Recent surface tectonics in a Palaeozoic deeply-exhumed basement: The Bresimo Valley (Western Trentino)

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ABSTRACT

The Bresimo Valley (Western Trentino, NE Italy) is a very peculiar area of the Alps (Nonsberg-Ultental) where very high pressure (about 3.0 GPa) gneisses, migmatites, eclogites and garnet peridotites of the Upper Austroalpine domain croup out. These rocks, which belong to the Adriatic crust, are derived from a very deep Palaeozoic subduction complex, dragged to 100 km of depth into the peridotitic mantle. They have been progressively exhumed and finally exposed at the surface during the late Alpine orogeny. The latest evolution is characterised by brittle faults and joints that deeply influenced the regional morphology. The geological map was the starting point for an integrated approach based on structural survey, petrographic, petrological, radiometric analyses, and on seismo- and morpho-tectonic studies.

AIMS

The aim is to show:
- which methodologies can be applied to investigate a very old and high grade basement of the Eastern Alps, strongly deformed by recent (Neogene and Quaternary) deformation;
- which information can be obtained combining field work, remote sensing, structural geology, geomorphology, petrology and seismotectonics;
- an example of geological map that can be realized in a very complicate area of the Alps, by applying the methodologies listed above.

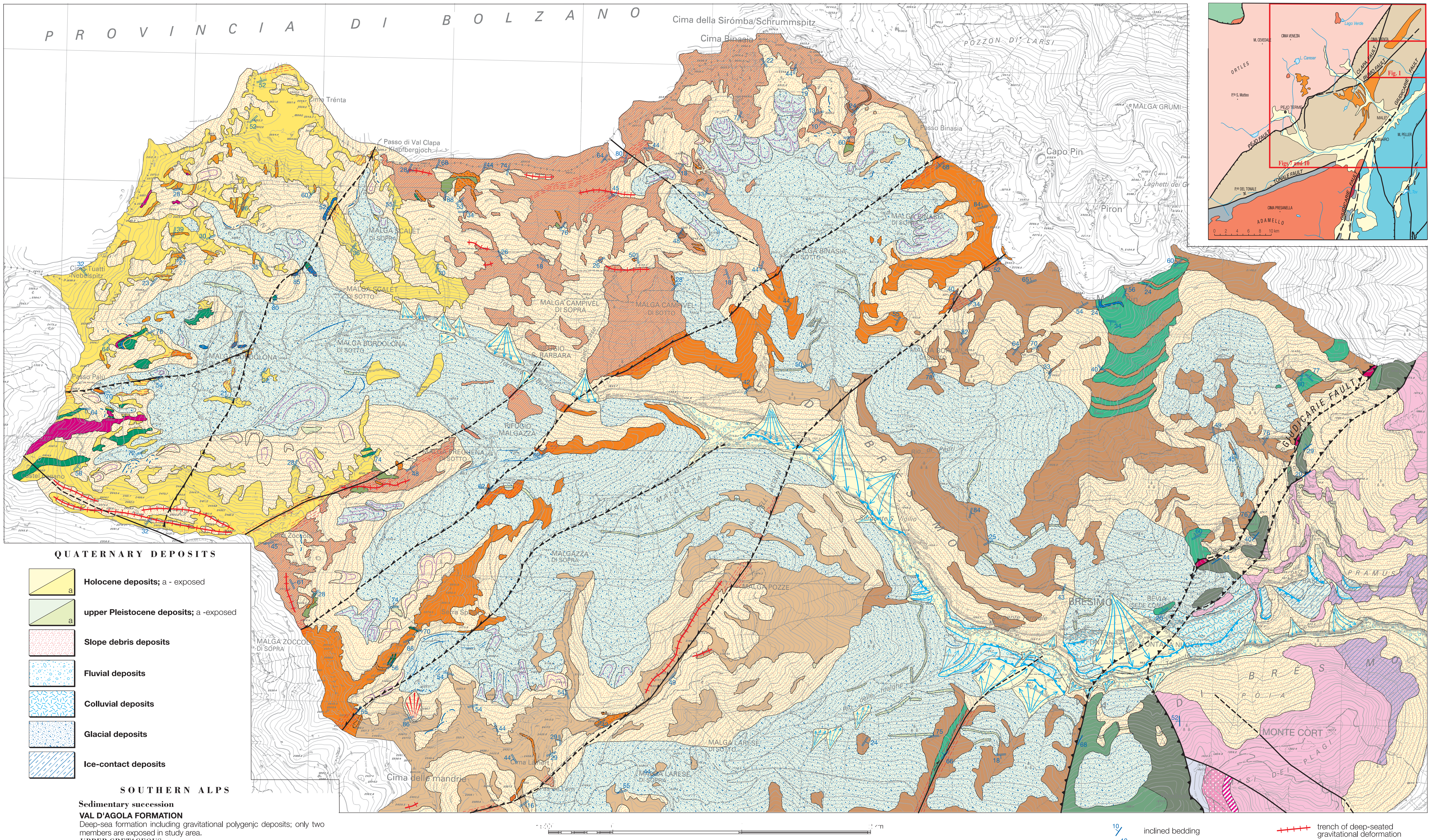
KEY WORDS

Eastern Alps, high grade crystalline basement, structural analysis, seismotectonics

RIASSUNTO

La Valle di Bresimo (Trentino Occidentale, Italia nord-orientale) è situata in un'area di grande interesse delle Alpi (Falda Austroalpino Superiore; Val di Non-Val d'Ultimo) in cui affiorano gneiss, migmatiti, eclogiti e peridotiti a granato cristallizzati ad altissima pressione (circa 3.0 GPa). Queste rocce, che appartengono alla crosta profonda Adriatica, si sono formate in una zona di subduzione Paleozoica e sono risalite da una profondità superiore a 100 km, dall'interno del mantello terrestre. Nel Miocene esse sono state esposte in superficie per effetto dell'attività di faglie e sistemi di frattura neoalpini che hanno profondamente influenzato la morfologia della valle. Le caratteristiche peculiari di quest'area sono rappresentate nella carta geologica riportata in Fig. 1.
Essa è stata il punto di partenza per ricerche petrografiche, petrologiche e geocronologiche, per l'analisi strutturale di deformazioni polifasiche duttili e fragili e per studi sismo- e morfotettonici.

GEOLOGICAL MAP OF THE VAL DI BRESIMO *(TRENTINO)*



QUATERNARY DEPOSITS

- **Holocene deposits;** a - exposed
- **upper Pleistocene deposits;** a -exposed
- **Slope debris deposits**
- **Fluvial deposits**
- **Colluvial deposits**
- **Glacial deposits**
- **Ice-contact deposits**

SOUTHERN ALPS

Sedimentary succession

VAL D'AGOLA FORMATION
Deep-sea formation including gravitational polygenic deposits; only two members are exposed in study area.
UPPER CRETACEOUS

- **Middle Member**
  Red and grey micritic limestone, grey sandstone and conglomerate lenses.
  CAMPANIAN-MAASTRICHTIAN
- **Lower member**
  Dark-grey marl and mudstone with turbiditic sandstone and conglomerate lenses.
  TURONIAN-SANTONIAN

CALCARE DEL SARCA
Grey, micritic limestone with algae, levels and pockets of red siltstone.
RHETIAN-SINEMURIAN

CALCARE DI ZU

- **Tremalzo Member**
  Micritic, grey limestone with stromatolitic levels.
  RHETIAN
- **Grostè Member**
  Dark-grey micritic limestone and black claystone.
  ?NORIC-RHETIAN

DOLOMIA PRINCIPALE
Stromatolitic dolostone.
CARNIAN-NORIAN

MENDOLA FORMATION
Stromatolitic dolostone.
ILLIRIC-CARNIAN

UPPER AUSTROALPINE

Ulten Unit

KYANITE- AND GARNET-BEARING PARAGNEISS
Plagioclase- biotite- white mica- K-feldspar- garnet- and kyanite- bearing paragneiss locally associated to:

- **Stromatic paragneiss**
  Plagioclase- biotite- ± K-feldspar- garnet- kyanite- and ± sillimanite-bearing migmatite.
- **Retrogressed kyanite-bearing paragneiss**
  Plagioclase- biotite- white mica- garnet- and ± kyanite-bearing paragneiss.
- **Garnet- and plagioclase-bearing leucosome**
  Plagioclase- amphibole- garnet-bearing leucosome.
- **Pegmatitic orthogneiss**
  K-feldspar- plagioclase- white mica- and biotite-bearing pegmatitic orthogneiss.
- **Strongly deformed orthogneiss**
  Mylonitic quartz rich, K-feldspar- plagioclase- white mica- and chlorite-bearing orthogneiss.
- **Peridotite**
  Spinel ±garnet bearing peridotite.
- **Plagioclase-bearing amphibolite**
  Amphibole- plagioclase- epidote- ± K-feldspar-bearing gneiss.

Tonale Unit

SILLIMANITE- AND GARNET-BEARING PARAGNEISS
Plagioclase- biotite- white mica- K-feldspar- garnet- and sillimanite-bearing paragneiss associated to:

- **Granitic orthogneiss**
  K-feldspar- plagioclase- white mica- and biotite-bearing granitic orthogneiss.
- **Quartzite**
  Fine-grained, grey or red (Fe-oxide bearing) rock.
- **Plagioclase-bearing amphibolite**
  Plagioclase- epidote- ± K-feldspar-bearing amphibolite.
- **Marble**
  Fine-grained whitish rock.

LATE ALPINE MAGMATISM

- **ANDESITIC DYKES**
  Amphibole-bearing porphyritic dykes.
  ?OLIGOCENE
- **VAL DEI RIVI TONALITE**
  Foliated and cataclastic tonalite.
  OLIGOCENE

- inclined bedding
- inclined schistosity
- fault with undetermined sense of movement
- dextral strike-slip fault
- thrust
- sinistral transpressive fault
- dextral transpressive fault
- mylonitic band
- lithological boundary, outcrop boundary
- trench of deep-seated gravitational deformation
- moraine crest
- rock glacier
- nivation ridge
- fluvial terrace scarp
- erosion scarp
- debris-flow fan
- debris fan

Fig. 1 - *Geological map of the Bresimo Valley (Western Trentino). From NW to SE the exposed rocks are:*
a) the Tonale sillimanite- and garnet-bearing paragneisses including marbles, orthogneisses and metabasites, bounded to the north by the Pejo fault;
b) the Ulten gneisses and migmatites including the garnet-peridotite body of Val Clapa pass, on the left side of the Bresimo Valley.
The boundary between the Tonale and Ulten lithologies is difficult to identify due to the late Paleozoic recrystallization of these rocks under amphibolite facies conditions. To the SE, Mesozoic cover rocks crop out in the Monte Cort area, at the Giudicarie fault footwall.
Along the Giudicarie fault some tonalitic slices occur.

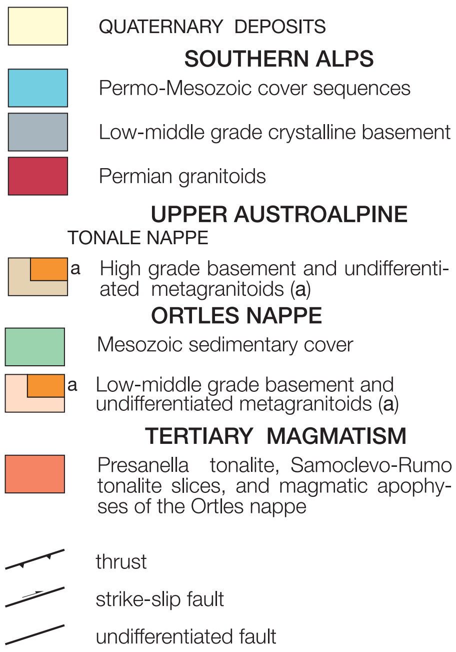


Fig. 2. *Tectonic setting of the Western Trentino. Study area (Fig. 1) and Figs. 7 and 10.*

GEOLOGICAL SETTING

The Eastern Alps are characterised by two main tectonic domains: the Austroalpine and the Southalpine (Southern Alps) separated by the Tonale, Giudicarie and Pusteria faults which belong to the Periadriatic fault system (Fig. 2).

Both, the Southalpine and Austroalpine domains are composed by basement and cover rocks derived from the northern margin of the Adria microplate which bordered the Tethys ocean during the Mesozoic (Martin *et alii*, 1998a with references), locally intruded by Tertiary magmatic bodies (e.g., the Adamello batholith in Fig. 2). During the Alpine orogeny both domains were involved into the nappe stacking. The Southalpine domain, corresponding to the more internal portions of the Adriatic margin, suffered a pellicular brittle deformation and a weak metamorphic reworking. By contrast, the Austroalpine domain, corresponding to the more external part of the margin, was involved into the stacking at the Adria margin as part of a subduction-type wedge, and suffered ductile deformation and metamorphic overprint, as shown by the rocks of the Upper Austroalpine Ortles nappe (Fig. 2). Nevertheless, the deep crust of the overriding Adria microplate was not involved in the Alpine subduction. The deep Adria crust escaped the Alpine metamorphic recrystallization preserving the fabrics and mineral associations related to the Late Palaeozoic (Variscan) evolution (Godard *et alii*, 1996). At present, this portion of the Adria crust crops out in the triangle-shaped area bounded by the Pejo, Giudicarie and Tonale faults and is known as the Tonale basement nappe (Fig. 2). It is well exposed in the Val di Sole, Val

Fig. 3 - *Basement rocks. a) Garnet-pyroxenite dyke transposed within layered garnet-peridotite in sillimanite-bearing gneisses and pegmatitic orthogneisses of the left side of the Val di Bresimo. The boudinage of the pyroxenite indicates a strong deformation, suffered by the peridotite in the mantle wedge before being incorporated in the subduction mélange corresponding to the Ulten rock complex. b) Migmatitic gneisses of the Binasia ridge exhibiting mm-to-cm spaced bands consisting of biotite+garnet+sillimanite±rutile-rich melanocratic component and quartz+plagioclase±K-feldspar-rich leucocratic component cut across by plagioclase-quartz leucosome (i.e., trondhjemite).*

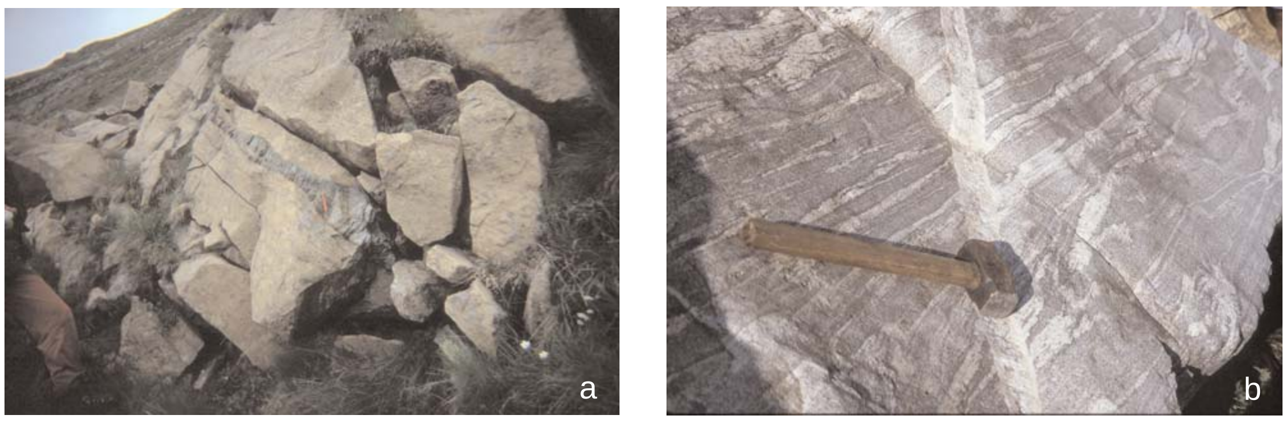
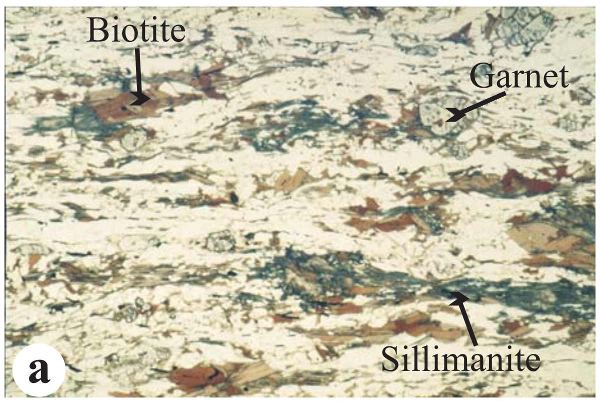
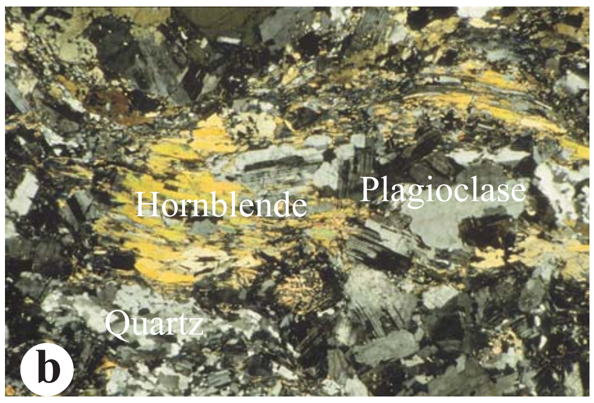


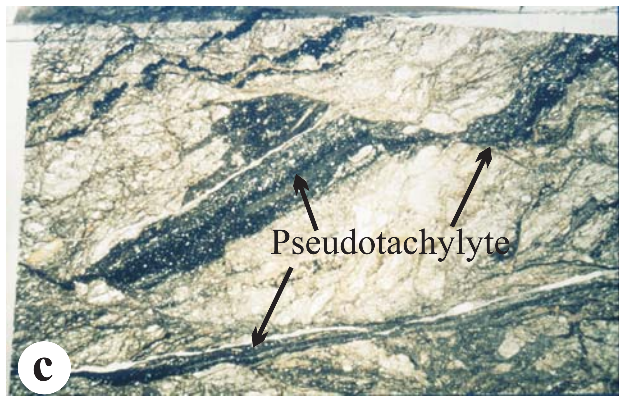
Fig. 4 - *Cover rocks. a) Upper Cretaceous Insubric Flysch (Val d'Agola Formation) at the footwall of the Giudicarie fault in the lower Val di Bresimo. This outcrop belongs to the lower levels composed of carbonatic turbidites and conglomerates. Here deformation, mainly characterised by pressure-solution processes related to the Giudicarie fault activity, is evidenced by a pervasive cm-to-mm spaced cleavage dipping to WNW of 45°. b) Conglomerate of the Val d' Agola Formation, lower levels, composed of more or less rounded clasts within a mud-, partly clast-supported matrix forming layers a few meters thick characterised by inverse gradation. The dominant clasts are black cher and Triassic dolomite, minor clasts are gneiss, quartzite, pelagic limestone and bioclasts.*

Fig. 5 - *Fault rocks. a) Cataclastic tonalite from the Baselga river. Thin slivers consisting of foliated tonalite occur within the Giudicarie fault zone. These rocks are similar to those of the Presanella pluton (Adamello massif). The cooling of the adjacent Rumo tonalite slive has been dated 28±1 Ma using the Rb/Sr methodology on biotite-whole rock. The age of the brittle deformation along the Giudicarie fault post-dates the Oligocene, as it affected the tonalite after the ductile deformation responsible for the foliation. b) Pseudotachylyte vein (at pencil point)and fault from Malga Bordolona di Sopra. Pseudotachylyte veins are associated to E-W directed and south steeply dipping fault planes. Pseudotachylyte glass of this outcrop yielded two groups of $^{39}Ar/^{40}Ar$ ages: an older group of pre-Oligocene age (time range 40-50 Ma) and a latter one of Oligocene age (35-30 Ma).*

Fig. 6 - *Microphotos from thin sections. a) Garnet-sillimanite-two micas, quartz-rich and well foliated gneisse from the Binasia ridge. Some rocks preserve an early (relict) kyanite-bearing high pressure assemblage (microphoto ca. 10 mm width, plane-polarized light). b) Aligned re-crystallized amphibole and plagioclase from the tonalite sliver of the Baselga river. The planar anisotropy is defined by recrystallized hornblende (temperature of recrystallization: above 450° C) together with biotite, plagioclase and quartz (microphoto ca. 5 mm width, cross-polarized light). c) Pseudotachylyte injection veins along the Rumo fault. Pseudotachylytes are associated to subvertical brittle fault planes which show a left-lateral transpressive to compressive deformation (D1 stereoplots, Fig. 7) (microphoto ca. 2 cm width, plane polarized light).*







di Non and in the right side of the Val d'Ultimo (Ulten). The Val di Bresimo, object of this work, is a left tributary of the Val di Non. In the lower part of this valley, the deep Adria crust (i.e., the Tonale nappe) is in tectonic contact with the Adria cover sequences along the Giudicarie fault.

In the Tonale basement, the Alpine deformation is represented only by a few narrow and well localized ductile shear zones of Late Cretaceous age related to the nappe stacking (VIOLA *et alii*, 2003) and by more numerous ductile-brittle and brittle compressive to transpressive faults of Oligocene and Miocene ages (FELLIN *et alii*, 2001; LAURENZI *et alii*, 2003). These latters are mostly concentrated to the east, in the hangingwall of the Giudicarie fault. This fault is a crucial zone where two important deformations occurred: (1) a relevant sinistral shearing during Late Oligocene, and (2) a consistent shortening at Miocene that transported the Austroalpine Tonale nappe above the Southern Alps cover sequences along thrust planes (namely the Giudicarie fault) (SANTINI & MARTIN, 1988; MARTIN *et alii*, 1993; PROSSER 1998). This shortening exhumed rapidly (time range: 15-10 Ma; MARTIN *et alii*, 1998b) the Tonale nappe and exposed at the surface the Ulten unit, part of which crops out in the Val di Bresimo area. From Quaternary to Present, continuous convergence between Adria microplate and Europe against the Giudicarie fault has produced in this area seismic events and morphotectonic structures as trenches, scarps, facets, etc. that are reported in the Bresimo map.

TECTONICS OF THE VAL DI BRESIMO

In the Val di Bresimo (Fig. 1), the Ulten basement extends between the Val Clapa fault to the NW and the Giudicarie fault to the SE. It is composed of high temperature (kyanite±sillimanite bearing) gneisses including spinel-peridotites (C. Zoccolo body), garnet-peridotites and pyroxenites (near Val Clapa Pass), retrogressed eclogites (Malga Preghena), and migmatites (Binasia ridge) (Fig. 3). In spite of the retro-

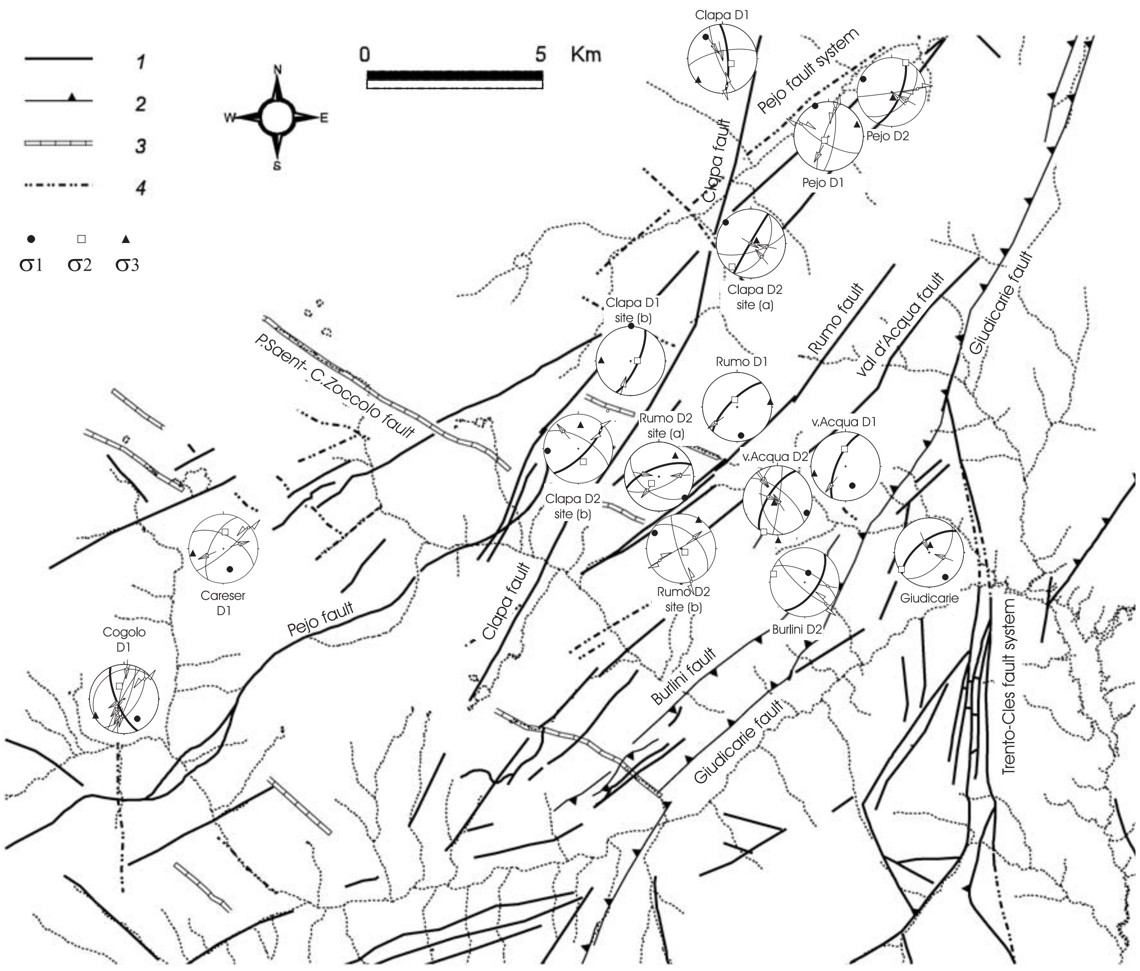
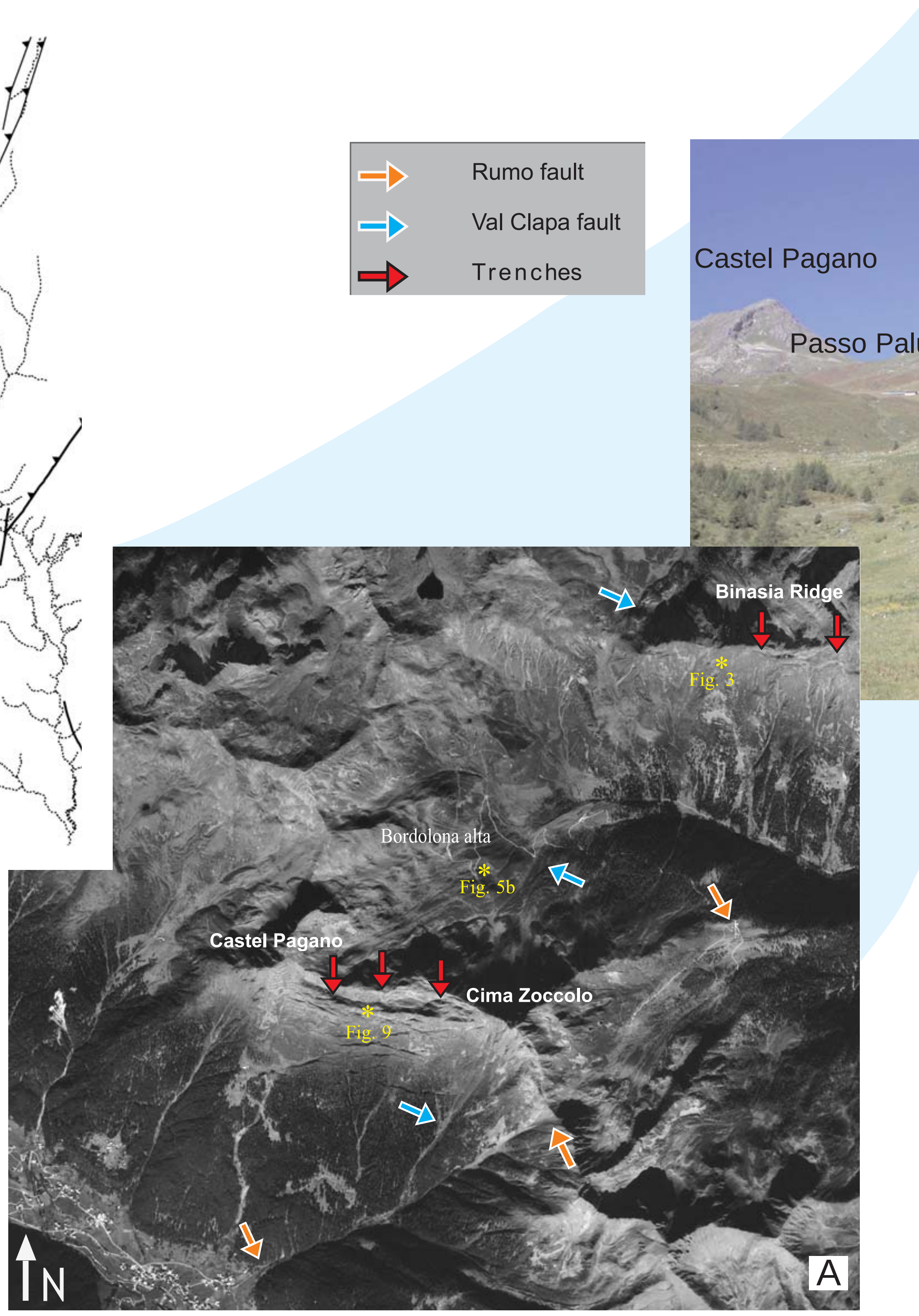


Fig. 7 - *Structural setting and kinematics of the faults in the Val di Bresimo and adjacent areas.*
1: fault; 2: thrust; 3: transtensional fault; 4: lineament from image interpretation; σ_1, σ_2, σ_3: stress axes inferred from kinematic data; great circle: fault plane; arrow: sense of movement of the hangingwall; great thick circle: main fault plane. Stereoplots show average kinematic data representative of D1 and D2 tectonic phases along the faults. The D1 phase, characterised by a sinistral strike slip along NNE-trending faults, has been dated at Oligocene on the basis of $^{39}Ar/^{40}Ar$ data. The younger D2 phase, characterised by reverse to dextral transpressive deformation along the NE- to -ENE planes, is assumed to be Miocene in age owing to the analogy with kinematics and age of the Giudicarie compressive deformation. The youngest deformation structure is the P. di Saent - C. Zoccolo fault, which controls the direction of the upper Val di Rabbi and the development of deep-seated gravitational slope deformations on the left side of the valley.



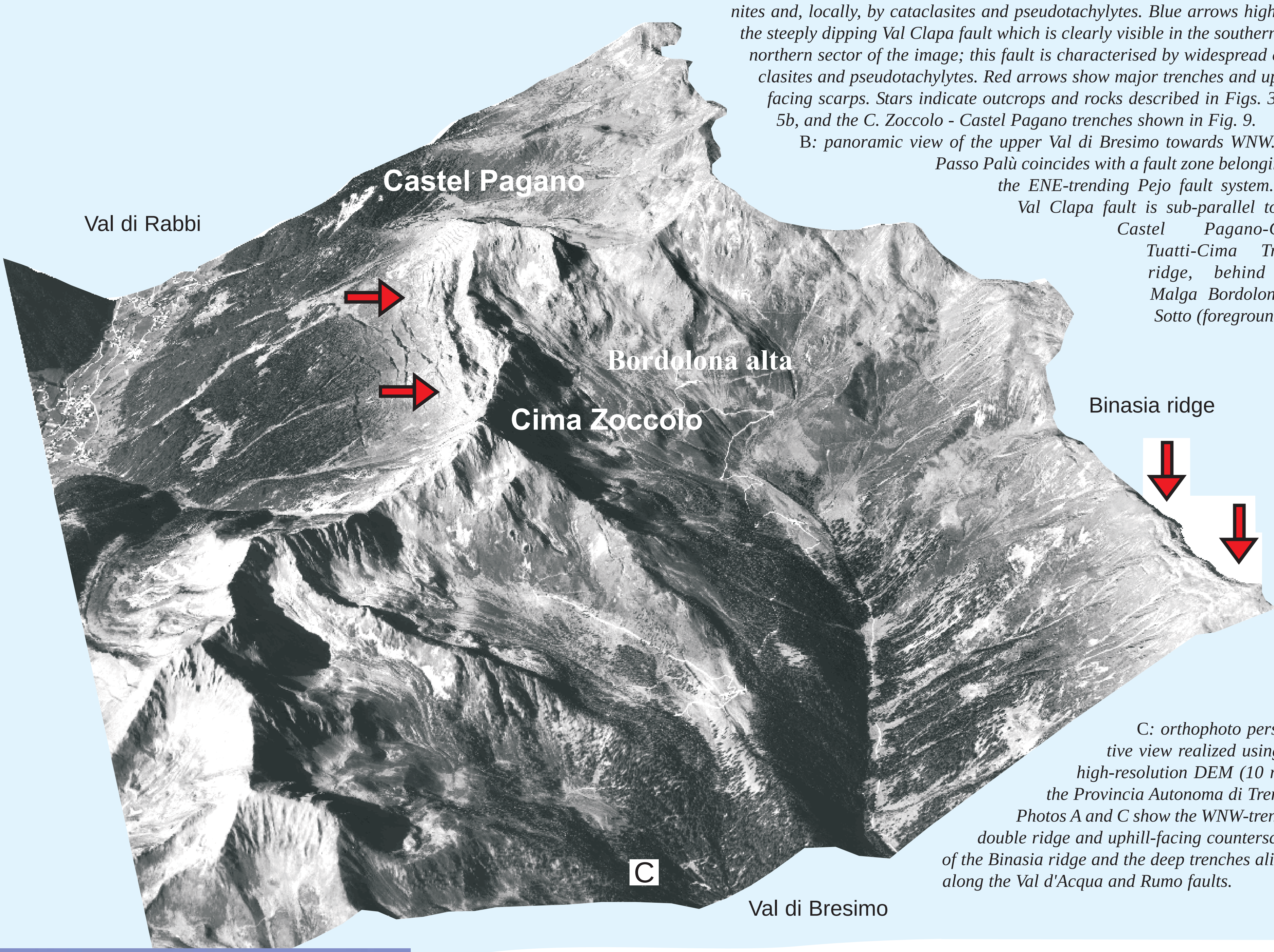


Fig. 8 - *Upper Val di Bresimo.*
A*: orthophoto plane view showing major faults and morphostructures. Orange arrows point out the NW dipping Rumo fault dominantly characterised by mylonites and, locally, by cataclasites and pseudotachylytes. Blue arrows highlight the steeply dipping Val Clapa fault which is clearly visible in the southern and northern sector of the image; this fault is characterised by widespread cataclasites and pseudotachylytes. Red arrows show major trenches and uphill-facing scarps. Stars indicate outcrops and rocks described in Figs. 3 and 5b, and the C. Zoccolo - Castel Pagano trenches shown in Fig. 9.*
B*: panoramic view of the upper Val di Bresimo towards WNW. The Passo Palù coincides with a fault zone belonging to the ENE-trending Pejo fault system. The Val Clapa fault is sub-parallel to the Castel Pagano-Cima Tuatti-Cima Trenta ridge, behind the Malga Bordolona di Sotto (foreground).*
C*: orthophoto perspective view realized using the high-resolution DEM (10 m) of the Provincia Autonoma di Trento. Photos A and C show the WNW-trending double ridge and uphill-facing counterscarps of the Binasia ridge and the deep trenches aligned along the Val d'Acqua and Rumo faults.*

gression processes which have masked previous fabrics and minerals, high pressure relics have been found supporting that these rocks belong to an old (Palaeozoic) subduction mélange which has been dragged almost to 100 km of depth into the peridotitic mantle and developed the main metamorphic imprint at Carboniferous (Tumiati *et alii*, 2003; Ranalli *et alii*, in press). Retrogressed gneisses including tholeiitic amphibolites (Bargossi & Morten, 1979) extend in the Monte Pin area up to the Giudicarie fault, tectonically adjacent to flysch and conglomerate of Upper Cretaceous age (Val d'Agola Formation, Insubric Flysch, Castellarin, 1977) (Fig. 4).

Northwestwards, the Ulten unit is in lithological contact with the Tonale unit composed of retrogressed sillimanite-bearing gneisses including marbles, amphibolites and orthogneisses. The boundary between the Tonale and Ulten lithologies is difficult to identify due to the Late Palaeozoic recrystallization under amphibolite facies conditions. Slices of Oligocene tonalites related to the Tertiary post-collisional magmatism (tectonically foliated) occur inside the Giudicarie fault zone (Fig. 5a) (Martin *et alii*, 1993).

The basement of the Val di Bresimo has been strongly affected by the Rumo, Val Malgazza, Val Clapa, Val Burlini, Valle dell'Acqua Alpine transpressive to compressive faults (Figs. 1, 2 and 7), and by more recent deformations referred to Quaternary. These faults cut across the basement and the Late Palaeozoic lithological contacts. They are characterised by peculiar rocks as mylonites, cataclasites, pseudotachylytes and kakirites (Fig. 5) associated to different kinematic indicators (e.g. SC' structures and fault slickensides), that have been carefully measured during the structural survey. Basement, sedimentary and fault rocks have been studied through the microscope, and the microstructures recognized in oriented thin sections (e.g. Fig. 6) have been compared with the mesoscale kinematic indicators.

To understand the Tertiary fault kinematics of this crucial area we have enlarged the structural survey to the adjacent Val Clapa, Valle di Pejo, Val di Rabbi and Val di Non. Therefore, Fig. 7 shows the faults active in the basement at the hangingwall of the Giudicarie fault since Late Oligocene (Laurenzi *et alii*, 2003). Fig. 7 derived from fault field and microscope data shows two tectonic phases (D1, D2) which

Fig. 9 - *Castel Pagano - C. Zoccolo double ridge, measuring 1.5 km in length parallel to the P. di Saent - C. Zoccolo fault. A number of trench sets are present, running parallel to the double ridge; the main trench reaches a maximum depth of 50 m.*

developed under brittle-ductile to brittle conditions. The first was characterised by a sinistral strike-slip activity along the major NNE to NE faults (D1 stereoplots in Fig. 7). The second brittle phase was characterised by a reverse to dextral transpressive behaviour of the main NNE to NE faults, and by a transtension along new developed NW faults (D2 stereoplots in Fig. 7). An example of this latter transtensive deformation is the P. Saent-C. Zoccolo fault (FELLIN *et alii*, 2001).

A strong relationship appears between the faults and the geomorphological features (trenches, uphill-facing scarps, triangular facets and large landslides) (Fig. 1). These peculiar features have been studied through remote sensing analyses at regional scale using geocoded satellite images and orthophotos visualized both in plane and as perspective views (Fig. 8).

Along the ridge between the Val di Bresimo and Val di Rabby the wide trenches belonging to the Castel Pagano - C. Zoccolo large landslide (a deep-seated gravitational deformation), are clearly visible and appear associated to the P. Saent-C. Zoccolo fault (Figs. 7, 8 and 9). On the left slope of the Val di Bresimo, the Binasia ridge trenches can be also recognized (Figs. 8A and C). Finally, some evidence of the present fault activity related to the continue convergence of Europe and Adria comes from the seismic events scattered along the tectonic lineaments in the Val di Bresimo, Val di Rabbi, Val Clapa and Val di Pejo (Fig. 10).

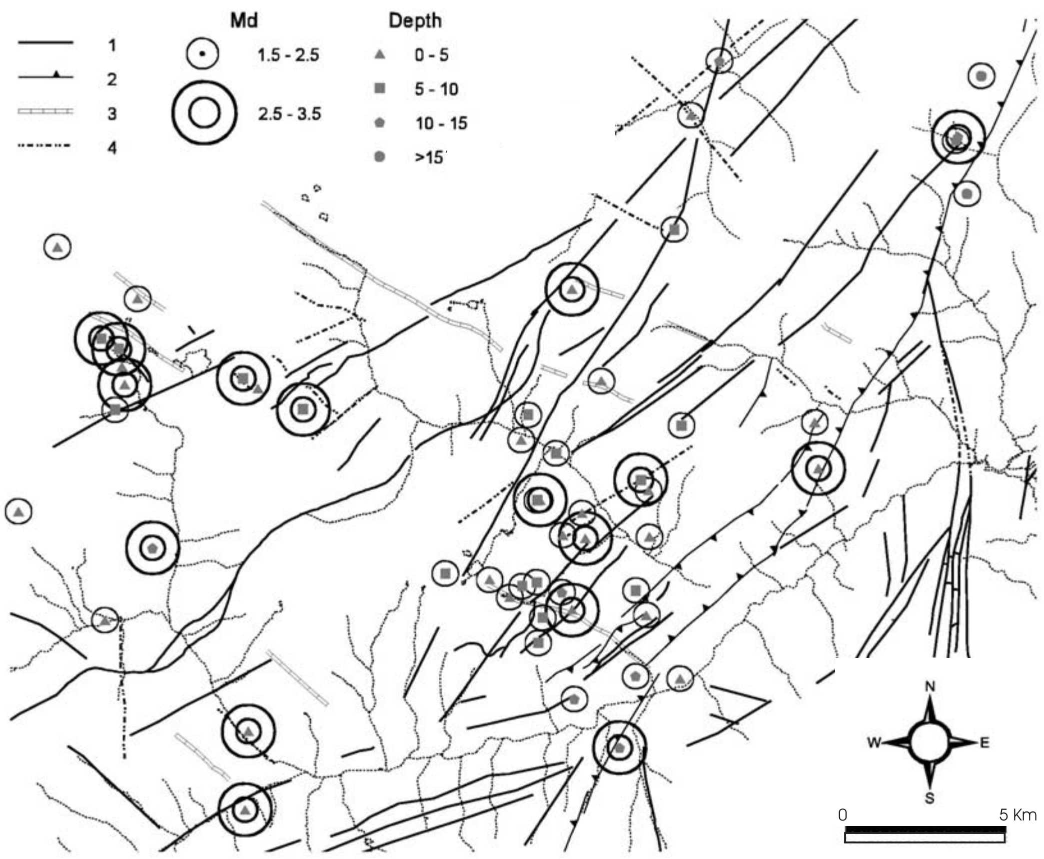


Fig. 10 - *Magnitude (Md) and depth of seismic events acquired by the Provincia Autonoma di Trento in the 1983-1999 time range. The hypocentre distribution is affected by an horizontal location error <2 km and <4 km for the periods 1991-1999 and 1983-1990 respectively. The vertical error is <4 km for the period 1991-1999, whereas in some cases it reaches considerable values (10-20 km) for the 1983-1990 events. The selected events (Md ≥ 1.5) were registered by at least three measurement stations.*
Legend. 1: fault; 2: thrust; 3: transtensional fault; 4: lineament from image interpretation.
Seismic events concentrate mainly around the Val di Rabbi and show a magnitude between 2 and 2.6. A few events of shallow to medium depth (max depth around 13 km) are aligned along the Val Clapa fault, whereas shallower hypocentres are concentrated at intersections between NW and NNE morphotectonic lineaments in the Val di Rabbi. A few medium-depth events (10-16 km) are scattered along the Giudicarie fault.

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