basement at around 226–245 Ma, and is therefore not related to the D_2 as described in this paper.

Permian fault zones and their internal structure

D_3 normal faults can be observed throughout the Orobic Alps along the contact of basement and Permian cover sediments, over a distance of 40 km. In most localities the fault rocks have been strongly overprinted by later events, but in the Lago del Diavolo area features developed during and shortly after D_3 are well preserved. Post-D_3 thrusting and folding caused development of foliations in the D_3 fault rocks, but also caused structural repetition that allows a detailed study of the faults and fault rocks (Zhang et al. 1994).

D_3 extensional faults (2 in Fig. 3) are best preserved in the northwestern part of the Lago del Diavolo area, north of the Monte Massoni, at the north side of Passo di Cigola, and southwest of Mt. Aga. At the Monte Massoni the contact zone between Gneiss Chiari and conglomerates of the Collio formation is exposed. The gneiss has undergone cataclasis and lost D_1 and D_2 foliations and small-scale structures in a zone up to 10 m wide along the contact. Along most of the contact, the basement is separated from conglomerates by two layers, a lower aphanitic grey cataclasite up to 2 cm thick, and an upper layer of ultra-fine-grained tourmalinite up to 8 cm thick (Figs. 4 and 5). This tourmalinite probably developed by metasomatic replacement of mica-rich cataclasite (Zhang et al. 1994). At other sites the contact zone is more complex, with several alternating cataclasite and tourmalinite horizons, commonly anastomosing. Locally, lenses of andesite occur in the contact zone; these lenses are always bounded by faults or cataclasite horizons and lack D_1 or D_2 structures; they are therefore thought to be associated with D_3 extension. An example can be seen on the eastern shore of Lago del Diavolo (5 in Fig. 3) where cataclased gneiss is overlain by a 3-cm-thick layer of light-coloured cataclasite with sharp boundaries. On top lies a 3- to 4-m-wide contact zone of alternating layers of tourmalinite up to 10 cm thick and lenses of grey cataclasite, deformed conglomerate, sandstone and andesite. North of Passo di Cigola, a similar contact occurs that may be continuous with that observed at Monte Massoni, but late faulting obscures the relationship. At this site the contact zone is up to 5 m wide. A tourmalinite layer is present on the contact between conglomerate and basement gneiss, but alternating lenses and layers of tourmalinite, cataclasite, gneiss and arenite do also occur in the conglomerate.

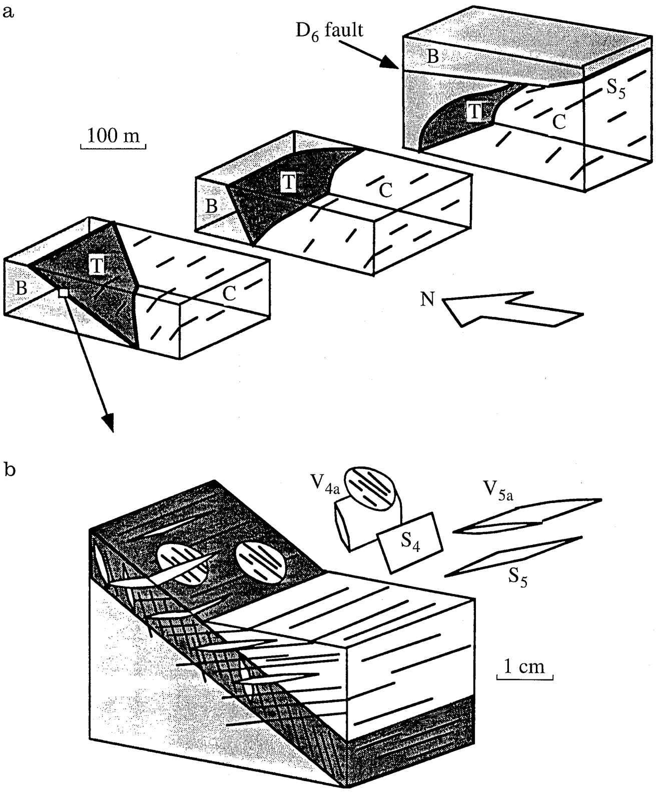


Fig. 4a, b The structural relation along a D_3 fault that forms the basement (*B*)–cover (*C*) contact in the Monte Massoni area (Fig. 2). **a** Large-scale structure in this area is a south-dipping D_3 fault plane marked by a tourmalinite layer (*T*), which is only weakly affected by Alpine deformation in the west (at left) but is steepened and eventually overturned in the east (at right). **b** Detail of the contact and small-scale structures therein. *V* different generations of quartz veins; *S* foliation planes. Explanation in text

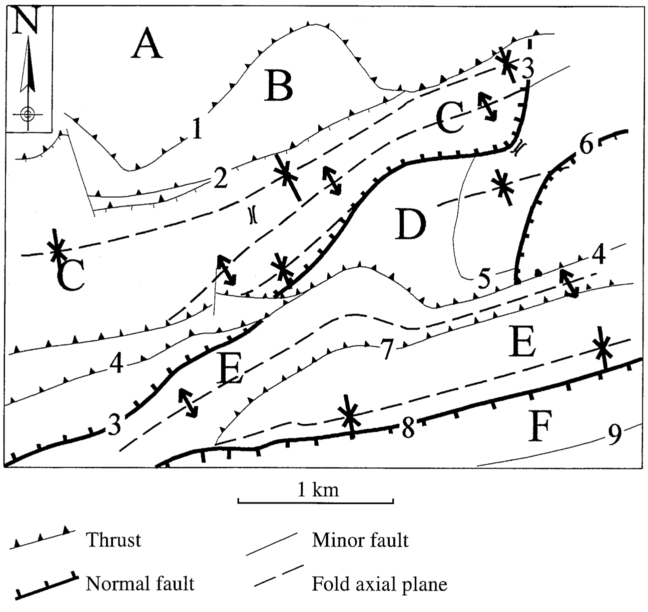


Fig. 3 Tectonic map of the Lago del Diavolo area. *Numbers* refer to faults, capitals to imbricates. See text for discussion

Geometry of post-D_3 faults

The Lago del Diavolo area (Fig. 2) has been strongly affected by deformation post-dating D_3. The principal expressions of this deformation are a large number of thrust and normal faults which define six imbricates, labelled A–F. The faults have been numbered 1–9 on a tectonic map (Fig. 3) and in sections (Fig. 6).

The northern part of the area consists of metamorphic basement, with Edolo micaschists (A) in the extreme north, separated from Gneiss Chiari (B) by fault 1. Slickensides and bending of foliation in micaschist along the fault indicate a southward-movement

Fig. 5 a Photograph of the contact in Fig. 4a, at left, seen from the east. A tourmalinite layer at the contact (*T*) is underlain by several metres of cataclased gneiss (*G*) which grades into orthogneiss at right. Collio-facies conglomerates (*C*) lie to the left of the tourmalinite. **b** The same contact 200 m further to the east, where it has been reoriented and cut by D_6 south-directed thrusting. This is the area shown in Fig. 4a at right. Monte Massoni area: location indicated in Fig. 2

direction of the schists over the gneisses along the north-dipping fault.

Gneiss in imbricate B is bounded in the south by one of the Permian extensional faults, with accompanying tourmalinite (Zhang et al. 1994), which has been reactivated as a reverse fault (fault 2). In the east this contact forms a nearly vertical fault plane, which is cut off by fault 1 at the Pizzo Cigola, and must therefore be considered older. In the west the fault splits into two faults just north of the Passo Venina, with a small imbricate of Basal conglomerate between these two planes.

Imbricate C is formed by Gneiss Chiari basement covered by a sequence of sediments of the Collio formation. In the west this unit has been folded into a westward opening synclinal structure, with a small amount of Verrucano conglomerates in its core just south of Monte Massoni (section AA' in Fig. 6), whereas toward the east an anticlinal structure becomes more pronounced.

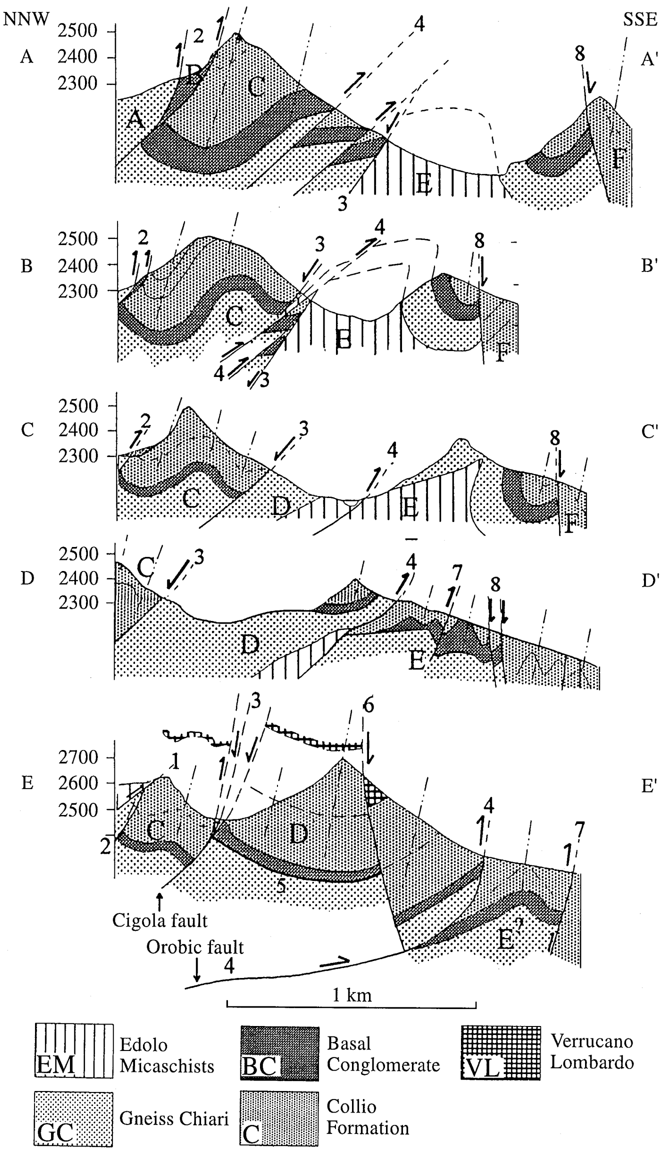


Fig. 6 Cross sections through the Lago del Diavolo area. Locations are given in Fig. 2. *Numbers* refer to faults, *capital letters* to imbricates in Fig. 3. *Dashed–dotted lines* indicate trace of S_5 foliation

In Imbricate C both the basement and the cover are offset by two thrust faults (fault 4), which join toward the east and continue as one fault past the southern shore of the Lago del Diavolo, where it is well exposed. These faults are the eastward continuation of the Orobic thrust described by other authors (De Sitter and De Sitter-Koomans 1949; Cassati and Gnaccolini 1967; Laubscher 1985; Schönborn 1992). In the region west of the Lago del Diavolo area, the Orobic thrust is one of the main faults along which the basement is thrust over the cover, with a displacement of up to 10 km (Schönborn 1992). In the Lago del Diavolo area, however, the importance of this fault is strongly diminished to displacements of at most a few hundred metres (fault 4).

This difference is probably caused by the Porcile line (Fig. 1), which must accommodate a large part of the displacement (Schönborn 1992). Also, the Lago del Diavolo displacement is spread over more thrust faults. The faults dip towards the north, with a dip varying between 40 and 70°.

The southern limit of the folded sequence of basement and cover is formed by the Cigola fault (fault 3), which has a general orientation of 330/45. The Cigola fault is offset by the Orobic thrust (fault 4) west of the Lago del Diavolo and is therefore older. It has a complex deformation history. The main component of movement along this fault, as indicated by the stratigraphic succession, with basement in the footwall and cover in the hanging wall (section CC′ in Fig. 6), is a normal (extensional) movement in which the northern block has moved down. Most kinematic indicators such as slickensides and the deflection of foliation and layering support this observation, but some indicate sinistral strike-slip or thrust movement. The situation becomes more complicated at the Passo di Cigola, where the fault splits into three branches (Fig. 7). The northernmost of these shows evidence for components of thrusting and sinistral strike-slip movement, whereas the two others are normal faults. A small imbricate of Verrucano sediments occurs between the two northern faults (Fig. 7). This occurrence means that the normal faults must have been active after the deposition of the Verrucano Lombardo formation in the Late Permian (D_4). Since the tops of nearby Monte Aga and Pizzo di Cigola both consist of Collio sediments and lie 250 m above the outcrop of Verrucano in the pass, the throw of the original normal fault must have been more than 250 m. Along the fault planes, contacts are very sharp and a zone of fine-grained cataclasite and brecciated material of a few centimetres has developed. The Cigola fault predates thrusts 1 and 2 according to Dozy (1935) and De Sitter and De Sitter-Koomans (1949). Therefore, it seems likely that the transcurrent thrust movement observed along segments of fault 3 also postdates extension. This classifies fault 3 as a reactivated normal fault.

Imbricates D and E consist of Edolo micaschists, covered by Gneiss Chiari. The contact between these formations is an intrusive contact around the Lago del Diavolo (section CC′ in Fig. 6), but a fault contact toward the SW. This basement in turn is covered by a sequence of Basal conglomerate and Collio sediments. The contact between basement and cover is formed on the eastern shore of the Lago del Diavolo by a D_3 fault with a Permian tourmalinite sequence (fault 5), as described above. Toward the SW in imbricate E, the contact has been faulted by the Orobic thrust (fault 4).

The complete sequence of basement and cover has been folded into a syncline–anticline–syncline group, of which the N-syncline lies in Monte Aga, (Fig. 3 and section D in Fig. 6). A well-developed axial planar cleavage (S_5) is present in these folds, dipping steeply toward the NNW. This folding was contemporaneous with small fault movement along the formational contacts.

The Orobic thrust system (fault 4) offsets this entire sequence along the southern shore of the Lago del Diavolo. Shear-band cleavage and slickensides indicate a southward movement of the hanging wall. The fault plane is lined with layers of cataclasite, up to 10 cm thick, as well as thin veins of black pseudotachylite with small injection veins.

Just below the summit of Monte Aga, an outcrop of Verrucano sandstones and conglomerates can be observed (section EE′ in Fig. 6) underlain by a normal

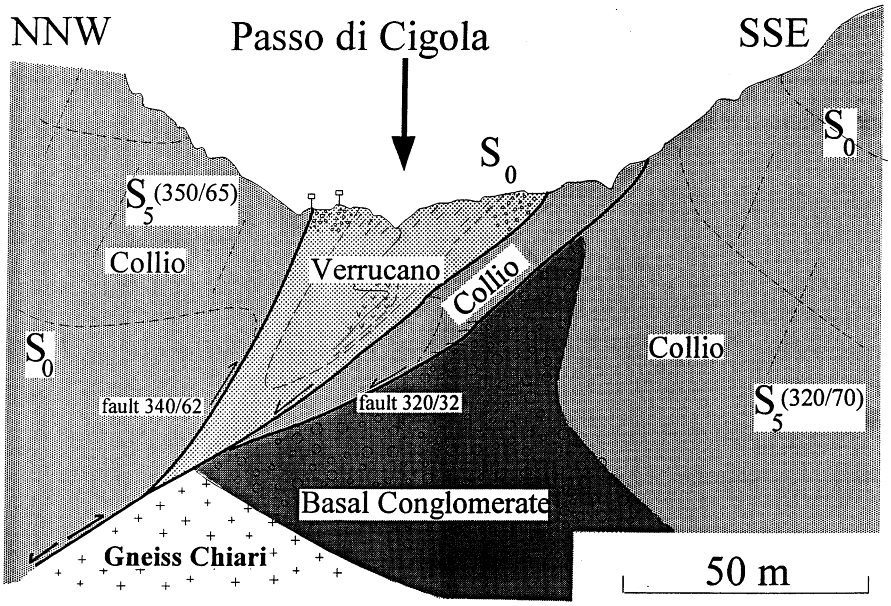


Fig. 7 Field sketch of the Passo di Cigola, with the Cigola fault dividing into three branches

sequence of Collio sediments. This sequence is separated from the Collio sediments which form the top of the mountain by a steeply SE-dipping normal fault (fault 6; E–E′ in Fig. 6). This fault offsets the tourmaline contact (fault 5), but is itself cut off by the Orobic thrust system (fault 4) and is therefore considered to postdate the first and to predate the latter, thus belonging to D_4.

In imbricate F the outcropping formations belong to the higher stratigraphic levels of the Collio formation, which have been deformed into tight E- to W-trending faults and are transsected by several E- to W-trending vertical faults. Dozy (1935) suggests a synclinal structure for this area. An E- to W-trending, vertical fault (8), transsects this area, as do several smaller faults with the same trend. These faults generally show evidence for a vertical displacement component, with the southern block going down. They are therefore interpreted as part of the Permian extension system, with minor reactivation during Alpine times. Further to the south lie thick sequences of Collio volcanics, which form part of the Trabuchello-Cabianca anticline (Schönborn 1992).

Late deformation in D_3 fault zones

Since it is usually difficult to establish the sequence of deformation on the faults, a detailed study was made of later deformation in and around the D_3 fault zones. In the D_3 zone 300 m north of Monte Massoni (fault 2), two foliations are developed in rocks of the contact zone, especially in the tourmalinite (Figs. 4, 5). An older gently SE-dipping foliation is exclusively present in a zone up to 50 cm wide in and around the tourmalinite (Fig. 4b). It is interpreted to postdate the locally brittle deformation phase D_3 since it is undisturbed by brittle extensional faulting and postdates tourmalinite genesis. It makes an angle of up to 30° with the sedimentary layering. The vergence of this angular relation is indicative of N-directed thrusting along the contact zone after tourmaline genesis, probably associated with early stages of D_5. Subsequently, small quartz veins are opened along the foliation. These veins are of the same age as the quartz fibre aggregates that lie parallel to the tourmalinite layers (Fig. 4b). The fibres plunge towards the south. These veins and fibres indicate minor south-directed normal movement after development of the foliation. No indications have been found, however, that this structure is of regional significance. The veins and fibres are folded during development of a strong foliation (S_5), which develops as a crenulation cleavage where the older foliation is developed, and as a slaty cleavage (the only cleavage present) in the Collio formation sediments (Fig. 4b). S_5 developed during prehnite–pumpellyite facies metamorphism in the Collio formation. It is steeply north dipping throughout the mapped area (Figs. 6 and 7). S_5 is rarely developed in basement gneiss; kinks in older foliations in the basement rocks may be of D_5 age.

A second set of quartz veins (V_{5a}) developed along S_5 planes in the contact zone and cut the older foliation, veins and fibres. These veins are associated with major brittle faults that cut S_5 in the Collio formation. One of these faults causes steepening and even local oversteepening of the contact zone of basement and cover (Figs. 4a and 5b). Riedel shears in the fault zone and deflection of S_5 indicate that movement on the fault was major south-directed thrusting (D_6).

Structural evidence in this small area near Monte Massoni thus indicates that at least two, and possibly three, phases of deformation postdate the D_3 in early Permian faults. A slightly different sequence of events was observed at a contact zone north of Passo di Cigola. No older foliation was observed here, but a steeply SE-dipping S_5 is present, cut by V_6 quartz veins and gently ESE-dipping D_6 thrust faults with a N-directed movement component. Porphyry dykes transsect these D_6 thrust faults.

Reconstruction of tectonic history

Based on the field observations and the constructed sections, the following tectonic evolution is deduced from the early Permian onwards (see Fig. 8).

During D_3 an elongated extensional, EW-trending basin was formed in the Orobic Alps (Fig. 8a). The Lago del Diavolo area is situated along the northern rim of this basin, which was filled with Basal conglomerates and the volcanoclastic sediments of the Collio formation. Fault 2 and possibly fault 8 are two of the original extensional faults forming this basin. The age of these structures is interpreted as Late Carboniferous to Early Permian, due to the ages of the Collio sediments (Early to Middle Permian; Cassati and Gnaccolini 1967) and geochronological data of metamorphism in the basement (Siletto et al. 1993).

After deposition of the Collio sediments, continued tectonic activity (D_{3b}), most likely also of an extensional nature, deformed and tilted the sediments (Fig. 8b), giving rise to the unconformity between the Collio and the overlying sediments (Cadel 1986). The basement cover contact below Monte Aga (5) is an example of a fault that was probably active during this period (Fig. 6B). These structures are attributed to the Permian since they are covered by the Late Permian Verrucano Lombardo formation (Schönborn 1992; Broglio Loriga and Cassinis 1992).

Following deposition of the Verrucano, further extension (D_4) caused normal fault movement along faults 3, 6 and possibly 2 and 8 (Fig. 8c). Along the Cigola fault (3), the throw must have been at least 250 m, and along the Aga fault (6), at most 100 m. This extensional phase may be related to the transgression of the Paleotethys in the Late Triassic (Bertotti et al. 1993), which caused establishment of marine conditions in the Orobic Alps. It is also probably responsible for

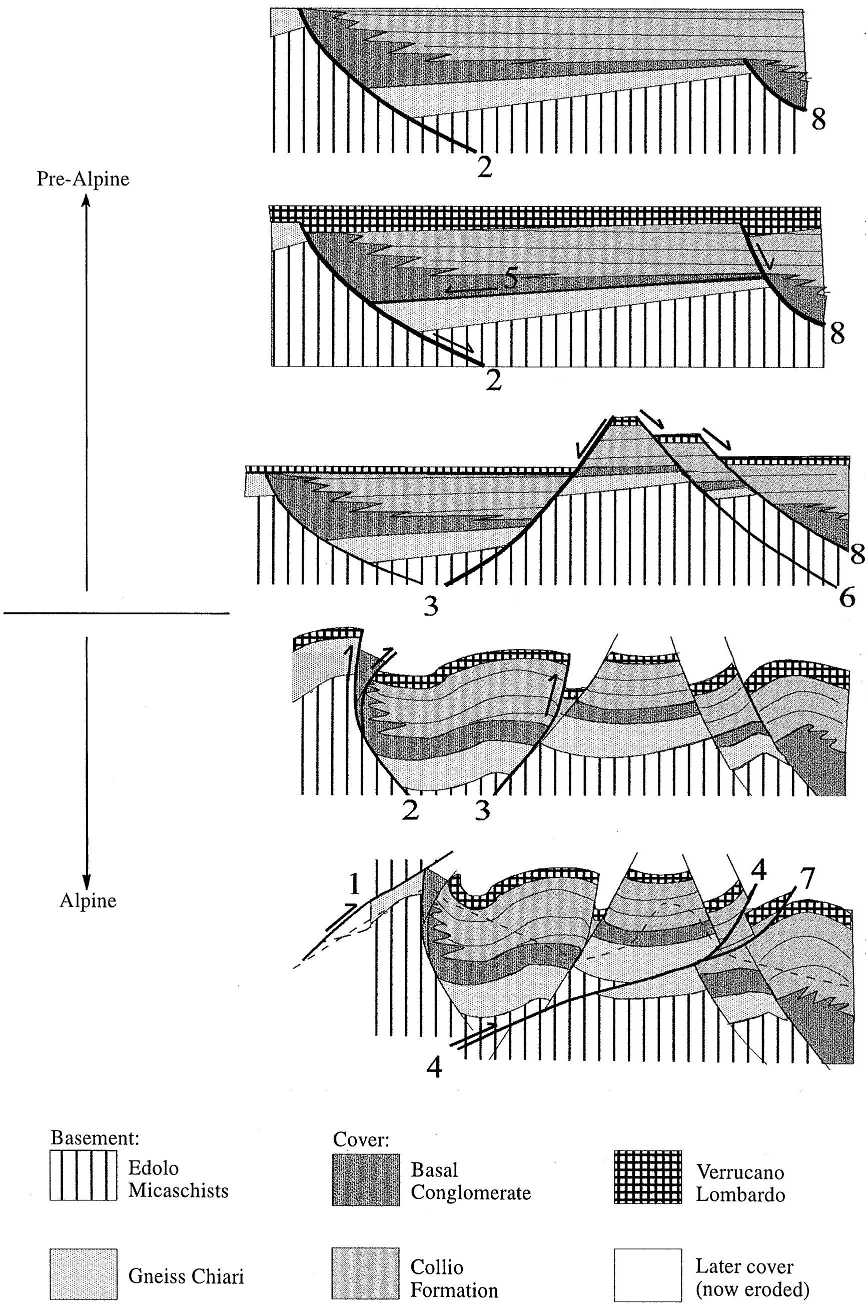


Fig. 8 Reconstruction of the post-Permian development of the Lago del Diavolo area. *Numbers* refer to faults in Fig. 3

the strange shape in this area of the tentatively reconstructed Collio basins (Fig. 9; Schönborn 1992). The tectonic highs of Fig. 8c match with the areas of no deposition in the reconstructions of Schönborn (1992).

The onset of Alpine compression tectonics caused the reactivation of the older extensional faults (2 and 3) as thrust or reverse faults (D_5; Fig. 8D), with displacement toward the south and with a small-scale sinistral component (Passo di Cigola). Data from fault 2 indicate that an initial phase of thrusting was followed by a second phase of activity (D_5), associated with ductile deformation throughout the Collio cover, and with the formation of large EW-trending folds, both in the basement and in the cover. The folding resulted in the formation of an axial planar cleavage (S_5) in the more pelitic layers of the sediments, with a general orientation of 350/80 and fold axes of approximately 080/10. Early folding resulted in formation of thin layers of a few centimetres of quartz fibres on the sedimentological layering, probably caused by flexural slip. At some localities this deformation leads to the formation of minor layer-parallel thrust planes, with imbricates on a decimetre scale. As the deformation progresses, the quartz fibres themselves are folded and broken, whereas the sediments tend to deform homogeneously, giving an even stronger foliation. Close to the fibre planes,

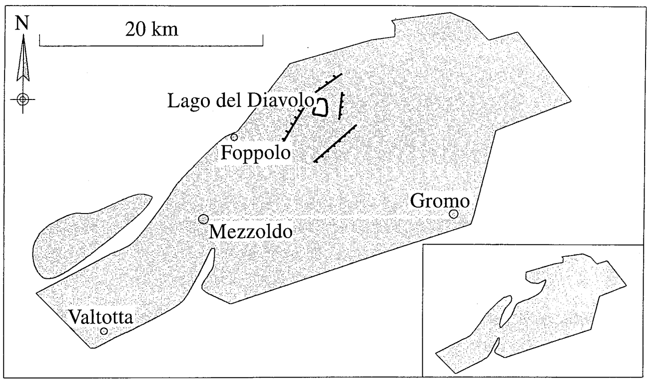


Fig. 9 Tentative reconstruction of the Permian Collio basin, showing the location of the Triassic extensional faults (*inset* shows basin shape proposed by Schönborn 1992)

however, the foliation tends to be folded with the fibres. Fold axes for this deformation tend more toward 060–070/20. Vergence of the folds corresponds to a southward movement of the hanging wall, as do occasional tension gashes. At least 40% of horizontal shortening can be deduced from the folding of these fibres. Since these fibres occur throughout the cover, this value seems to be relevant for the entire structure. S_5 was probably due to increasing metamorphic conditions due to burial under a nappe pile created during D_5.crustal shortening caused steepening and blocking of the reactivated faults. As a result, two new fault planes were formed (D_6; Fig. 8E): the Orobic thrust (fault 4), which offsets faults 3 and 6 and, further north, fault 1, which offsets fault 2. This phase of thrusting corresponds to thrust system 1 of Schönborn (1992). Folding in imbricates B and C between these faults continued during this phase, causing further strengthening of the foliation (S_5). The quartz fibres formed during earlier folding, may have been folded late during D_5, or during D_6.

The intrusion of hornblende–diorite porphyry dikes, some of which can be found in the SW face of Monte Aga and north of the Passo di Cigola, occurred after thrusting. Further east, close to the Pizzo del Diavolo di Tenda, these dikes cut the Orobic thrust, indicating that they are younger in age (Dozy 1935). The age of these dikes is uncertain, but they may be related to the intrusion of the Adamello pluton in the east (Fig. 1), which has been dated at 38 Ma (Brack 1981).

Discussion

The tectonic history as deduced from detailed mapping and constructed sections corresponds well with the history for the entire Orobic Alps as proposed by Schönborn (1992). However, we found that the tectonic evolution in the studied area is locally more complex. First of all, evidence exists for an additional extensional phase in the area, which took place after the deposition of the Permian cover, but before the onset of Alpine compressional tectonics (Fig. 8). This extensional phase is probably related to the opening of Tethys in the Triassic. A similar structure has been found further to the west in the southern Alps. Bertotti et al. (1993) describe the E-dipping Lugano extensional fault, which became active during the Late Triassic. Bernouilli et al. (1990) describe other N- to S-striking normal faults. The extensional phase observed in the Lago del Diavolo area may be related to this widespread extension in the southern Alps.

It appears that Alpine compressional tectonics progress in a particular sequence in the central part of the Orobic thrust studied here. Initially, there is inversion of the original extensional faults which bound the sedimentary basins. The presence of these earlier extensional faults, both of Permian and Triassic age, precluded the formation of new thrust planes during initial stages of Alpine compression and lead to their general reactivation as reverse faults locally with a strike-slip component.

After some initial thrust movement on the reactivated faults (e.g. fault 2), further thrusting (D_5) is contemporaneous with ductile deformation in the imbricates, indicated by folding of bedding and development of a foliation. Such contemporaneous activity of brittle faults and ductile deformation in the wall rock was predicted by Means (1989) for so-called shortening faults: the fault plane itself may have shortened and even folded in north–south direction while it was active as a thrust plane. This internal deformation probably led to steepening of faults while these were still active. While compression continued, the steepened faults became inactive, probably since a decrease of critical resolved shear stress and increase of normal stress on the fault planes inhibited their further activity. New thrust faults that offset the older structures were subsequently formed.

These new faults are not obviously associated with reactivation of older structures such as faults or stratigraphic contacts. These later faults are more gently dipping than the older ones, and cut the older foliation S_5.

The reason for contemporaneous ductile and brittle deformation in the initial stages of Alpine compression may be that the normal faults had a relatively steep original dip which means that shortening could be only partly accommodated by faulting along these reactivated faults. In response to ductile shortening in the imbricates, the reactivated normal faults became too steep and eventually new thrust faults were formed, after which bulk shortening was mainly accommodated by brittle faulting along the thrust planes. This sequence of events may also be of importance in other thrust belts where reactivation of older normal faults as thrusts occurs.

In the investigated area, the Orobic thrust is not a single discrete thrust plane along which major displacement has occurred, as it is in the west of the Orobic Alps (Siletto 1991; Schönborn 1992). In part, this is because some of the displacement was taken up by the Porcile line, but also because the presence of earlier extensional faults caused the spreading of the displacement over several fault zones during Alpine shortening.

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