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The kinematics of the late Alpine Muretto fault and its relation to dextral transpression across the Periadriatic line

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Key words: Muretto fault, Periadriatic line, Engadine line, transpression

ZUSAMMENFASSUNG

Die spät-Alpine (post-Bergell) N30°W-streichende Muretto-Störung ist eine dextrale Schrägabschiebung. Einige, kleinere Störungen am Septimer und Lunghin Pass sind kinematisch mit der Muretto-Störung gekoppelt und haben eine schräge, ostsüdost-gerichtete Extensionsrichtung und eine ebenfalls schräge, nordost-orientierte Verkürzungsrichtung. Die Kinematik der N50°E-streichenden Engadiner Linie ist ähnlich. Die Kinematik der Indentation der Adriatischen Plate und der assoziierten dextralen Transpression entlang der E-W-streichenden Periadriatischen Line ist durch nordost-gerichtete Dehnung und nordwest-orientierte Verkürzung gekennzeichnet und ist somit anders als die Kinematik der Muretto-Störung. Es wird daher vermutet, daß die Intrusion und gleichzeitige bis subsequente schnelle Hebung und dextrale Scherung des Bergellplutons, dessen Intrusion von Bewegungen an der Periadriatischen Linie kontrolliert wurde, ein lokales Verformungsfeld am nordöstlichen Rand des Plutons hervorrief, welches die Kinematik der Muretto und assoziierter Störungen kontrollierte.

ABSTRACT

The late Alpine (post-Bergell) N30°W-striking Muretto fault is a dextral oblique-normal fault which is kinematically compatible with some minor faults immediately north and east of the Bergell pluton. Their kinematics are due to oblique eastsoutheast-directed principal extension and also oblique northeasterly-directed contraction. The kinematic evolution of the adjacent N50°E-striking sinistral oblique-reverse Engadine line is similar. The kinematics of indentation of the Adriatic plate and associated dextral transpression across the E-W trending Periadriatic line is different, with northeast-directed extension and shortening oriented NW-SE. It is suggested that the intrusion and simultaneous to subsequent rapid uplift and dextral displacement of the Bergell pluton, the intrusion of which is kinematically related to movement at the Periadriatic line, created a local, near-field kinematic framework which controlled faulting at the Muretto and related faults at its northeastern tip.

Introduction

The Austroalpine and Pennine units of the Swiss and adjacent Italian Alps were intensely deformed during Cretaceous and Paleogene crustal shortening (e.g. Liniger & Guntli 1988, Merle et al. 1989, Schmid & Haas 1989, Ring et al. 1989, Schmid et al. 1990). Thrusting was the principal response to shortening and led to the building of a thick orogenic wedge. Accompanied burial of continental and oceanic material resulted in high-pressure and subsequent amphibolitefacies metamorphism in the Lepontine realm (e.g. Frey et al. 1974, Heinrich 1982, 1986; Fig. 1), where deep parts of the nappe pile are

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exposed. Immediately after the Early Tertiary peak of high-pressure metamorphism in the Ticino area (Becker 1993) very rapid exhumation and cooling of rocks started. The processes of initial exhumation of these high-pressure rocks are as yet poorly understood, but the advanced stages of cooling within the upper crust are closely related to southward backthrusting and simultaneous to subsequent dextral strike-slip along the Periadriatic line (Schmid et al. 1987, 1989, Heitzmann 1987). This deformation is related to postcollisional shortening between the Adriatic and European plates that caused dextral transpression in front of the Adriatic plate which acted as a rigid indenter (Schmid et al. 1989, Merle et al. 1989). Dextral transpression across the Periadriatic line led to variable amounts of updoming in the Lepontine area (Merle et al. 1989, Schmid et al. 1989). Indentation-related processes commenced in the eastern Central Alps and caused regional uplift and the subsequent intrusion of the Bergell pluton at about 30–32 Ma (Grünenfelder & Stern 1960, Gulson & Krogh 1973, von Blankenburg 1992). These processes progressed west and northward towards the central Ticino area (updoming as deduced from cooling ages of mica and fission-track studies at 25–20 Ma and the Simplon region

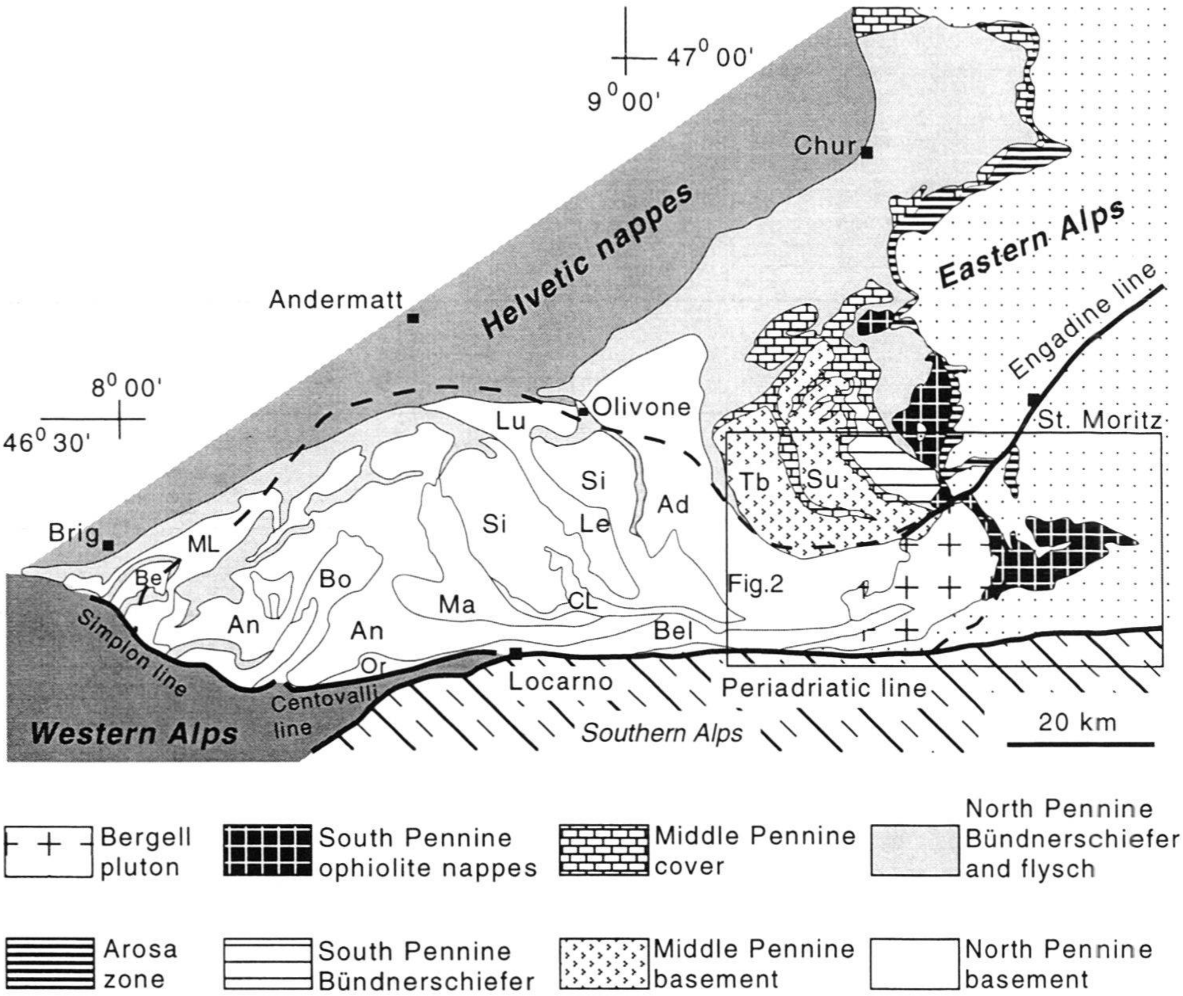


Fig. 1. Tectonic sketch map of the Central Alps and location of figure 2. Note strongly dextrally displaced Bergell pluton suggesting that initial intrusion occurred somewhere in the Ticino area close to the town of Locarno (Schmid et al. 1989). Dashed line shows staurolite – in isograd (Frey et al. 1974).

(uplift at 15–10 Ma, Wagner et al. 1977, Hurford 1986). This temporal and spatial uplift pattern indicates that the Adriatic plate indented the Pennine units in a northwesterly direction and not in a simple N-S direction. Successive regional uplift increased the gravitational potential of the mountain chain and triggered extension in the Central Alps. In the eastern Central Alps the nappe pile was extended in an easterly direction (e.g. Ring 1989, Nievergelt et al. 1991, Ring et al. 1991), whereas the rocks in the Ticino and Simplon areas were extended west- to southwestward (Mancktelow 1985, 1990, Merle et al. 1986, Mancel & Merle 1987, Steck 1989, Ring & Merle 1992).

The Periadriatic line is a major result of postcollisonal dextral transpression and the structural evolution of this important lineament has been analysed in great detail (Argand 1916, Spitz 1919, Laubscher 1971, 1983, Ahrendt 1980, Heitzmann 1987, Schmid et al. 1987, 1989). Possibly related lineaments received less attention and are much less understood. Schmid & Froitzheim (1993) recently presented a block rotation model for the Engadine line and predicted downfaulting of the southeastern block in the northeastern part of this fault, sinistral horizontal movement along the central segment between Maloja and Zernez, and relative uplift of the southeastern block for the southwestern part of the fault. Merle et al. (1989) relate the emplacement of the Bergell pluton to conjugated dextral displacement at the Periadriatic line and sinistral off-set at the Engadine line. A genetic relationship between the rapid uplift of the Bergell pluton and the kinematic evolution of its bounding faults (Periadriatic, Engadine and Muretto faults) has already been suggested by Wagner et al. (1979). The kinematic evolution of the Muretto fault (Riklin 1978, Peretti 1985), which strikes almost perpendicular to the Engadine and Periadriatic lines and which is exposed immediately northeast of the Bergell pluton (Fig. 2), is, however, poorly constrained (see review below).

This contribution presents fault-slip data from the late Alpine Muretto and possibly associated faults, and Oligocene to Miocene extensional structures in the Bergell area. I will discuss these data in the context of postcollisonal dextral transpression between the Adriatic and European plates and the intrusion of the Bergell pluton.

Regional geology of the Bergell area and previous work at the Muretto fault

The region belongs to the Pennine and Austroalpine nappe edifice of eastern Switzerland and northern Italy (Fig. 2). Pennine nappes occur to the west, north and east of the Bergell intrusion and comprise from bottom to top: North Pennine units (basement nappes and Bündnerschiefer with some intercalated ophiolite occurrences); the Middle Pennine domain (Tambo and Suretta basement and Schams, Falknis and Sulzfluh cover nappes); and the South Pennine ophiolitic zones. The latter include the Avers Bündnerschiefer (Oberhänsli 1977), the Platta nappe (Dietrich 1970), and the Forno (Peretti 1985) and Malenco zones (De Capitani et al. 1981). The boundary between the Pennine and Austroalpine nappe system is made up by the Arosa suture zone (Ring et al. 1988) which forms a tectonic melange of both Austroalpine and Pennine rock types (Lüdin 1987, Ring et al. 1990). The Austroalpine domain in the Bergell area encompasses the Margna (Liniger & Guntli 1988) and Err-Bernina nappes (Cornelius 1950) and the Tonale zone (Lardelli 1981).

The calc-alkaline Bergell pluton consists of early and volumetrically subordinate gabbros and gabbroic and ultramafic cumulates which were intruded by a tonalite at 32 Ma

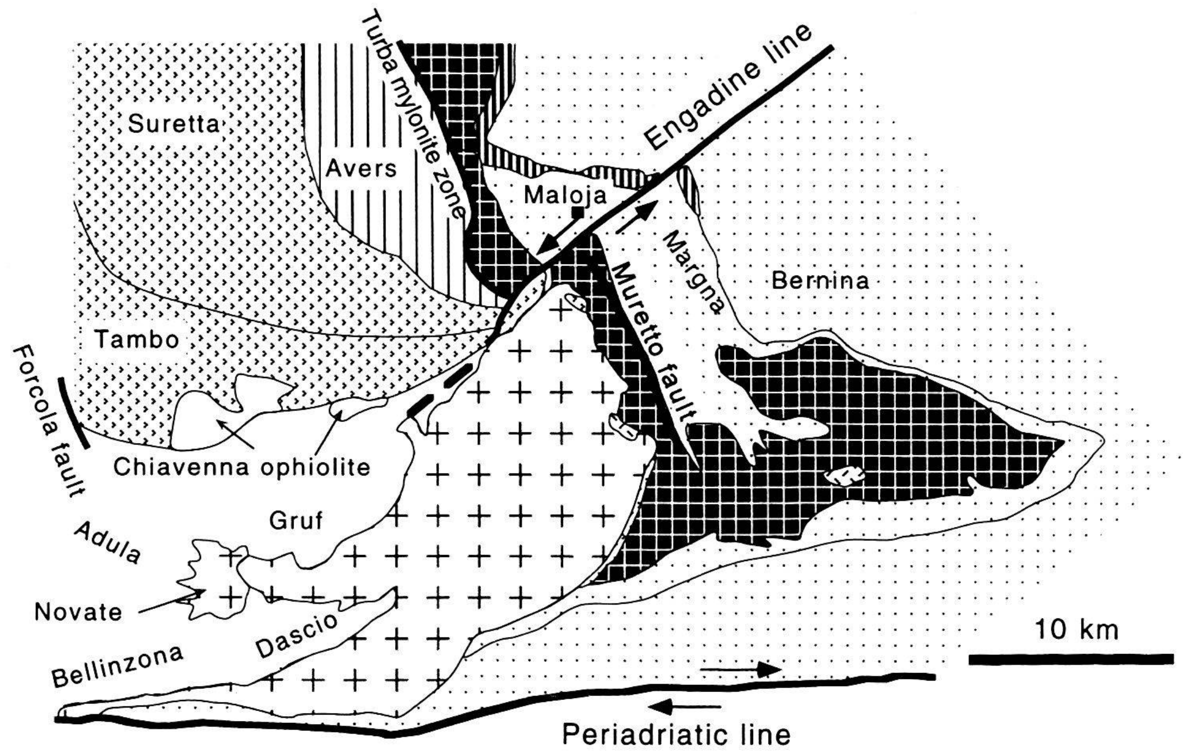


Fig. 2. Tectonic sketch map of study area.

(v. Blanckenburg et al. 1992). The tonalite was in turn intruded by the major Bergell granodiorite at 30 Ma (v. Blanckenburg et al. 1992). The Novate intrusion cross-cuts the Bergell pluton. Gulson (1973) assigned an age of ca. 26 Ma to the granitic rocks of the Novate intrusion and found no genetic relation of the Novate igneous rocks to the Bergell pluton. Theobald (1866) already observed that the Bergell pluton cross-cuts the Penninic and Austroalpine units in its northeastern part, whereas the pluton developed a penetrative foliation in its southern and western parts which parallels the major structures in the surrounding units. According to Trommsdorff & Nievergelt (1983) the Bergell igneous rocks and their country rocks become progressively deeper seated and increasingly foliated in a southwesterly direction. Potassium-feldspar megacrysts in the granodiorite show a preferred orientation that is parallel to the main foliation and some folds in the surrounding nappes (Drescher-Kaden & Storz 1926). A brief investigation of the feldspar structures in the northern part of the pluton suggests, however, that most of these structures are magmatic foliations, although tectonic foliations that are parallel to the magmatic foliations have also been observed. More recently, Vogler & Voll (1981) quantified the strong deformation in the southern part of the Bergell pluton some 25 km east of Locarno and concluded that the amount of shortening is on the order of 95%. The principal shortening direction trends NW-SE. The amount of extension parallel to the NE-plunging penetrative stretching lineation is on the order of several hundred percent, with extreme values of up to 3000% (Vogler & Voll 1976). The orientation of the principal finite strain axes implies that this deformation is due to dextral transpression across the Periadriatic line.

The Engadine line is generally regarded as an overall sinistral fault with an average displacement of between 3–6 km in the Upper Engadine and of between 15–20 km in the Lower Engadine (Trümpy 1977). The northeastern Engadine line is thought to have an additional normal slip component related to updoming of the Lower Engadine window (Schmid 1973). The off-set of the Arosa zone and the Margna nappe in the Maloja-Sils region suggests a left-lateral displacement of about 3–4 km along the southwestern Engadine line (Fig. 2). Structural studies show that sinistral strike-slip is coupled with reverse off-sets in this area (Liniger & Guntli 1988). The aforementioned block rotation model of Schmid & Froitzheim (1993) largely explains the transition from oblique-reverse to oblique-normal slip along the Engadine line.

The northern Muretto fault runs within the Forno zone, along its central segment it juxtaposes the Forno zone in its footwall against the Margna nappe in its hangingwall, and along its southern part the fault runs within the Margna nappe or juxtaposes the latter against the Malenco zone (Fig. 3a). The Muretto fault terminates at both ends by splaying. From the cross-sections of Riklin (1978), it appears that the off-set of the fault is on the order of a few hundreds of meters, a view also expressed by Trommsdorff & Nievergelt (1983). However, the latter authors regarded the Muretto fault as a thrust, whereas Riklin (1978, p.345) proposed a strike-slip nature for this fault. Based on measurements of foliation planes on either side of the fault, Riklin (1978) proposed a 72° rotation of the hangingwall relative to the footwall. The rotation axis given by Riklin (1978) trends to the SW and has a subhorizontal plunge. A subhorizontal rotation axis, however, contradicts the proposed strike-slip kinematics. The rotation axis as constructed by Riklin (1978, p.351, her Fig. 5) represents one possible solution out of an infinite number of rotation poles in the rotation plane. Furthermore, the use of planar elements to deduce the amount of rotation across a fault is not diagnostic. Following the work of Riklin (1978), Peretti (1985) also gave a brief description of the structures E and W of the northern Muretto fault and confirms the rotation angle of Riklin (1978). Nonetheless, Peretti (1985) used the same questionable approach as Riklin (1978). From this discussion it may be concluded, that further data are needed to untie the kinematics of the Muretto fault.

The Muretto fault

Methods and philosophy of kinematic analyses

To evalute the kinematics of the approximately N30°W-striking Muretto fault, the orientation of primary and secondary fault planes, strike and dip of striations and the sense of relative displacement on these planes were mapped in order to determine principal strain axes. The scale of observation was usually held small (i.e. outcrop scale). The brittle fault zones observed in these outcrops commonly are penetratively fractured into an array of blocks whose surfaces have a wide distribution of orientations. Individual blocks are separated by thin, slickensided surfaces with fibrous striae, which make these fault zones suitable for brittle strain analysis. Sliding of the blocks past one another occurs along these surfaces and accommodates displacement in the fault zone. Therefore, the surfaces are local faults. The direction and sense of shear on these surfaces can be deduced from the orientation of fibres and fractures associated with the fault (e.g. Petit 1987). It should be emphasized here, that fibre orientations have been measured at the contact of the

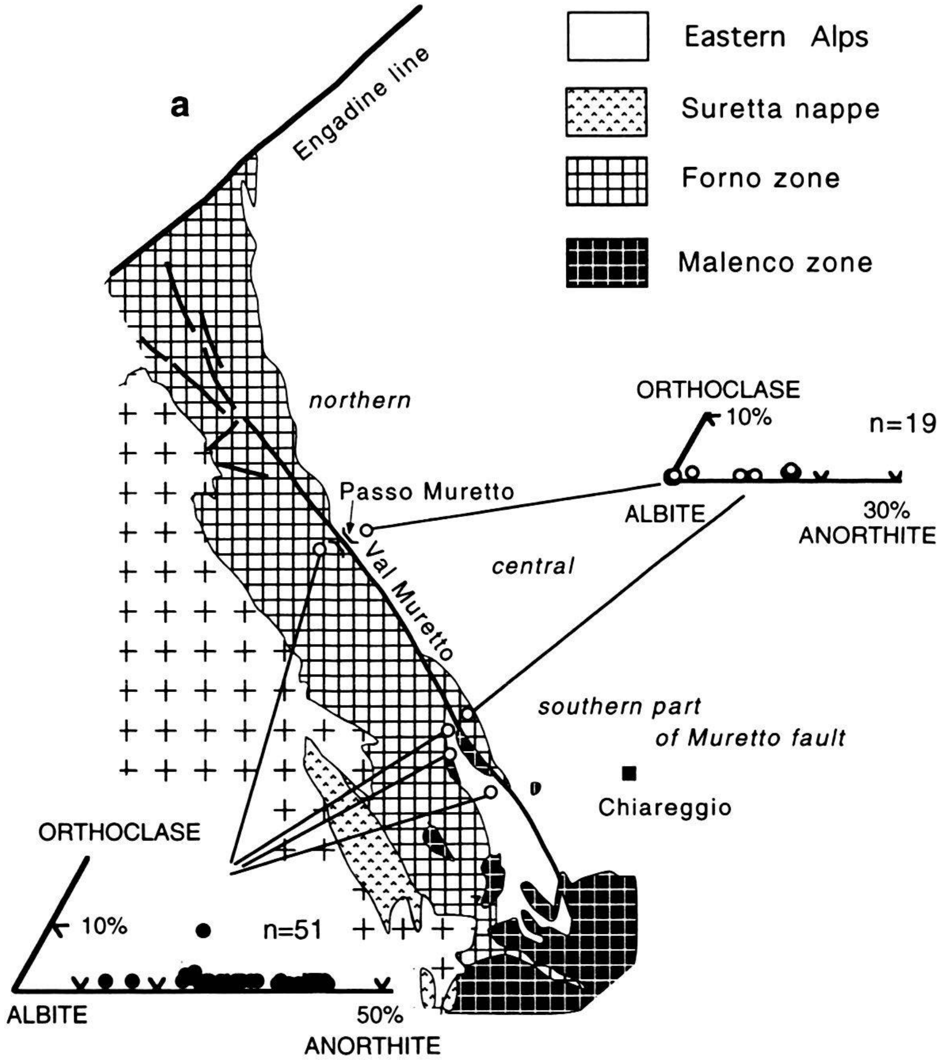
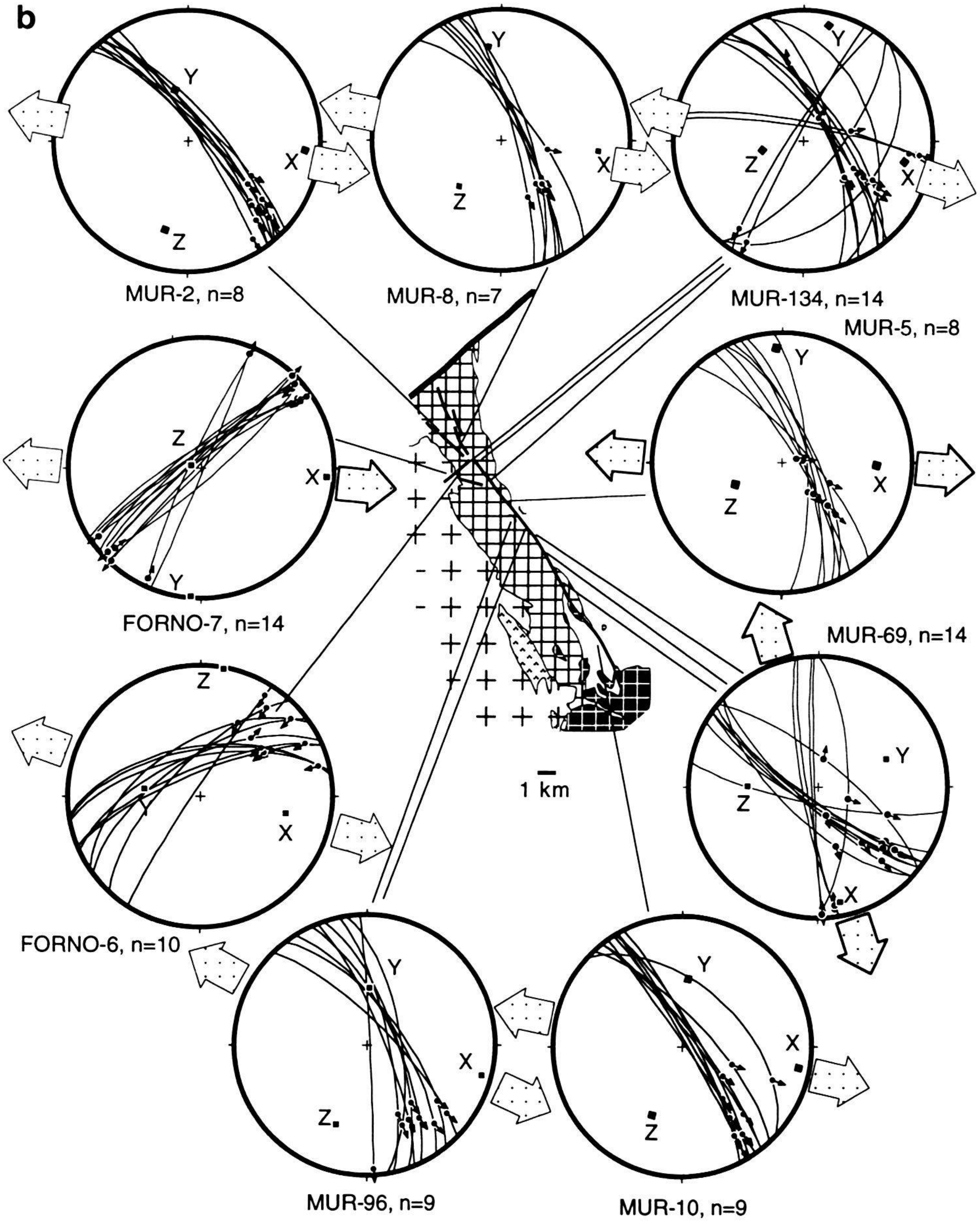


Fig. 3. (a) Simplified geologic map of the Muretto fault (modified from Riklin 1978, Peretti 1985). The anorthite component of plagioclase due to contact metamorphism on both sides of the fault are shown; also shown are the sample localities used for microprobe work on plagioclase. (b) Locations and fault kinematic data with deduced extension directions are shown; diagrams show great circle of fault plane and projected trace of striae.

gouge zones with the country rock and not within the gouge zone itself. Fibre orientations on the slickensides are usually simple, consistent, and are easily interpretable with the geometry of the Muretto fault at a regional scale. The displacement of the measured fault planes is generally in the centimetre- to metre-range. The main argument for relating these minor faults to the kinematic evolution of the Muretto fault was their spatial relationship to the main fault plane. Away from the main trace of the Muretto fault usually no minor fault planes have been observed, so that the increasing number of secondary faults in the near vicinity of the Muretto fault is thought to imply a genetic link between the minor faults and the Muretto fault.

The cataclastic rocks in the vicinity of the main trace of the Muretto fault have a rubbly to fragmental appearance and show numerous mesoscopic brittle faults. The fault



planes are characterized by anastomosing clayey and carbonatitic gouge layers with thin (1 mm–10 cm) zones of cataclasite, breccia and hematite-clay-coated fractured rock. Bleaching and alteration of intact rock occurs in the vicinity of faults. Weakly oriented phacoid-shaped tectonic slivers of country rock within the fault zone are in the centimetre- to decimetre-range. The fault-surfaces contain Riedel-shears which caused lunate and crescentric structures at their intersections with the fault plane. In a section parallel to the striation and perpendicular to the fault plane the Riedel-surfaces are characterized by fine seams of greyish-brown material. The clayey and the greyish-brown material apparently derived from the alteration of calcite/dolomite, feldspar, amphibole and phyllosilicate.

It should be emphasized, that the investigation of faults and movements on them in anisotropic, thus inhomogenous rocks, are believed to reflect displacement versus strain relationships (Choukroune 1989). Because deformation is finite and involves internal rotations, fault-slip data are fundamentally kinematic. Stress inversion methods (e.g. Angelier & Mechler 1977, Angelier 1984, Reches 1987) on the other hand require assumptions that are not often met in nature. 1. Homogenous stress – otherwise the axes of stress and infinitesimal strain will not generally be parallel (Malvern 1969). 2. All slip on fault planes must be resolved in the direction of shear stress – faults do not interact mechanically. 3. All structures must have formed simultaneously in the same, constant stress field – this implies that the rocks cannot undergo deformation which would produce a stress drop. The rocks at both sides of the Muretto fault do not conform these assumptions. They are foliated and have definitely undergone brittle deformation. Furthermore, cross-cutting relationships suggest that the faults interacted mechanically.

In this study, a simple graphical method has been used to determine principal strain axes (program 'Fault Kinematics' written by R. Allmendinger). This method graphically constructs the principal incremental shortening and extension axes for a given population of faults. Each pair of axes lies in the movement plane of the fault (i. e., a plane perpendicular to the fault plane that contains the unit vector parallel to the direction of accumulated slip, and the normal vector to the fault plane). Furthermore, each pair of axes make angles of 45° with each of both vectors, respectively. For distinguishing between the shortening and extension axes it is indispensable to have information on the sense of slip. Since such a method only converts the measurements into a fault-plane solution, the kinematic axes of a fault portray only a different and visually more convenient presentation of the original data. Bingham distribution statistics for axial data were used to optimate clusters of kinematic axes of a fault array (Mardia 1972).

If the direction of plunge of a slickenside striation and the dip-direction of the corresponding fault plane differ less than 30° from each other; the fault will either be called a normal or a reverse fault, depending on the sense of relative movement on the fault. If both structures have angles of between 30–60° to each other, the fault will be referred to as an oblique-slip fault. If the plunge of the striation deviates more than 60° from the dip-direction of the associated fault plane, the fault will be termed a strike-slip fault.

Kinematic analysis using minor fault populations

The fault kinematic data and the sample localities are shown in figure 3b. The Muretto fault strikes perferrentially NNW-SSE and NW-SE and dips steeply (70–90°) to the ENE to NE. Minor fault planes follow in general the trend of the Muretto fault and dip also to the ENE to NE (Fig. 3b, MUR-2, -8, -5, -10, -96), although occassionally dips to the WSW/SW occur, too (Fig. 3b, MUR-69). The striations on those minor faults dip in general intermediately (30–50°) to the southeast. Associated sense of shear criteria indicate a consistent top-down-to-the-SE-directed relative displacement. The kinematic axes deduced from these data indicate a consistently ESE-trending extension axes. The intermediate and the short axes of the finite strain ellipsoid lie on a great circle which strikes approximately NNE-SSW in the Schmidt-net and which dips steeply to the WNW. The shortening axes show shallow, intermediate and steep dips in the various plots. This suggests temporal and/or spatial changes between a normal, oblique and strike-slip mode of faulting.

This general structural trend at the Muretto fault shows some modifications at Plan Canin and in the Forno valley at the northern tip of the Muretto fault. In the Forno valley a small cross-fault occurs. Minor fault planes related to this cross-fault strike NE-SW and dip preferably steep (75–90°) to the N to NW. Associated striations plunge gently and show sinistral off-sets. The extension axes as deduced from the minor fault planes (FORNO-7 in Fig. 3b) are comparable to those from the fault planes at the Muretto fault. The subhorizontal shortening axes imply a dominant strike-slip mode of faulting. It is suggested, that the small cross-fault in the Forno valley is kinematically related (i. e. conjugate) to the Muretto fault. At Plan Canin both faults apparently merge, which caused a number of differently striking minor fault planes (MUR-134 and FORNO-6 in Fig. 3b). However, the deduced kinematic axes are again compatible with the axes from the other localities along the Muretto fault. From the above kinematic data it is concluded, that the Muretto fault is a dextral oblique-normal fault.

Displacement

The anorthite-component of contact-metamorphic plagioclase in metabasic rocks containing the assemblage hornblende + chlorite + plagioclase on either side of the fault (Fig. 3a) is different. In the central part of the Muretto fault, where the fault off-set is greatest, it appears that the talc + olivine versus tremolite + olivine isograd of contact metamorphism has been cut out. These observations suggest displacement at the 100m-scale on the Muretto fault. To achieve more constraints on the amount of displacement across the fault, the relationship between the fault gouge thickness and the width of the Muretto fault to the displacement have been used to approximate fault off-set. Fault growth models (Sammis et al. 1987, Cox & Scholz 1988, Power et al. 1988) predict a linear increase of fault gouge thickness (t) with displacement (d) at the fault according to:

$$d = b \cdot t,$$

where b is an empirical constant for which Hull (1988) determined a value of 63 for a wide variety of rock types. The fault gouge at the Muretto fault varies in thickness between a few decimeters at its tips to approximately 3–10 m at its central section, leading to a local displacement in the tectonic transport direction in the central part (in the vicinity of the Muretto Pass) of between 190 and 630 metre. The critical factor in this calculation is the approximation of the gouge thickness. In this study I define fault gouge as a unit of cataclastic rock that exceeds 10 microfaults per meter. Nevertheless, it was still problematic to unequivocally define the transition from fault gouge to country rock. Therefore the upper limit of 10 meters of fault gouge may be an overestimation of the gouge thickness.

According to Walsh & Watterson (1989) the maximum displacement (d_{max}) at a fault is proportional to the square of maximum fault plane width (w, defined as the maximum dimension of a fault plane normal to its slip direction):

$$d_{max} = \frac{c \cdot w^2}{\mu^2},$$

where μ is the elastic shear modulus and c is a proportionality constant averaging $2 \cdot 10^{-4}$ GPa^2m^{-1} for faults in a variety of rock types with displacements ranging from 10 m to 100 km (Walsh & Watterson 1989). The width of the Muretto fault is difficult to estimate. The surface trace length of the fault in plan view is approximately 12–14 km. To relate the fault surface trace length to the width of the fault, the fault geometry at depth and in the rock now eroded away should be known. However, since there is no control on the fault geometry in the eroded part of the fault, I assume that the fault surface length and fault width are approximately the same. This leads to a maximum displacement at the Muretto fault of between 200 and 270 metre. Since the fault surface length must not necessarily pass through the centre of the fault, the fault width might be larger than the surface length and then the above numbers are an underestimation of the displacement.

It should be emphasized that these values are not very accurate, however, they are probably more accruate than previous attempts (see above). Nonetheless, the result that the displacement across the Muretto fault is on the order of a few hundred meters is essentially the same as has been proposed previously (Trommsdorff & Nievergelt 1983).

Oligocene to Miocene easterly displacing extensional structures in the Bergell region

Ductile to brittle structures in the hangingwall of the Turba mylonite zone

The Turba mylonite zone (Fig. 4) is a ductile, low-angle, east-dipping, easterly displacing, extensional shear zone (Liniger & Nievergelt 1990, Liniger 1992). Based on peak metamorphic temperatures at the base (350 °C) and top (280 °C) (Nievergelt et al. 1991) a minimal off-set of about 2–3 km can be calculated (assuming a geothermal gradient of about 30°/km). Assuming that the present dip of the mylonite zone of 20° is close to its original dip yields a displacment of 5–8 km in the down-dip direction of the zone (see similar calculations in Liniger 1992). The age of movement is pre-Bergell (35–30 Ma) and is followed by postmylonitic folding due to N-S shortening (Nievergelt et al. 1991).

In the Arosa zone and the immediately underlying Margna and overlying Err-Bernina nappes in the hangingwall of the Turba mylonite zone, eastward-displacing extensional structures (Fig. 4) developed under gradually decreasing temperatures. Ductile extensional crenulation cleavage sets (ecc for short) are restricted to carbonate- and phyllosilicate-rich lithologies and have angles of between 20° and 40° to the main foliation (Fig. 5a, see also Fig. 3b in Ring et al. 1991). Calcite shows limited plasticity (twinning, undulatory extinction), phyllosilicate is bent and kinked and locally new retrograde chlorite grew. Quartz is commonly cracked and shows undulatory extinction which might be a relic of earlier deformations. Feldspar exhibits brittle micro-normal faults that dip at moderate to high angles to easterly and westerly directions, although the east-dipping planes are more common. These microstructural features suggest temperatures consider-

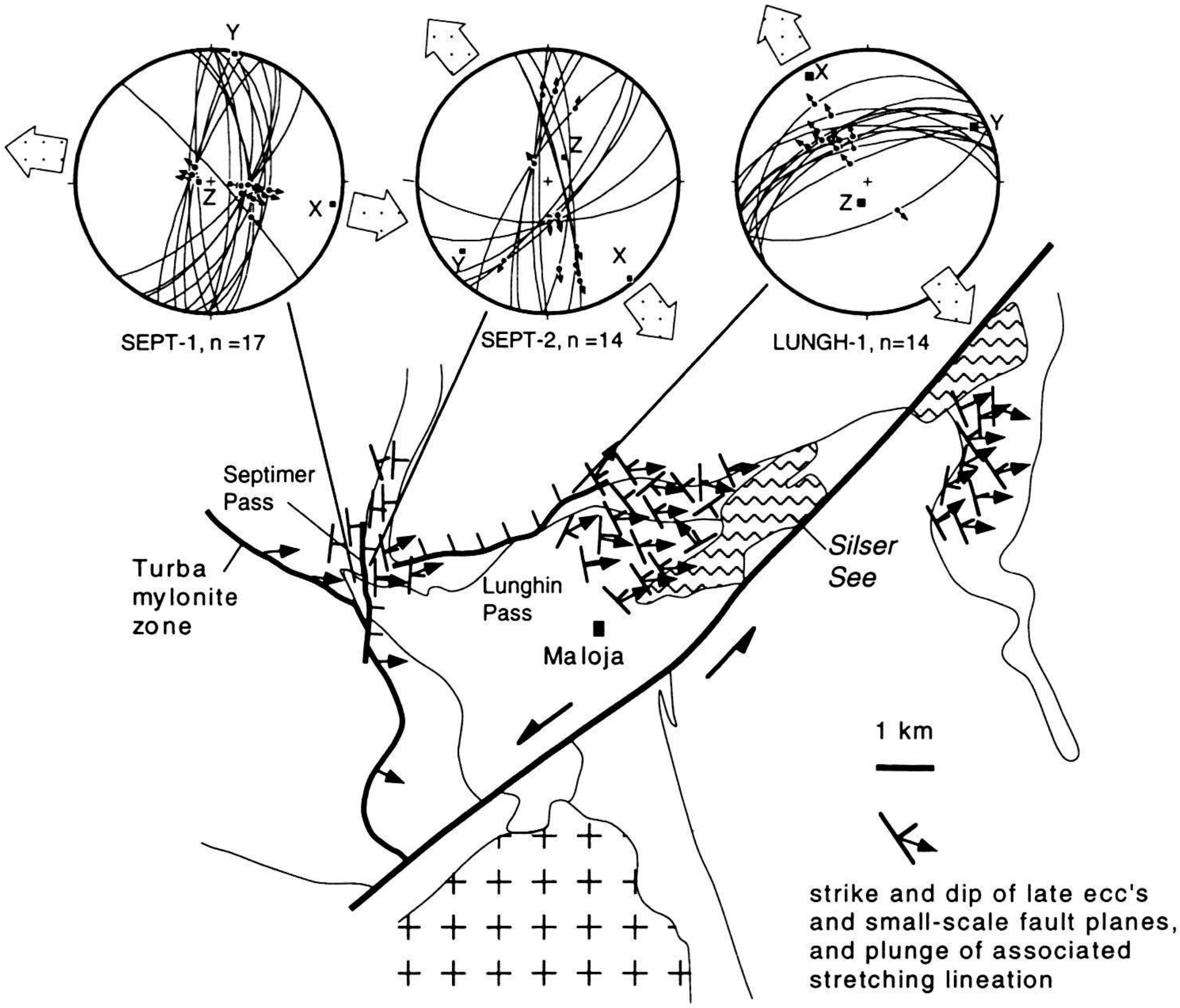
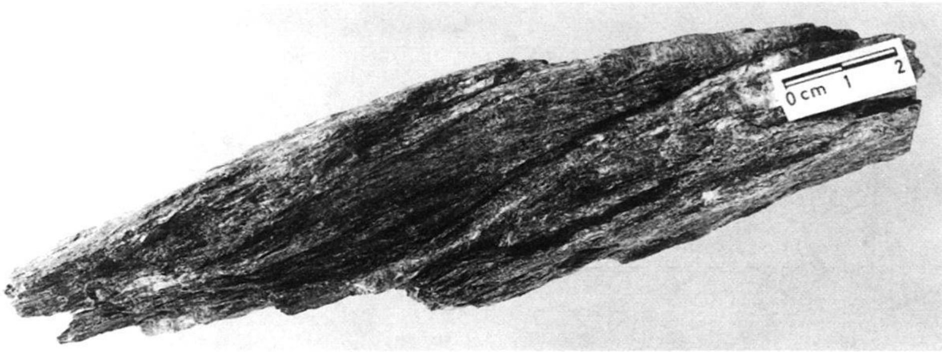


Fig. 4. Easterly displacing structures in the Oberengadin area. Turba mylonite zone (Nievergelt et al. 1991) is thought to be kinematically coordinated with brittle-ductile to brittle extensional structures in its hanging wall. Fault-slip data from faults at Septimer Pass and Lunghin Pass area are also shown.

ably below 300 °C (Voll 1980). In more competent materials (quartz-rich schist, gneiss, serpentinite and amphibolite) brittle-ductile ecc's with angles of 40° to 60° developed. In places high-angle extensional structures cut low-angle structures. The high-angle shear bands evolved into brittle normal faults (Fig. 5c; the term 'brittle' is used here when a macroscopic plane of failure, i.e. a fault is formed). Locally, conjugate west-dipping high-angle shear bands and normal faults occur, too. Fault-slip data from the normal faults indicate dominantly eastward extension (Fig. 4, SEPT-1) which is compatible with the extension direction deduced from the ductile and brittle-ductile structures. These brittle-ductile easterly-displacing structures apparently correlate to D5-structures as recently described by Hermann and Münterer (1992) from the Penninic-Austroalpine boundary zone east of the Bergell intrusion.

In some places north and east of the Bergell intrusion tight to open folds at the decameter-scale occur. Fold axes strike generally NE-SW and the axial planes of these folds are commonly vertical or dip steeply to the southeast, although dips to the northwest



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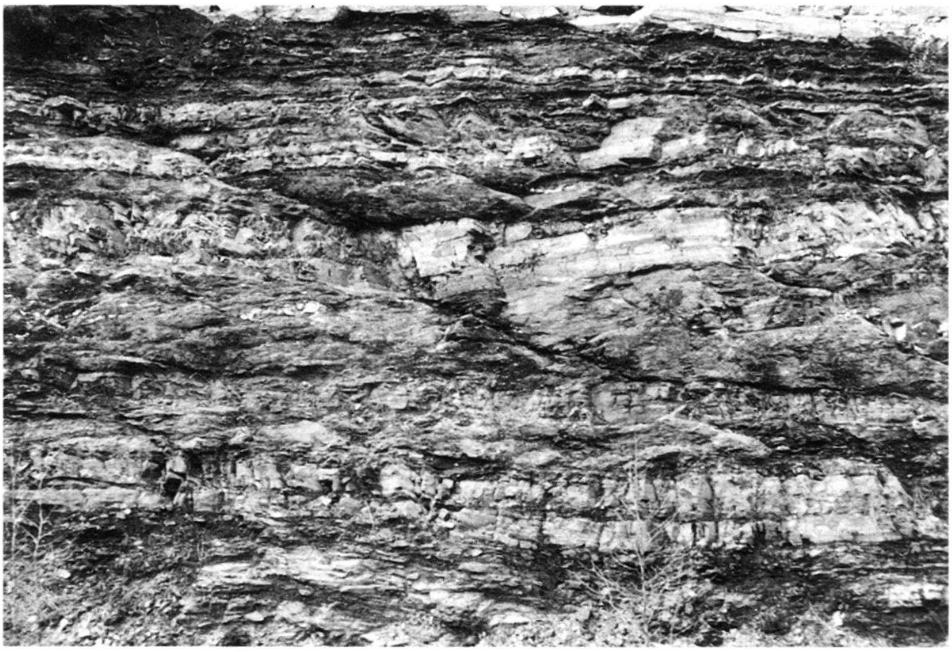
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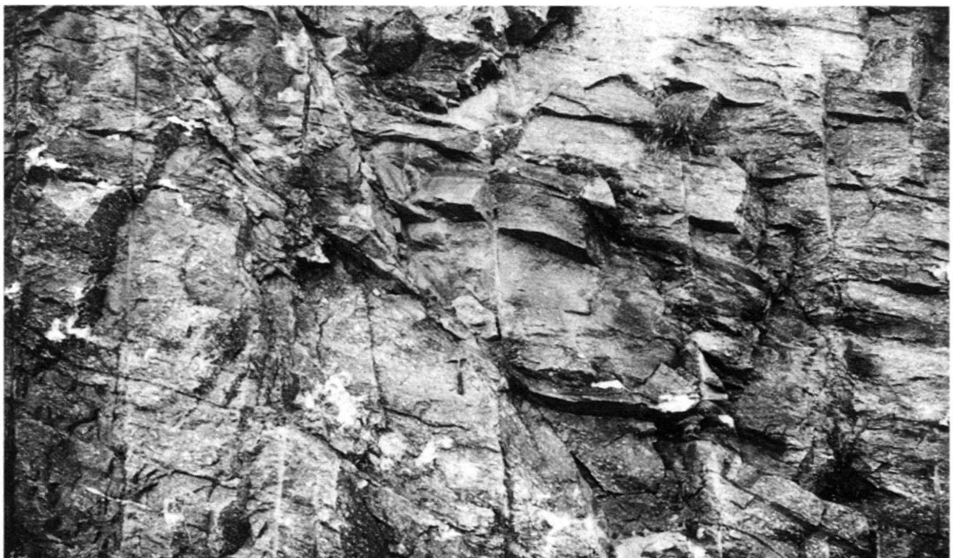
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have also been observed. This variable dip of the folds axial planes is thought to have no kinematic significance. South of the Engadine line the dips of the axial planes are almost exclusively to the northwest. No consistent overprinting relationships between the ecc's and the folds could be established, although in some places they definitely postdate the ductile eastward-displacing ecc-structures. The normal faults at the Septimer Pass cut the folds. Hermann and Münterer (1992) described southerly vergent large-scale folds (D6 in their nomenclature) which postdate the easterly displacing structures (D5) and northwest-vergent folds (D4 of Hermann & Münterer 1992) that predate the east-vergent extensional structures. Liniger (1992) reported south-vergent large-scale folds in the hangingwall of the Turba mylonite zone which possibly correlate to the D6-structures of Hermann & Münterer (1992). Folds with northeasterly-trending axes in the Novate area deform the Bergell granodiorite. These folds can be correlated to the Cressim antiform. The latter is related to backthrusting at the Periadriatic line (Heitzmann 1987).

At the N-S-striking faults in the Septimer Pass area, dextral oblique- and strike-slip-components occur (Fig. 4, SEPT-2) which overprint east-vergent down-dip displacements in this fault zone. In the area east of the Lunghin Pass (Fig. 4, LUNGH-1), sinistral oblique-slip took place along a N65°E-striking fault. These faults cut the dominant regional foliation in which the ecc's developed and also cut the late folds. Therefore, the faults appear to postdate either the east-directed extensional movements and the NW-SE oriented shortening event. Fault-kinematic analysis indicates that these faults, which seem to be related to each other, developed during southeast-directed extension (Fig. 4).

Brittle fault planes at the Engadine line

The N50°E-striking Engadine line at the northeastern tip of the Bergell intrusion depicts sinistral oblique-reverse kinematics (Mützenberg 1986, Liniger & Guntli 1988; Fig. 6, ENG-1, -2). Based on a N30°E-oriented and 50°–60° to the southwest-dipping displacement direction (Mützenberg 1986) the total off-set at Maloja is 2.5 km (factorized in 1.5 km horizontal and 2.2 km reverse movement, Mützenberg 1986) and 2 km near Sils (1.1 km horizontal, 1.6 km reverse off-set, Liniger & Guntli 1988).

The secondary fault planes which have been analysed in this study strike ENE-WSW to NE-SW and dip steeply to the SSE and SE, although northerly dipping faults have been mapped too. These data approximately match those measured by Liniger (1992, p.99). The sense of slip is sinistral with a reverse slip component. The extension directions trend E-W to ESE-WNW and plunge with an angle of ca. 20–30° to the E to ENE, whereas the shortening directions trend horizontally N-S.

Fig. 5. (a) East-dipping shear band in shale from the Arosa zone, ca. 1 km west of Grevasalvas. East is to the left. (b) Low-angle normal fault in carbonate layers within shale from the Arosa zone ca. 1.5 km westsouthwest of Grevasalvas; the inclination of the fault plane gets progressively more shallow in the incompetent and more ductile behaving shaly layers. (c) Set of eastward displacing high angle normal faults in crystalline schist of the Margna nappe ca. 2 km eastnortheast of Maloja. In (b) and (c), east is to the right.

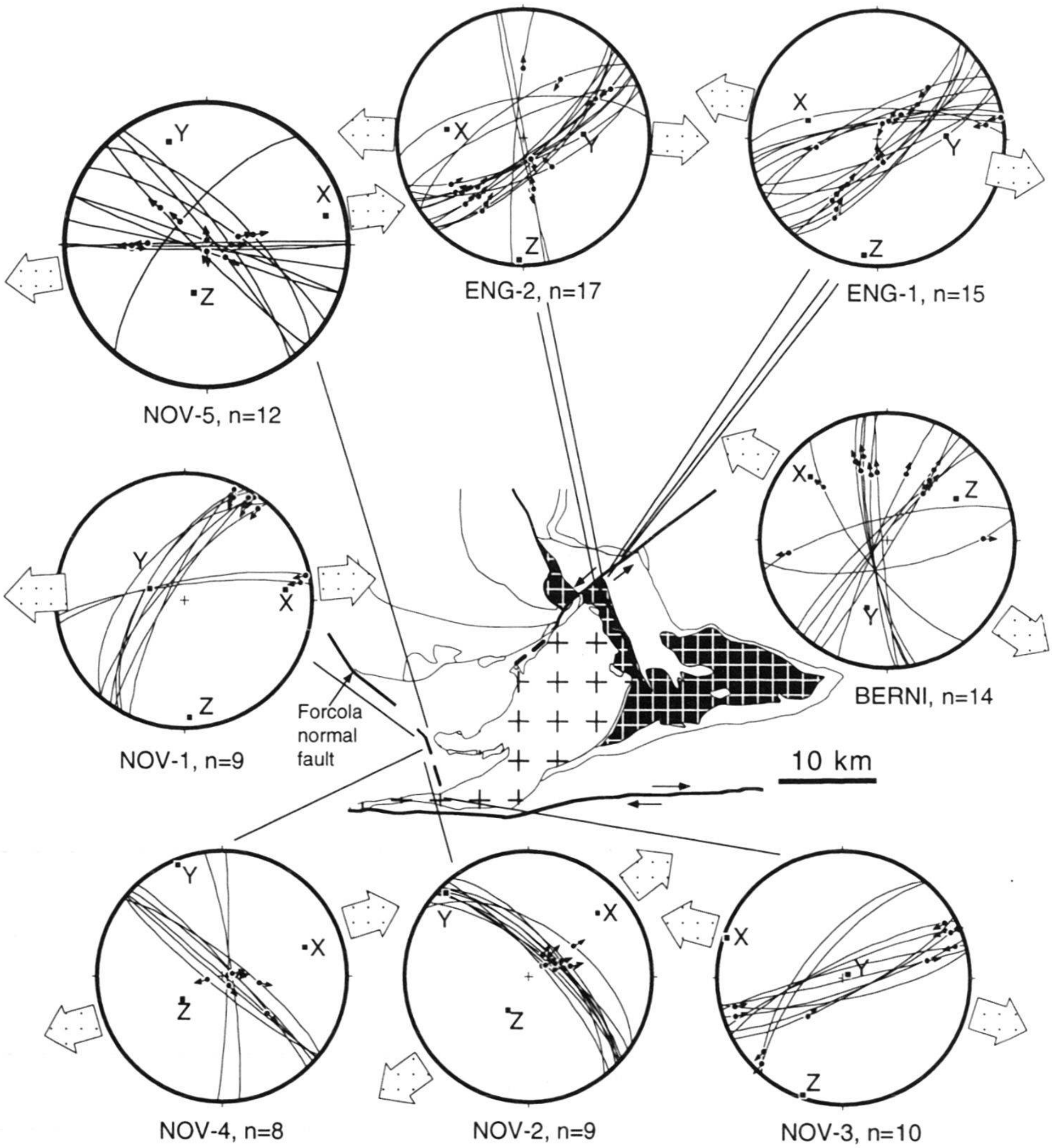


Fig. 6. Locations and fault kinematic data from some faults in the Bergell area. Note that few striated fault planes south of the Bernina Pass (BERNI) coincide with the kinematic data from the Muretto fault.

Brittle fault planes west of the Novate intrusion

Approximately northwest-striking faults in the Novate region (Fig. 6, NOV-2, -4, -5) show down-dip to dextral oblique-normal displacements. Northeast-striking faults depict sinistral to sinistral oblique-reverse off-sets (Fig. 6, NOV-1). The extension directions obtained from these faults are oriented dominantly NE-SW to ENE-WSW and the shortening and intermediate axes commonly lie on a north- to northwest-striking great circle.

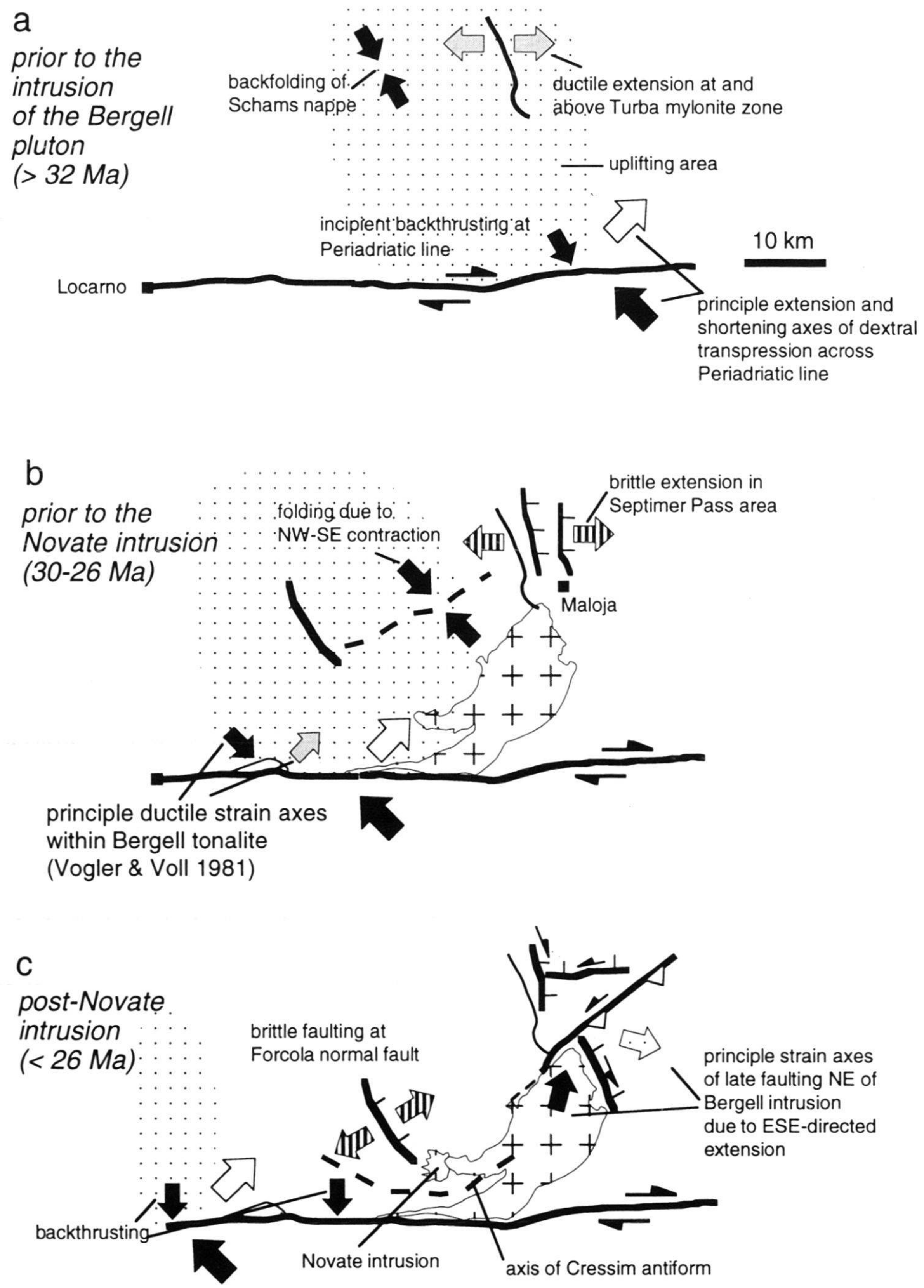
The displacements associated with these faults is negligible and it is assumed that the fault planes represent the southeasternmost tip of the Forcola normal fault (Weber 1966).

Relative age relations between ductile to brittle-ductile E-W extension and faulting

Ductile east-directed extension along the Turba mylonite zone predated the emplacement of the Bergell pluton in its hangingwall (Nievergelt et al. 1991) and can be bracketed into the time span between 35 and 30 Ma (Liniger 1992). Easterly displacing extensional structures in the hangingwall of the Turba mylonite zone developed under lower temperatures and are thus in general brittle-ductile to brittle. The parallelism between the mylonitic elongation in the Turba zone and the extension direction as deduced from and the brittle-ductile ecc's and the fault-slip data at the Septimer Pass area (first faulting increment there) suggests kinematic coordination between ductile normal shearing at depth (i. e. formation of the Turba mylonite zone) and extensional deformation in its hangingwall. Liniger & Guntli (1988) reported approximately N-S-striking kink bands which are younger than the Bergell granodionite (i. e. < 30 Ma). The kinks probably correlate to the above outlined E-W-oriented brittle extensional structures. Therefore, it may be followed that ductile extension in the lower part of the nappe pile (Turba mylonite zone) commenced prior to the Bergell intrusion, whereas in higher portions of the stack brittle-ductile structures may have formed simultaneously with ductile normal shearing at the Turba mylonite zone and than evolved into brittle structures through time. Those brittle extensional structures might have been formed at the same time as contractional folds with NE-striking fold axes formed because the Bergell granodiorite is affected by open folds with northeasterly trending axes. According to Heitzmann (1987) the Cressim antiform formed at about 25 Ma. The folding at the northeastern tip of the Bergell pluton is followed by faulting due to eastsoutheast-directed extension at the Muretto and Engadine faults. Both faults cut either the intrusion itself or contactmetamorphic rocks related to the Bergell intrusion (see also Liniger 1992). Finally faulting due to southeast-directed extension in the Septimer-Lunghin Pass area occurred.

Regional tectonic implications

Dextral transpression between the Adriatic and European plates caused approximately northwest-directed shortening and northeast-directed extension. Dextral horizontal displacement along the Periadriatic line is a major result of this process and may have controlled the intrusion of the Bergell pluton (Merle et al. 1989) at about 30–32 Ma (Gulson & Krogh 1973, v. Blanckenburg 1992). Simultaneous to subsequent strong shearing and NE-directed extension of the Bergell intrusion took place (Vogler & Voll 1976, 1981). K/Ar-biotite and zircon fission track ages fall into the same time-span suggesting that very rapid regional uplift and subsequent cooling of the Bergell pluton occurred roughly at the same time (Giger & Hurford 1989). Regional uplift caused eastward- to northeastward ductile extension of the nappe pile in the eastern Central Alps (Merle et al. 1989, Ring 1992). This extensional phase evolved into brittle faulting through time. The fault kinematic data from the Novate region fit properly into this kinematic framework (Fig. 7).


a
prior to the intrusion of the Bergell pluton (> 32 Ma)
backfolding of Schams nappe
ductile extension at and above Turba mylonite zone
uplifting area
incipient backthrusting at Periadriatic line
10 km
Locarno
principle extension and shortening axes of dextral transpression across Periadriatic line
b
prior to the Novate intrusion (30-26 Ma)
folding due to NW-SE contraction
brittle extension in Septimer Pass area
Maloja
principle ductile strain axes within Bergell tonalite (Vogler & Voll 1981)
c
post-Novate intrusion (< 26 Ma)
brittle faulting at Forcola normal fault
principle strain axes of late faulting NE of Bergell intrusion due to ESE-directed extension
backthrusting
Novate intrusion
axis of Cressim antiform

Liniger (1992) related movements at the Turba mylonite zone at 30–35 Ma to southeast-directed backflow possibly related to major southeastward backfolding and backthrusting of the Schams nappe (Niemet-Beverin phase of folding). In contrast, Schmid et al. (1990) postulated that southeast-directed backflow graded into backthrusting at the Periadriatic line at about 25–20 Ma. However, the data of Milnes (1978) and Liniger (1992) suggest that the southeast-vergent backfolds were cut by the Bergell granodiorite, implying in age > 30 Ma for the backfolding event. If the age constraints of Milnes (1978) and Liniger (1992) were taken into consideration (Fig. 7a) they would indeed suggest that southeastward backfolding and backthrusting are either older than or simultaneous with east-directed extension at the Turba zone. Although backthrusting can bring lower grade rocks above higher grade ones, the extensional character of the Turba zone (Nievergelt et al. 1991) may favour a link to normal shearing rather than to backthrusting. Furthermore the stratigraphy in the area is partly eliminated rather than duplicated. Therefore it is tempting to relate normal shearing to easterly directed sideways escape of the Central Alps as proposed by Schmid et al. (1989). This would, however, imply that eastward escape already started in the Early Oligocene (i. e. at 30 to 35 Ma) in the eastern Central Alps. Albeit the fact that I relate backfolding and eastward extension to two different processes (see below), it is nevertheless likely that southeastward backfolding/backthrusting and easterly-directed extensional deformation may have been competing events.

Liniger (1992, p. 167–169) envisions that the backfolding event had an E-W-trending extensional component that caused the east-directed extensional shearing at the Turba mylonite zone. This approach demands strong flattening strains associated with the formation of the Niemet-Beverin fold and also with SE-directed thrusting in its upper limb. Such a strong flattening component of deformation should produce a radial stretching pattern rather than two distinct sets of stretching lineation, both of which have a notably preferred orientation. Moreover, Schmid et al. (1990, p.285) reported strong reorientation of fold axes in the hangingwall of the Niemet-Beverin fold which they attribute to top-to-the-south simple shear, thereby implying a plane-strain geometry of deformation associated with backfolding of the Schams nappe.

Fig. 7. Schematic interpretation. (a) Dextral transpression between the Adriatic and European plates commenced in Oligocene time prior to the intrusion of the Bergell pluton. The kinematics of the Periadriatic line is a result of the overall kinematic framework (large black and white arrows show principal direction of crustal shortening and extension). Gravitational collapse of the eastern Central Alps are thought to have caused easterly-directed extension and may have triggered ductile extensional movement at the Turba mylonite zone and brittle-ductile extensional structures in its hangingwall (arrows with dotted pattern). The kinematics of the backfolding event in the Schams nappe is thought to be due to NW-SE-oriented shortening due to NW-directed indentation of the Adriatic plate. (b) Intrusion, uplift and dextral displacement of the Bergell pluton. Brittle eastward-displacing faulting in Maloja area (black and white striped arrows). Note that uplifting area progressively shifts to the west. (c) Final emplacement of Bergell pluton. A local kinematic field at the northeastern tip of the Bergell pluton (shown by black arrow and white arrow with black dots) is thought to have controlled the kinematics of the Muretto and some minor related faults in the Engadine region. Note that movements at the Engadine line commenced after the initial emplacement of the Bergell pluton and therefore did not facilitate the intrusion of the latter. Black and white striped arrows indicate brittle normal faulting at Forcola normal fault.

The geometry of the backfolding event can be directly linked to northwest-directed contraction exerted by the indentation of the Adriatic plate into the nappe pile north of the Periadriatic line (see Schmid et al. 1989 for a general model of the indentation process). The orientation of the principal strain axes due to dextral transpression suggest a northeast-trending extension direction and not an E-W-trending one. The easterly oriented extensional structures therefore appear to demand an additional process to explain their orientation. It is conceivable that overall crustal thickening as a result of the backfolding and backthrusting event, and, more importantly, the deformations preceeding backfolding, caused isostatic response and uplift of the crust which subsequently created gravitional forces that controlled the easterly orientation of the extensional structures. It should be emphasized that I envision two separate processes, one is the backfolding of the Niemet-Beverin fold which produced strong SE-directed backfolding and backthrusting and the other process is a gravitational collapse that is spatially and temporarily superimposed on the backfolding event and caused the east-directed extensional structures. This scenario might explain why contractional and extensional structures occur at roughly the same time. From the sketches of Schmid et al. (1990) and Schreurs (1993) it appears that backfolding and backthrusting resulted in some 30 km of southeastward-directed displacement, whereas extension across the Turba mylonite zone apparently only accounts for less than 10 km of east-directed displacement. This suggests that gravitation-induced extension parallel to the mountain chain was a secondary processes.

Faulting at the Muretto and also along the faults in the Septimer Pass (second increment there) and Lunghin area are also kinematically incompatible with a model of dextral transpression alone (Fig. 7) because they indicate a ESE- to SE-trending extension direction. Since all of these structures formed shortly after the intrusion and rapid uplift of the Bergell pluton, it appears to be alluring to relate their kinematics to those processes. One possbility might be an influence of strong dextral displacement that accompanied the intrusion of the Bergell pluton (see also Schmid et al. 1989). Heitzmann (1987, his Fig. 6) calculated some 60 km of horizontal off-set which appears to be in accord with the high finite strain values reported by Vogler & Voll (1976, 1981). The northeastward advancing Bergell body may have subsequently created a local kinematic field at its northeastern tip (Fig. 7c). The new forces may have then begun to exert control on the region immediately east and northeast of the Bergell intrusion. Therefore movements at the Muretto and associated faults were not controlled by the far-field kinematics of dextral transpression across the Periadriatic line but responded to the new near-field kinematic framework in front of the Bergell pluton. Another possibility might simply be that the Bergell pluton created local gravtiational forces which strongly influenced the kinematics of the faults at the northeastern tip of the intrusion. Both possibilities indicate that the Muretto fault and the faults in the Septimer and Lunghin Pass areas are the result of a rather local cause.

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