Ascent, emplacement and exhumation of the Bergell pluton within the Southern Steep Belt of the Central Alps

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Ascent, emplacement and exhumation of the Bergell pluton within the Southern Steep Belt of the Central Alps

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Abstract

Ascent and final emplacement of the Bergell pluton took place in a tectonic scenario dominantly characterized by north-south shortening during the last stages of Alpine orogeny. Ascent was facilitated by the pre-existence of a steep belt, i.e. the root zone of the Austroalpine nappes. Final emplacement was related to regional deformation within the surrounding country rocks, characterized by nappe-refolding during the post-collisional stage of Alpine orogeny and associated with transpression and orogen-parallel extension. Vertical extrusion of crystal mush along the feeder dike within the Southern Steep Belt was deflected into synmagmatic north-directed flow of the main body of the pluton both with respect to the footwall exposed at the western contact (i.e. along the pre-existing N-Penninic suture zone), and the hangingwall exposed at the eastern contact (i.e. the S-Penninic and Austroalpine units). This first stage of final emplacement was immediately followed by folding of the base of the pluton during a second stage of synmagmatic deformation. Syn-emplacement regional deformation was followed by ongoing regional deformation after complete solidification of the pluton: further backfolding and, in particular, backthrusting of the pluton together with the immediate country rocks along the Insubric line, combined with differential vertical movement of the Bergell area near its northern margin (Gruf-Engadine line). This post-emplacement compressional deformation lead to the rapid exhumation of the pluton, associated with tilting. It is proposed that pluton ascent and emplacement were an integral part of regional deformation in the deep crust, taking place at very low differential stresses.

Keywords: magmatism, fabric analysis, pluton emplacement, Bergell (Bregaglia) pluton, Southern Steep Belt, Central Alps.

Introduction

Final emplacement of the Bergell pluton (TROMMSDORFF and NIEVERGELT, 1983) is related to synmagmatic regional deformation during late-stage post-collisional north-south shortening of the Alpine orogen (ROSENBERG et al., 1994b, 1995). The pluton has a nappe-like geometry (WENK, 1973), it roots within the Southern Steep Belt north of the Insubric line, and it occupies a structural position (Fig. 1) equivalent to that of the Tambo- and Suretta nappes further to the north (BERGER, 1996; ROSENBERG et al., 1995; DAVIDSON et al., 1996; SCHMID et al., 1996c). According to DAVIDSON et al. (1996) the pluton was tectonically emplaced over the highly ductile Adula-Gruf unit and the North-Penninic suture zone (Misox zone, Chiavenna ophiolite, Bellinzona-Dascio zone), deformed and metamorphosed in the Tertiary (SCHMID et al., 1996 a, b). At its eastern margin, near the top of the intrusion, the Bergell pluton is in contact with the South-Penninic ophiolitic units and the Austroalpine nappes (BERGER and GIERÉ, 1995), internally deformed and metamorphosed during Cretaceous orogeny but displaced as a relatively rigid entity (the orogenic lid) towards the north during Tertiary orogeny (FROITZHEIM et al., 1994). Due to a very pronounced easterly axial plunge of up to 25° (BERGER and GIERÉ, 1995), formed during and after emplacement, increasingly deeper levels are exposed westwards within and around the Bergell pluton.

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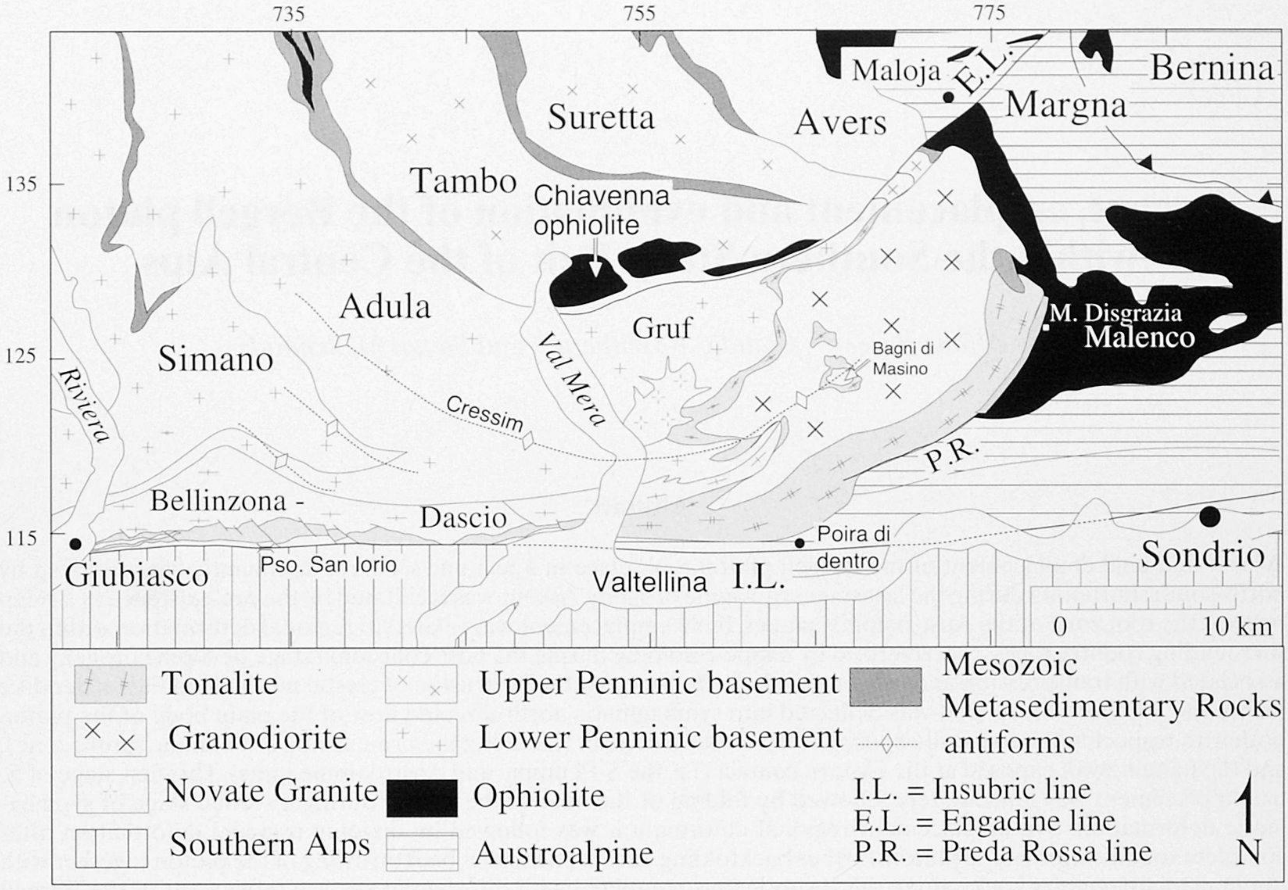

Fig. 1 Tectonic map of the Bergell area. Fold axial traces of backfolds are indicated.

Certain aspects of synmagmatic regional deformation of this pluton, occupying a unique tectonic position between Austroalpine and Penninic units near their "root zone" (Southern Steep Belt; MILNES, 1974), have been previously discussed by ROSENBERG et al. (1995), BERGER and GIERÉ (1995) and DAVIDSON et al. (1996). This contribution focuses on the southern and southeastern contacts of the pluton with the country rocks and integrates these findings, together with the above mentioned very recent related studies, into a larger scale regional picture. Furthermore, this study adresses the following topics of more general interest:

(1) This well-dated pluton (VON BLANCKENBURG, 1992; HANSMANN, 1996) provides ideal age constraints regarding the timing of Tertiary deformation and metamorphism in the Penninic nappes.

(2) Because the 60 km long E–W section across the southern part of the pluton roughly corresponds to a 20 km depth interval between the lower Penninic units and the orogenic lid, style and geometry of Tertiary deformation vary within and outside the pluton. This variation gives further insight into deformation and pluton emplacement as a function of structural depth. The Bergell pluton offers a unique opportunity to discuss deformation related to pluton emplacement over such an impressive depth interval.

(3) Ascent, final emplacement and post-emplacement tilting of the pluton are all closely related to tectonic movements within the Southern Steep Belt and across the Insubric line. In particular, we shall provide additional evidence for the working hypothesis proposed by ROSENBERG et al. (1995) and DAVIDSON et al. (1996), that the southern part of the pluton, a 60 km long tabular body of tonalite, represents the feeder of the pluton.

Geological setting

Near the eastern margin, tonalite and granodiorite of the Bergell pluton went through their solidus at 32 and 30 Ma ago (VON BLANCKENBURG, 1992). This calcalkaline pluton predominantly consists of tonalite at the rim and granodiorite with K-feldspar megacrysts in the core. This study focuses on the tonalite which is made up of plagioclase, amphibole, biotite, quartz, K-feldspar, and accessory minerals (allanite, zircon, sphene, magnetite, apatite). In the western and southern part of the pluton a zone of magma mixing and mingling forming a contact zone to the granodiorite (Übergangszone of MOTICSKA, 1970; WENK and CORNELIUS, 1977), is often present and was mapped as "granodiorite" in figure 1 for simplicity. The southernmost part of the tonalite is a steep tabular body oriented parallel to the Insubric line. The latter is formed by a 1 km wide mylonite belt (SCHMID et al., 1989) formed from Upper Austroalpine protoliths (Tonale Series). This tabular body of tonalite extends over some 30 km in an east-west direction and is always oriented parallel to the Insubric mylonites (Fig. 1). Its western part (i.e. west of Val Mera) will be referred to as "Iorio tonalite", the eastern part as "Southern Bergell tonalite".

The western contact of the pluton with the underlying lower Penninic country rocks has previously been described by DAVIDSON et al. (1996) who concluded that the pluton was emplaced onto and folded together with the remnants of a former nappe boundary (see also DIETHELM, 1989), correlated with the Misox zone and the Bellinzona-Dascio zone, on top of the underlying Adula-Gruf unit. In these Penninic units amphibolite- to granulite facies metamorphism is of Tertiary age (HUNZIKER et al., 1992). High-grade metamorphic conditions were reached partly before (BUCHER-NURMINEN and DROOP, 1983) and partly after the intrusion (see discussion of diachronism in ENGI et al., 1995). Final emplacement at the western margin occurred at a depth of 22–26 km (corresponding to 6–7 kbar derived by hornblende barometry in tonalite; REUSSER, 1987; DAVIDSON et al., 1996) and at temperatures leading to partial melting in the Adula-Gruf unit, although final equilibration to peak temperature conditions (at pressures of less than 5 kbar) post-dates the emplacement of this pluton further to the west (ENGI et al., 1995). Migmatites are also widespread in the Penninic units west of the intrusion. Structural observations (HAFNER, 1993) as well as isotopic dating (GEBAUER, 1996) indicate an Alpine age for many of these migmatites. Some of them are contemporaneous with or immediately followed the emplacement of the Bergell pluton. All of them predate the intrusion of the Novate granite (HAFNER, 1993), a leucogranite formed by crustal melts and genetically unrelated to the Bergell suite (TROMMSDORFF and NIEVERGELT, 1983).

At the northern margin of the pluton the granodiorite discordantly cuts up-structure and across the Tambo- and Suretta nappes, as well as across the tonalitic rim (Fig. 1; ROSENBERG et al., 1995). At the northeastern margin, representing a higher structural level near the roof of the intrusion (BERGER and GIERÉ, 1995), the contact with the country rocks is of fundamentally different nature, when compared to the western contact, as already noted by TROMMSDORFF and NIEVERGELT (1983). The South-Penninic ophiolites of the Forno- and Malenco units and the Austroalpine Margna nappe have been deformed and metamorphosed mainly during Cretaceous times (DEUTSCH, 1983; SPILLMANN, 1993). During the Tertiary, i.e. at the time of the intrusion, the ambient temperatures were below 350 °C. This led to contact metamorphism (TROMMSDORFF and EVANS, 1972 and 1977). In spite of synmagmatic deformation related to ballooning (BERGER and GIERÉ, 1995), caused by late vertical ascent of crystal mush squeezed out at a deeper structural level (western contact, see ROSENBERG et al., 1995) by N–S-shortening, primarily discordant contacts are generally preserved. Along the Preda Rossa shear zone (Fig. 1) the southeastern margin of the pluton climbs structurally upwards from NE to SW into the vertically oriented Upper Austroalpine units which follow the Insubric line. Backthrusting and dextral strike slip movements (transpression) across the Insubric mylonite belt (SCHMID et al., 1989) post-date final emplacement of the pluton.

Structures in the Iorio tonalite west of Val Mera

This east-west elongated, steeply north-dipping tabular body of tonalite (see WEBER, 1957, for historical background) extends westwards to Giubiasco near Bellinzona (Fig. 2; TROMMSDORFF and NIEVERGELT, 1983). According to hornblende barometry (7–8 kbar; REUSSER, 1987; DAVIDSON et al., 1996) the Iorio tonalite reached its solidus at a depth of 26–30 km and hence represents the deepest part of the Bergell intrusion. At its southern margin the Iorio tonalite grades into a porphyritic and more differentiated rock type: the Augengneiss of Melirolo (AGM), a tonalite with plagioclase phenocrysts and no hornblende, representing a marginal facies of the Bergell pluton (FISCH, 1989).

FABRIC ELEMENTS

According to microstructural investigations (ROSENBERG et al., 1994a; ROSENBERG, 1996) the macroscopically visible fabric elements reflect the total sum of magmatic, submagmatic and solid state deformation. Foliations within the Iorio tonalite dip steeply 60 to 80° to the NNW and are oriented strictly parallel to the contact with the

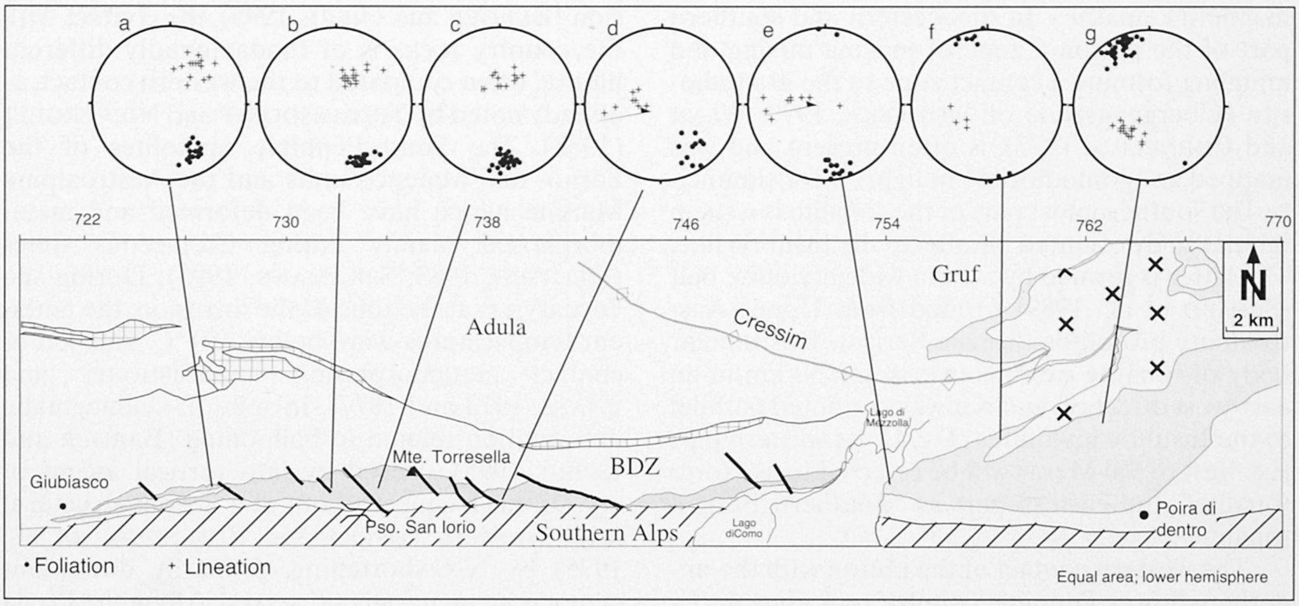

Fig. 2 Foliations and lineations in the Bergell root zone and the Iorio tonalite. Shaded: Bergell tonalite; Crosses: Bergell granodiorite including the "Übergangszone", cross-hatched: Paina marbles between Adula-Gruf unit and Bellinzona-Dascio zone. Stereographic projections are equal area, lower hemisphere. Arrow in figure 2 d, e indicates the trend of lineations steepening from S to N.

country rocks. The strike of these foliations is deflected in a counter-clockwise sense from the east–west strike of the northern part of the Bellinzona-Dascio zone and the Tonale Line. This reorientation is interpreted to be due to block rotations related to the movement across dextral Riedel faults. These Riedel faults formed in response to east-west extension connected with late-stage brittle transpressive strike slip movements along the Tonale fault (FUMASOLI, 1974). Rotation of the tonalite blocks (Figs 1 and 2) is in accordance with a domino model and with observations from other major strike slip faults (e.g. RON et al., 1983).

The lineations, however, considerably vary in orientation from west to east along the Iorio tonalite (see Fig. 2). From Giubiasco to the Passo S. Iorio area, lineations have an easterly pitch (Fig. 2 a, b). East of Passo S. Iorio (Fig. 2c) the lineations plunge down-dip. Still further east they systematically exhibit a pitch to the west which continues along the Iorio tonalite to the east-side of Val Mera (Fig. 2 d, e). West of Mt. Torresella, and particularly in the Val Mera section there is also a trend towards nearly near-down-dip orientations prevailing in the north from a more gently west-plunging pitch of the lineations in the south (arrows in Fig. 2 d, e). This trend correlates with a decreasing amount of solid state deformation towards the north, where magmatic flow predominates (BERGER and STÜNITZ, 1996). The lineations, primarily defined by the preferred alignment of hornblende, formed during the magmatic stage and continued to form in the solid state. They are parallel to the major axis of extension inferred from mafic enclaves. Therefore, they represent stretching lineations. The variably oriented lineations all formed more or less simultaneously during magmatic and solid state deformation since they are all contained within the same foliation.

Mesoscopically visible shear sense indicators are very rare and, where present, are related to solid-state overprint. Shear bands form a very low angle with respect to the foliation. This makes their use ambiguous. S-C structures (BERTHÉ et al., 1979), typically associated with the solid state deformation of granitoids, have only rarely been observed. We attribute (see also ROSENBERG et al., 1994a) the rareness of shear sense indicators to the very high temperatures which also prevailed during solid-state deformation of the tonalite in the western Bergell area, causing very homogeneous deformation. In fact, in the area of Val Mera, where the temperatures of deformation are lower with respect to the western Iorio tonalite (BERGER, 1995; ROSENBERG, 1996), shear bands and asymmetric clasts are more common. Shear bands in strongly deformed tonalite samples are only found within the southernmost part of the Iorio tonalite where they all show north-side-up shear sense, conforming with the shear senses related to backthrusting and found within the Insubric mylonites south of the Iorio tonalite. As already observed by FISCH (1989), microstructural shear-sense indicators within dynamically recrystallized foliation-parallel quartz veins are widespread in the Passo S. Iorio area, but only within the southernmost part of the Iorio tonalite. These veins show a stretching lineation parallel to that in the tonalite. In 15 samples collected west of Val Mera the oblique shape of the recrystallized quartz grains invariably indicates north-side-up shear sense. Fast grain boundary migration associated with grain growth, occasionally leading to diamond structures (LISTER and DORNSIEPEN, 1982) indicates that the shear senses recorded are related to a stage of high temperature solid-state deformation within these tonalites. Hence, they do not merely indicate a retrograde overprint.

STRAIN MEASUREMENTS

Because the tonalite was continuously deformed from the magmatic to the solid state, the strain measurements reported below represent the sum of magmatic plus solid state deformation. However, it cannot be determined how much of the total strain is due to magmatic and solid state deformation, respectively.

Solid state deformation of the tonalites goes together with metamorphic reactions involving break-down of hornblende and growth of new biotite and epidote (BERGER and STÜNITZ, 1996). Therefore the modal composition of these rocks changes dramatically with the southwards increasing amount of solid state deformation. However, the bulk chemistry of the highly deformed rocks remains constant (BERGER and STÜNITZ, 1996). This indicates that the system was closed at the time it was affected by solid-state deformation and metamorphic reactions. Therefore, the shape of the strain ellipsoids purely reflects the distortional part of strain at constant volume (VOGLER and VOLL, 1981; RAMSAY and HUBER, 1983).

Strain measurements within the Iorio tonalite on the base of elongated mafic enclaves found in the area of Passo S. Iorio (Fig. 2) were carried out by VOGLER and VOLL (1976, 1981). Their enclave measurements (Fig. 10 of VOGLER and VOLL, 1981), taken together with our own measurements (Fig. 3), show considerable scatter away from plane strain. At low strains and restricted to a few outcrops within the northernmost part of the Iorio tonalite (in area 1 of VOGLER, 1980), where magmatic flow predominates, we locally observed constrictional strains. In all other areas flattening strains predominate, as documented by the average of axial ratios measured by VOGLER (1980) and VOGLER and VOLL (1981) within 8 east-west striking areas along a north to south traverse across the Iorio tonalite (Fig. 3). Similar observations, i.e. a transition from prolate to oblate enclave shapes with increasing strain intensity, are reported from the Adamello pluton by JOHN and BLUNDY (1993). BERGER and STÜNITZ (1996) showed that there is a clear correlation between the increase in hornblende content (due to metamorphic reactions during solid state overprint) with strain intensity (aspect ratios). From this we infer, that, for some unknown reason, prolate strains were produced while the melt percentage was still high. Subsequently, flattening strains (no further substantial increase in the X/Y ratio) predominated during the later stages of straining, near the transition through the solidus and during solid state deformation, characteristic for the high strain zones.

DISCUSSION

Deformation within the Iorio tonalite did not occur under plane strain conditions, flattening clearly predominating at high strains. Independently, flattening strain is indicated in sections cut perpendicular to the lineation from samples of the southernmost tonalite. Plagioclase clasts are boudinaged and indicate a real stretch parallel to the subhorizontal Y-direction, the X-direction in the Passo S. Iorio area is indicated by the lineation fabric of figure 2c.

SANDERSON and MARCHINI (1984) and FOSSEN and TIKOFF (1993) demonstrated that flattening strains are expected in a transpressional scenario. The transpression geometry envisaged by these authors implies a component of horizontally oriented transcurrent shear, shortening across this

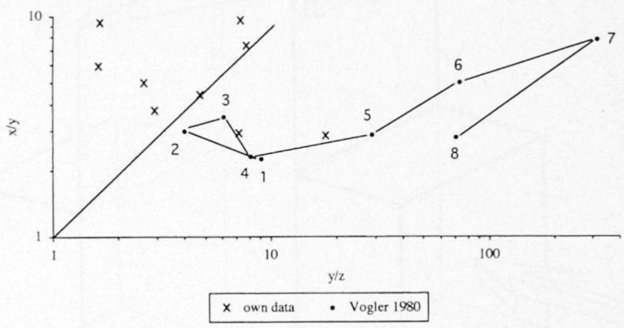

Fig. 3 Logarithmic Flinn diagram of enclave strain data from the area of Passo S. Iorio (locality indicated in Fig. 2). Our own data points are only representative for a small area near the northern margin of the tonalite tail where solid state overprint is weak. Each of the data points of VOGLER (1980), see also VOGLER and VOLL (1981), encompasses the mean of around 30 measurements per area along a complete N–S traverse through the tonalite tail (profile A–B in VOGLER and VOLL, 1981). Increasing numbers denote a relatively more southerly area along this profile.

shear zone being compensated by vertical thickening leading to vertical extrusion of the deformed zone between two rigid blocks (Fig. 4a). Assuming a strain path characterized by simultaneous simple (horizontal) and pure shear (vertical) FOSSEN and TIKOFF (1993) provided a deformation matrix for calculating the amount of shear strain and the amount of flattening across the shear zone achieved by this transpression geometry (their Fig. 7) on the basis of the strain data. Taking the average axial ratios for each area (Fig. 3) measured by VOGLER (1980), the present-day width of the Iorio tonalite of 1.02 km (across profile A–B of VOGLER and VOLL, 1981) would have been 1.97 km before deformation, transcurrent motion accommodated within the tonalite amounting to 18.3 km. Of course, these figures only apply for the particular strain path chosen by FOSSEN and TIKOFF (1993).

ROBIN and CRUDEN (1994) modified this simple model of a transpression zone in two respects: (1) they did not allow the material to freely slip along the boundaries of the transpression zone during vertical extrusion, (2) they generalized the model by allowing transcurrent motion departing from the horizontal ("oblique transpression"). They developped a continuous mechanics model based on linear viscosity and showed that lineations are expected to vary in orientation across and along the shear zone, as actually observed in the Val Mera section. Transpression with oblique transcurrent motion has been postulated for the movements across the Insubric mylonite belt (dextral shear combined with north-side-up backrusting) by SCHMID et al. (1989). However, it is uncertain whether this scenario also applies for the deformation within the Iorio tonalite which predates backthrusting (see later discussion on timing of movements).

The substantial variation of stretching lineations from west to east may also be caused by upwards divergent flow during non-plane-strain pure shear (Fig. 4b). In such a scenario, the original width of the Iorio tonalite would have been larger than the 2 km, calculated by assuming the strain path inherent to the model of FOSSEN and TIKOFF (1993) to be valid. We regard a combination of the model of figure 4a (vertical extrusion during transpression) with that of figure 4b (vertical extrusion by divergent upwards flow in pure shear) to be most appropriate. Given the not very substantially larger thickness of the tonalite tail east of Val Mera (Fig. 1), where total strain is very low within the southern half of the tonalite tail (plate 1), the original thickness of 20 km estimated by VOGLER and VOLL (1981), based on assuming a strictly coaxial strain path, seems unrealistically large. Since shear sense criteria are only available for the southern margin of the tonalite tail, it cannot be decided yet if vertical extrusion (common to both models discussed in figure 4, and predicting opposing senses of shear near the northern and southern margin) is indeed a reasonable model for the emplacement of the Bergell

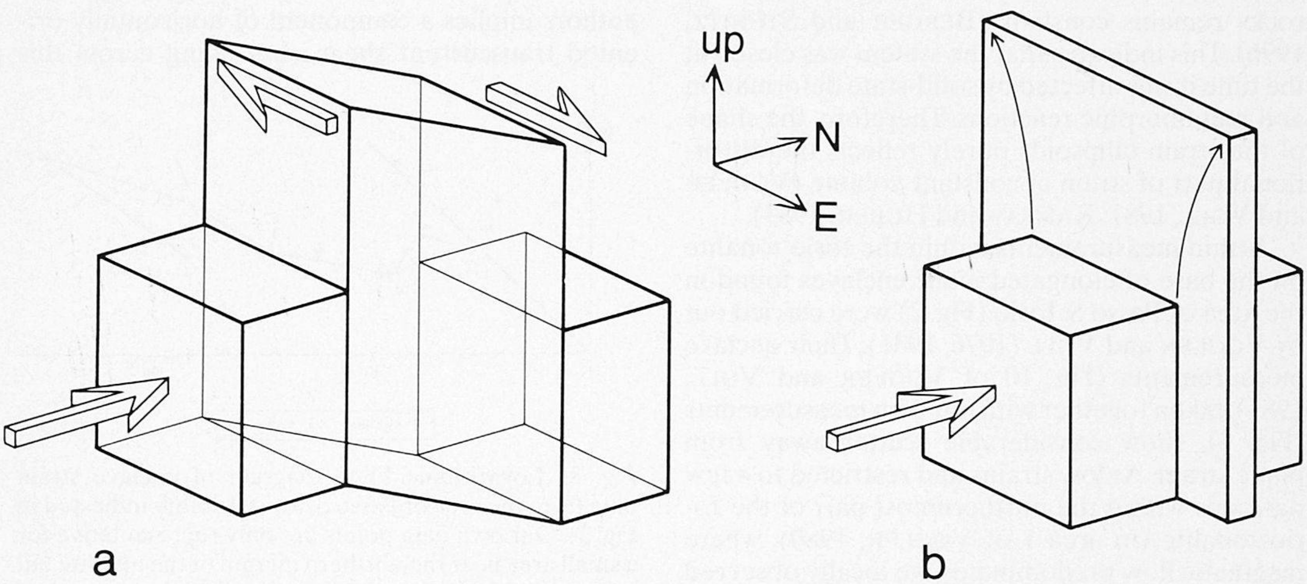

Fig. 4 Two alternative models for vertical extrusion. (a) The transpression model of SANDERSON and MARCHINI (1984) and TIKOFF and FOSSEN (1993), proposing vertical extrusion to result from N–S compression across a dextrally transcurrent shear zone. Note that the resulting stretch will be a combination of the regionally imposed displacement path (dextral strike slip) and vertical extrusion towards the free surface of the earth. (b) A model of non-plane-strain pure shear leading to vertical extrusion associated with upwards diverging flow, capable of explaining the substantial variations in the orientation of the stretching lineations along strike depicted in figure 3.

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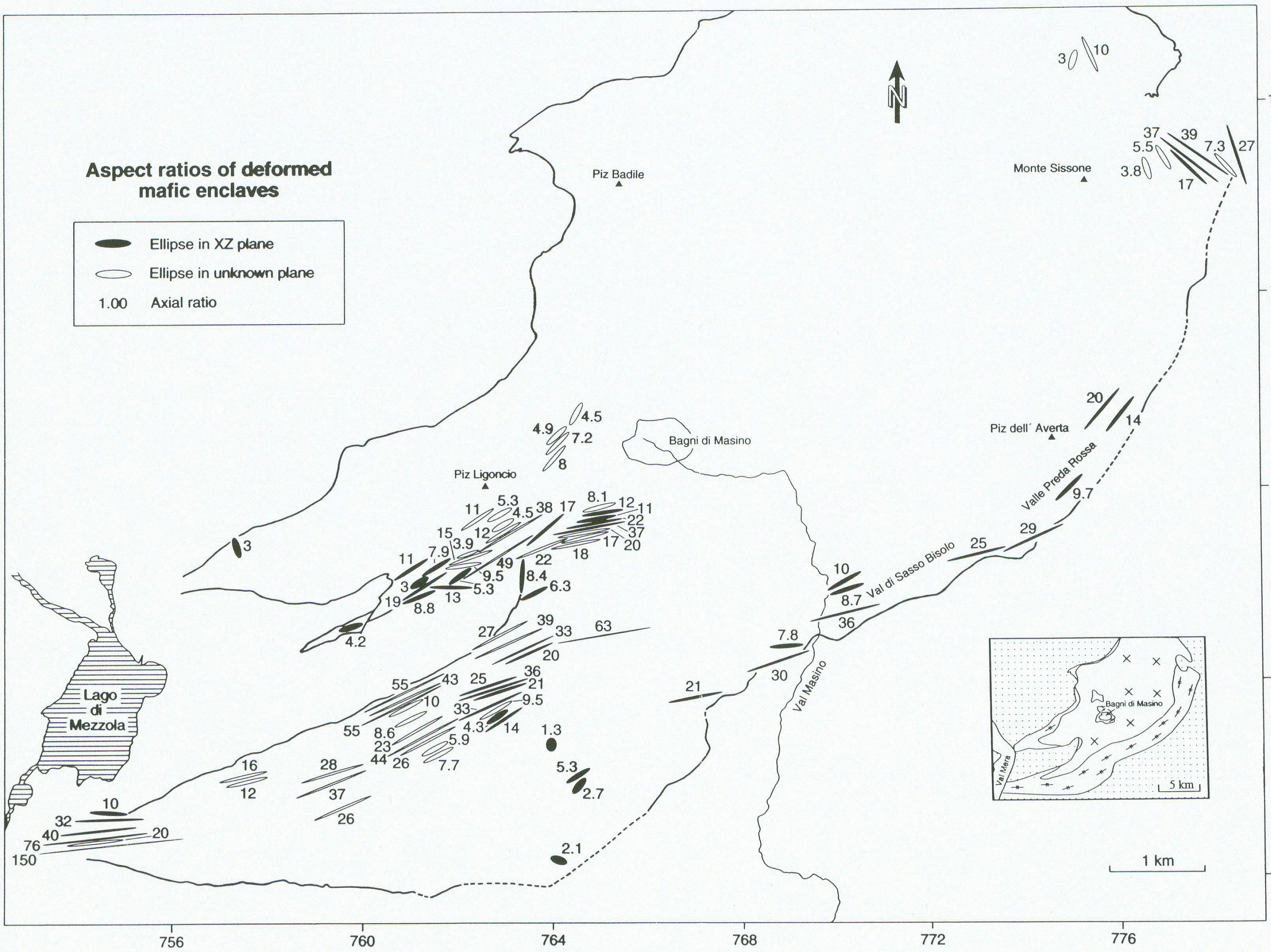
Plate 1 Aspect ratios of deformed mafic enclaves.



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tonalite. However, we will see later that opposing senses of shear are actually oberved east of Val Mera.

The root of the main intrusion east of Val Mera and the Austroalpine steep belt

STRUCTURAL OBSERVATIONS INSIDE THE PLUTON

The Iorio tonalite extends to the eastern side of Val Mera, where the foliations start to exhibit a fan-shaped geometry in a north-south cross section through what we refer to as the "southern Bergell tonalite" (Fig. 5; MOTICSKA, 1970). In the south the foliations are steeply north dipping and concordant to the mylonitic foliation of the Tonale series. Further north foliations become vertical and then south-dipping (Figs 5, 6). This fan-shaped geometry of the foliations can be traced further to the east. As described above for the Iorio tonalite, the fabric in the southern Begell tonalite is the sum of the strains caused by magmatic and solid state deformation, the intensity of solid state overprint increasing southwards.

Strain measurements in two perpendicular planes could not be achieved in this part of the pluton. However, elongated enclaves have been measured on surfaces parallel to the XZ plane, and where this was impossible, on sub-horizontal surfaces. These measurements allow for a qualitative comparison of strain intensities from different localities (plate 1). Clearly, a zone of high strain can be identified along the northern boundary of the Bergell root zone. This is in contrast to the Iorio tonalite, where strain increases towards the southern margin (Fig. 3).

Near the northern part of the southern Bergell tonalite and near Val Mera (Fig. 6), lineations plunge to the west (as was observed in the eastern

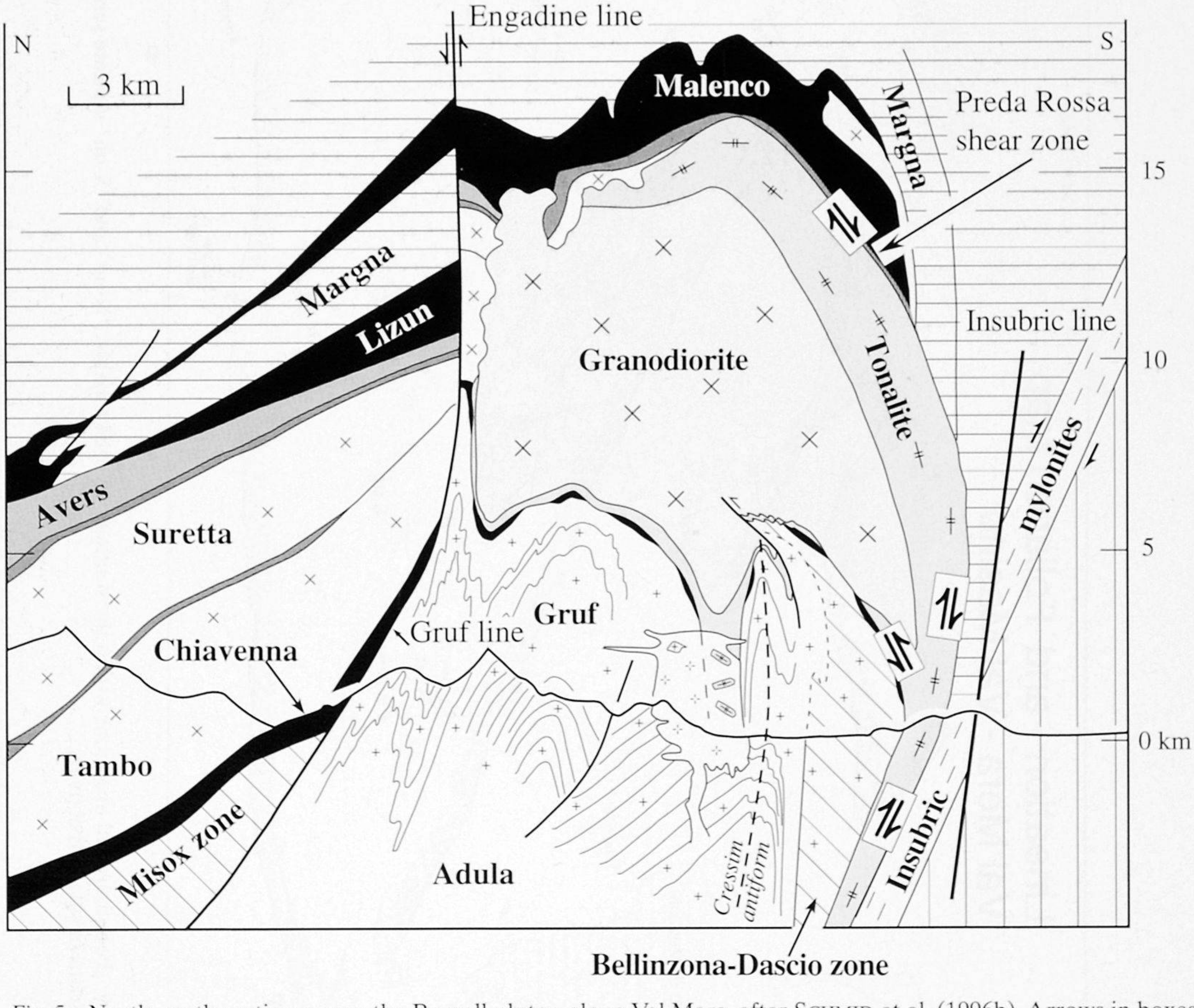

Fig. 5 North-south section across the Bergell pluton along Val Mera, after SCHMID et al. (1996b). Arrows in boxes indicate mesoscopically and microscopically derived senses of shear in tonalite.

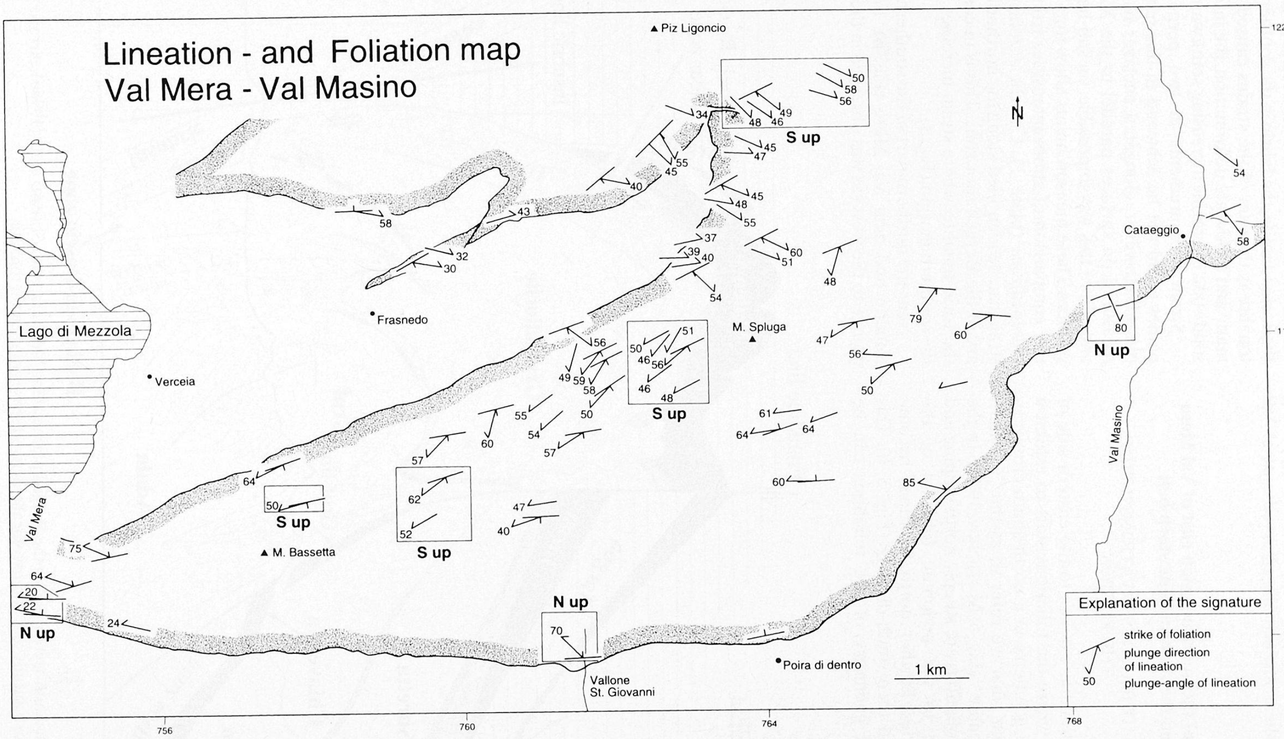

Fig. 6 Foliations and lineations within the southern Bergell tonalite. "N-up" and "S-up" indicate senses of shear associated with relative uplift of the northern and or southern side, respectively.

part of the Iorio tonalite). However, further east and north of M. Spluga (Fig. 6) this orientation gradually changes into a plunge to the east. Within the same region the northern contact of the southern Bergell tonalite curves into a SW–NE-strike, as it approaches the hinge zone of the Valle dei Ratti antiform (south of the Cressim antiform indicated in figure 5, see DAVIDSON et al., 1996). This very substantial change in the orientation of the lineations occurs within a single foliation plane (Fig. 7). No superposition of foliations and/or lineations could be detected. This indicates a very complex flow pattern. Along the southern contact of the southern Bergell tonalite (Valtellina), and in contrast to the northern contact, the solid state stretching lineations remain west-plunging until Val Masino in the east (Figs 6 and 7). The opposing plunging directions of the lineations near the northern and southern margin of the eastern part of the southern Bergell tonalite near Poira di Dentro (Fig. 7) also implies a major change in the flow pattern along a north to south profile.

Shear senses are relatively more abundant east of Val Mera, and they reverse from south to north. In the south, all shear-sense indicators within the tonalite (shear bands) clearly indicate a north side up shear sense. Towards the northern contact shear senses based on abundant shear bands, observed in thin section as well as on the outcrop scale, consistently give south side up movements. Hence, it appears that, in contrast to the southern part of the Iorio tonalite and the southern contact of the southern Bergell tonalite, the southern

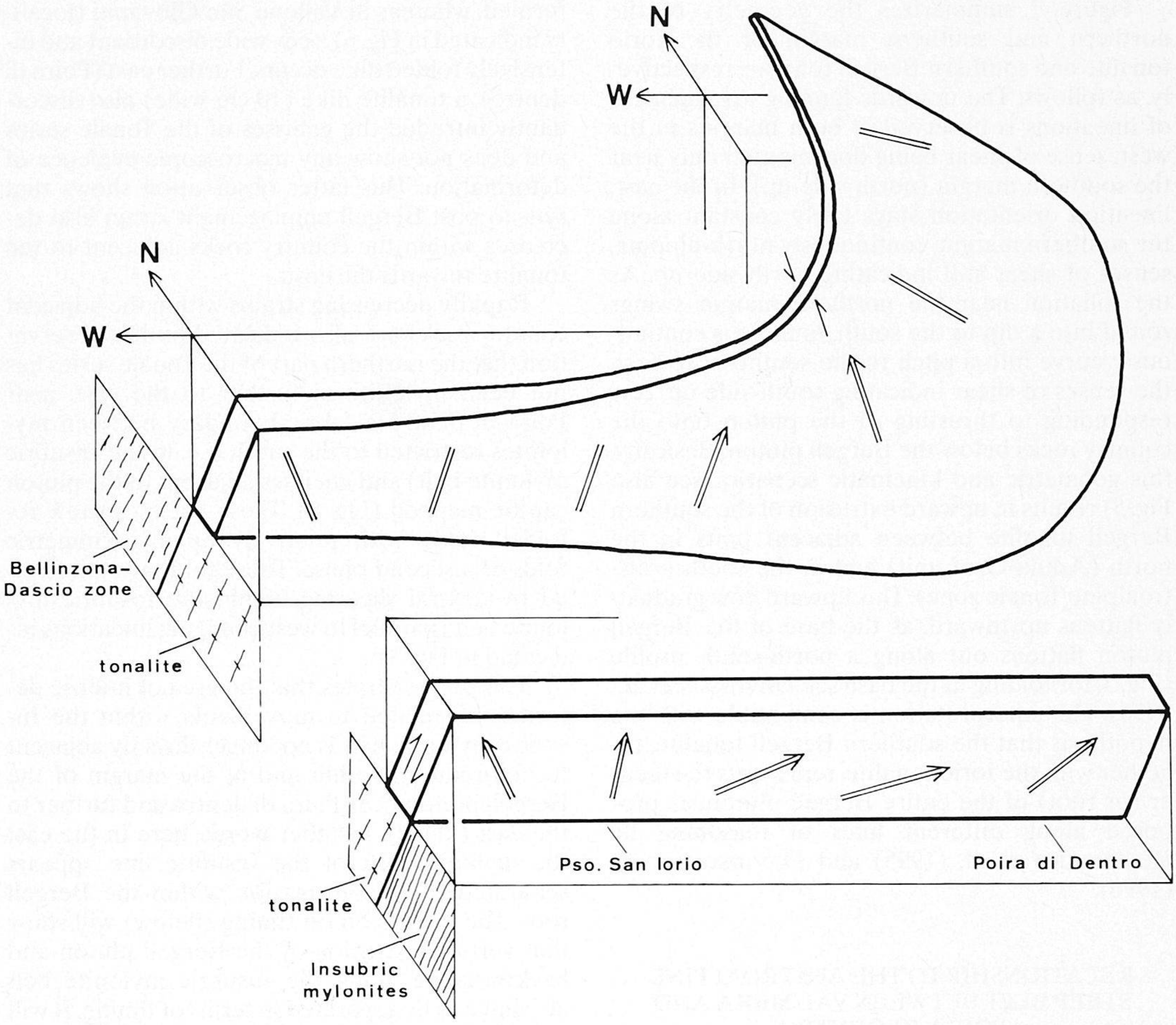

Fig. 7 Sketch of the orientation of foliations and lineations within the Iorio tonalite and the southern Bergell tonalite as measured near the tonalites northern (top figure) and southern (bottom figure) margin. Arrows on lineations denote the relative movement of tonalite in respect to the country rocks, as derived from shear sense criteria (compare Fig. 6).

block is uplifted. Due to the south-dipping foliation observed within the northern part of the southern Bergell tonalite this shear sense implies thrusting of the tonalite on top of the country rocks to the north. In the easternmost Valle dei Ratti and upper Valle Spluga, where the lineations are seen to turn into a plunge to the east or southeast (Fig. 6, north of M. Spluga) the observed shear senses still indicate a relative uplift of the southern part (i.e. the main body of the southern Bergell tonalite), the movement direction now being west to northwest-directed (cf. Fig. 6). Resolved onto a N–S-section (Fig. 5) the shear senses deduced for the northern margin of the southern Bergell tonalite are opposite to those found at the southern margin of the same tonalite (and within the Iorio tonalite west of Val Mera), as is expected for vertical extrusion (Fig. 4).

Figure 7 summarizes the geometry of the northern and southern margin of the Iorio tonalite and southern Bergell tonalite, respectively, as follows. The upwards fanning arrangement of lineations is observed at both margins in the west, sense of shear being documented only near the southern margin (north-side-up). In the east, lineation orientation stays fairly constant along the southern margin, continuously north-dipping, senses of shear still indicating north-side up. As the foliation near the northern margin swings round into a dip to the south, lineations continuously curve into a pitch to the southeast to east, the senses of shear indicating south-side-up, corresponding to thrusting of the pluton onto the country rocks below the Bergell pluton. Basically, this geometric and kinematic scenario (see also Fig. 5) results in upward extrusion of the southern Bergell tonalite between adjacent units in the north (Adula-Gruf unit) and in the south (Austroalpine Tonale zone). This upward flow gradually flattens northward, as the base of the Bergell pluton flattens out along a north-south profile (Fig. 5, for folding at the base see DAVIDSON et al., 1996). This interpretation is compatible with the hypothesis that the southern Bergell tonalite, together with the Iorio tonalite, represents the feeder (or root) of the entire Bergell pluton, as proposed along different lines of reasoning by ROSENBERG et al. (1995) and DAVIDSON et al. (1996).

RELATIONSHIP TO THE AUSTROALPINE STEEP BELT BETWEEN VAL MERA AND POIRA DI DENTRO

The root of the Bergell pluton is embedded in the Southern Steep Belt. In its southern part this belt comprises different Austroalpine units along the E–W strike, assigned to the Tonale-, Campo-Languard, Sella-Bernina- and Margna-units or nappes (VENZO et al., 1971; BERGER, 1996; SCHMID et al., 1996c). These different tectonic units cannot be clearly distinguished from each other in this area, because metasedimentary nappe dividers are missing.

The intensity of deformation within the southern margin of the southern tonalite decreases continuously to the east, as shown by the aspect ratio of the mafic enclaves within the tonalite (plate 1): at Poira di dentro (locality indicated in Fig. 6), very low strains (aspect ratio of 2 : 1) are measured. The same trend is confirmed by the dikes of the Bergell suite intruding the country rocks. In Val Mera all intrusive dikes are parallel to the foliation in the country rocks and intensively deformed, whereas in Vallone San Giovanni (locality indicated in Fig. 6) a cm-wide discordant and intensively folded dike occurs. Further east (Poira di dentro), a tonalite dike (10 cm wide) also discordantly intruded the gneisses of the Tonale series and does not show any macroscopic evidence of deformation. This latter observation shows that syn- to post Bergell emplacement strain also decreases within the country rocks adjacent to the tonalite towards the east.

Rapidly decreasing strains within the adjacent country rocks are also indicated by the observation that the northern part of the Tonale series has not been mylonitized further to the east: near Poira di dentro a fabric-boundary between mylonites restricted to the south (i.e. to the Insubric mylonite belt) and gneisses adjacent to the pluton can be mapped (Fig. 8). These gneisses show refolded folds, with relatively open, asymmetric folds of a second phase. These folds are unaffected by dextral shearing within the Insubric mylonite belt (parallel to west-plunging lineations indicated in Fig. 8).

This demonstrates that the area of intense deformation related to movements within the Insubric mylonite belt is no longer directly adjacent to deformation within and at the margin of the Bergell pluton near Poira di dentro and further to the east (Fig. 8). In other words, here in the east the mylonite belt of the Insubric line appears separated from deformation within the Bergell root. The discussion on timing (below) will show that vertical extrusion of the Bergell pluton and backthrusting along the Insubric mylonite belt also have to be separated in terms of timing. It will be shown that backthrusting followed extrusion of the tonalite.

RELATIONSHIP TO THE AUSTROALPINE STEEP BELT BETWEEN POIRA DI DENTRO AND VAL MASINO

Northeast of Poira di dentro the contact between intrusion and country rocks abruptly changes its orientation: the contact becomes discordant to the main foliation within the steep zone (Fig. 8). The contact strikes SW–NE, and turns into a N–S orientation south of Valle Spluga. In the lower Valle Spluga (Fig. 8) the strike of the contact is perpendicular to the main-foliation both in the country rocks and in the pluton over a distance of about 1 km. In this area, clearly intrusive contacts are preserved within a 10 meters wide contact zone (Fig. 9). Isolated small stocks of tonalite and dikes within the gneisses, as well as xenoliths of gneisses within the tonalite, are observed. The tonalite has a very weak or no fabric anisotropy. A few meters inside the pluton a weakly developed magmatic foliation is south dipping, the fabric being dominated by steeply west plunging lineations.

Away from the contact, the E–W-striking foliation in the strongly deformed country rocks (Upper Austroalpine, VENZO et al., 1971) is steeply inclined and discordantly intruded by the tonalite. This implies that here the magma intruded into a pre-existing steep zone. The lack of substantial deformation within the tonalite shows that, here at the southeastern margin, the Bergell pluton intruded a Southern Steep Belt which formed before magma ascent and emplacement, and, conse-

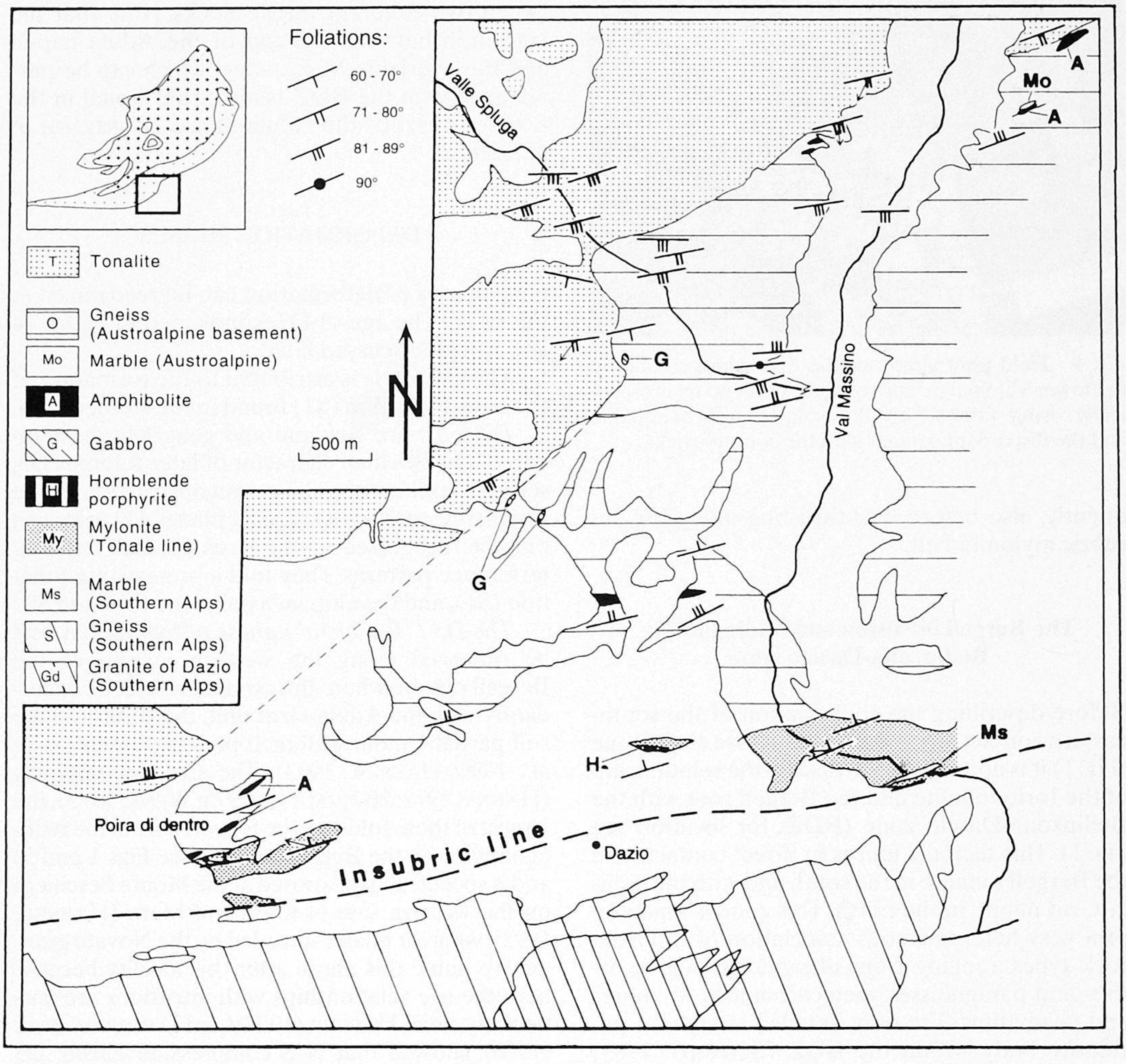

Fig. 8 Geological and structural map of the area between Poira di dentro and Val Masino, modified and completed after VENZO et al. (1971).

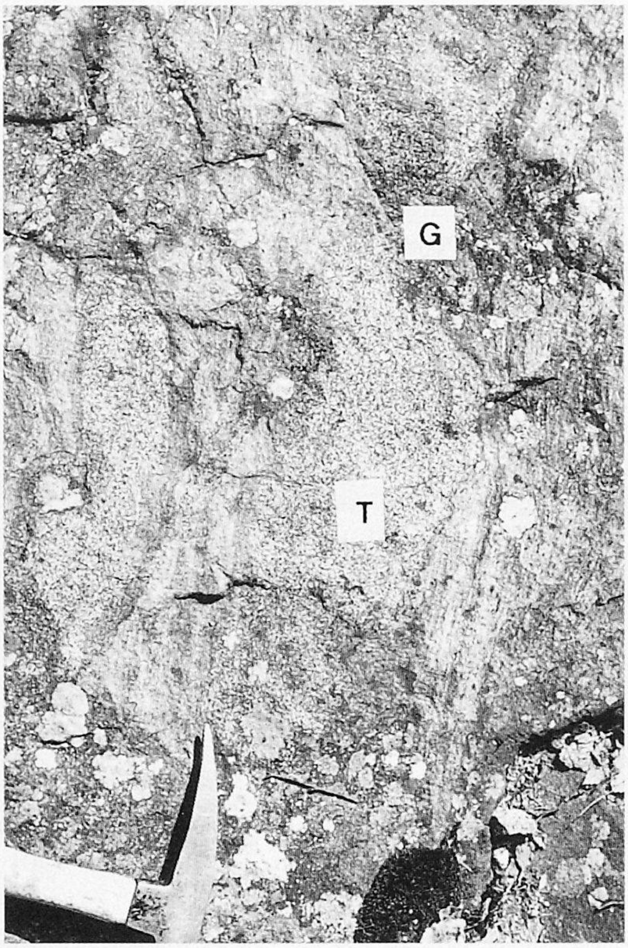

Fig. 9 Field photograph of the discordant contact in the lower Val Spluga. The tonalite shows no macroscopically visible fabric. Note the isolated pods of tonalite and the discordant contact with the country rocks.

quently, also before backthrusting along the Insubric mylonite belt.

The Bergell intrusion and folding in the Bellinzona-Dascio zone

Before describing the continuation of the southeastern contact along the Preda Rossa shear zone (Fig. 1) it is appropriate to discuss the relationship of the Iorio tonalite and the Bergell root with the Bellinzona-Dascio zone (BDZ; for location see Fig. 1). This tectonic unit is in direct contact with the Bergell tonalite in the south and with the Adula-Gruf nappe in the north. This zone is made up of a very heterogeneous association of different rock types, ranging from ultramafics, mafics, ortho- and paragneisses, metacarbonates to aplites and pegmatites. The only detailed study of a peridotite body within the BDZ (SCHMIDT, 1989) demonstrated that it represents a relic of an ophiolitic association, part of the North-Penninic suture zone according to DAVIDSON at al. (1996). The deformation of the BDZ has been previously studied by FUMASOLI (1974), VOGLER and VOLL (1976), and HEITZMANN (1986, 1987). HEITZMANN (1987) showed that the Paina marble, separating the BDZ from the Adula nappe, partly represents a subvertical lower greenschist facies mylonite zone with horizontal east-west oriented stretching lineations and a dextral shear sense, related to right-lateral movements that took place along the Insubric Line. We regard the Paina marble as a useful marker between two highly heterogeneous units that, however, cannot be traced across Val Mera to the east where the transition from the BDZ into the Adula-Gruf unit is a gradual one (DAVIDSON et al., 1996). However it does not represent a classical Mesozoic nappe boundary, between two coherent thrust blocks. Note that the transition between the top of the Adula nappe and the overlying Misox zone, which can be parallelized with the BDZ is also transitional in the northern part of the Adula nappe (PARTZSCH et al., 1994).

DEFORMATION PHASES

Four phases of deformation can be recognized in the BDZ. The age of D3 is indicated in figure 14 and will be discussed later.

The *D1 phase* is attributed to the formation of the oldest foliation (S1) found in the studied area.

D2-folds are isoclinal and generally dismembered. The isoclinal character of later folding (D3, see below) does not allow a reconstruction of the primary geometry of D2 axial planes. D2 folds can only be recognized on the basis of small scale interference patterns. They fold a pre-existing foliation (S1), and develop an axial plane foliation S2.

The D3 ("Peschiera") phase of folding can best be observed along the western margin of the Bergell pluton, where this contact is folded concordantly with the Adula-Gruf unit, the BDZ and the still partially molten Bergell pluton (DAVIDSON et al., 1996; HAFNER, 1993). The Cressim antiform (HÄNNY, 1972; HEITZMANN, 1975; WENK, 1973), the largest of these folds, can be followed from the Adula nappe into the Bergell pluton (see Figs 1 and 5) and is spectacularly exposed at the Monte Peschiera on the western side of lower Val Mera (HAFNER, 1993), where it is later intruded by the Novate granite. We name this phase after this locality because here the age relationships with intrusions are particularly clear. HAFNER (1993), and DAVIDSON et al. (1996), showed that N–S compression during D3 folding is contemporaneous to a component of east-west stretching, parallel to the fold axes (Fig. 10a).

D4-folding is the youngest tectonic event in the studied area, producing open folds with a chevron-type geometry. These folds have south-dipping axial planes and gently east-dipping fold axes. An axial plane foliation did not develop. D4 folds affect older steep foliations of the BDZ as well as the greenschist facies mylonites of the Tonale series. Hence, they post-date backthrusting. However, these locally developed D4 folds hardly affect pre-existing large scale structures.

THE PESCHIERA PHASE OF FOLDING (D3)

Because this particular folding phase is of special interest for discussing relationships with regional deformation and emplacement of the Bergell pluton it deserves a more detailed description (see also DAVIDSON et al., 1996). The Cressim fold, at least partly due to this deformation phase, is an east-west striking backfold which brings the Adula nappe into the southern steep zone (MILNES, 1978; MILNES and PFIFFNER, 1980; HAFNER, 1993). At Monte Peschiera, HAFNER (1993) interpreted this fold as resulting from dextral transpression along the Insubric Line.

However, the axial trace of the Cressim antiform (Fig. 1) changes its orientation across the area of Val Mera: it strikes WNW–ESE west of Val Mera, turns into an W–E orientation across Val Mera (HAFNER, 1993), and finally swings into a WSW–ENE strike east of the Val Mera (DAVIDSON et al., 1996).

An eastward change in strike of the axial planes from WNW–ESE to W–E and parallel to the Insubric line can also be observed for other map scale D3 backfolds, exposed west of the Cressim antiform (Fig. 1). Figure 1 shows the en-echelon arrangement of backfolds. Hence, a single backfold extending all the way from Bellinzona to the Bergell area does not exist. This raises the question whether these backfolds formed contemporaneously. We tentatively propose that previously formed NW–SE-striking series of folds have been subsequently overprinted by N–S shortening in a dextrally transpressive scenario during what we call the Peschiera-phase. This is because the geometry of the NW–SE-striking series of folds is incompatible with dextral transpression, as found for the Peschiera phase at the "type locality" Monte Peschiera (HAFNER, 1993). In the following we confine the discussion to the E–W to SW–NE-striking younger folds which we relate to the Peschiera phase.

The swing of the axial planes from an W–E into an WSW–ENE orientation, as expected for dextral transpression (SANDERSON and MARCHINI, 1984), is in fact seen in a series of antiforms and synforms folding the base of the Bergell pluton all along its western contact and in the window of Bagni di Masino (DAVIDSON et al., 1996). Because they all formed synmagmatically they are the result of the same phase of deformation (Peschiera phase). We therefore suggest that the WSW–ENE strike of these axial planes corresponds to the primary orientation developed during dextral transpression along the Southern Steep Zone, the swing into an east-west strike resulting from a gradient with southwards increasing strain. Such a strain gradient is in fact also observed further to the west when approaching the Iorio tonalite, as will be described below.

The folds in the southern BDZ, attributed to the Peschiera phase, always have subvertical axial planes. The style varies along a N–S profile, folds becoming tighter towards the south. Fold axes in the Adula nappe further north, which possibly formed earlier (as previously discussed), constantly plunge to the east, with 30 to 50°. However, in the BDZ and approaching the Iorio tonalite they become strongly dispersed within their axial plane (Fig. 10a). Although true sheath folds have never been found, curved hinges are very common (see also DAVIDSON et al., 1996 for such folds in the Valle dei Ratti) and may argue for a substantial component of shearing.

In spite of the isoclinal character of these folds, an axial plane foliation is absent or only weakly developed, except for the southernmost part of the BDZ. Many outcrops of folded migmatitic gneisses show that leucosomes intruded parallel to the axial plane of these folds, indicating that folding was syn-migmatitic. ROSENBERG et al. (1995) and DAVIDSON et al. (1996) have shown that this syn-migmatitic folding phase is also a synmagmatic one: the floor of the Bergell pluton is synmagmatically folded by Peschiera phase folding. Hence the Peschiera phase has to post-date the emplacement of the Bergell intrusion over the Adula-Gruf unit. While these folds also affect some early Novate-type leucogranitic dikes and leucosomes of the migmatites, the later dikes and the stock of the Novate granite cross-cut the already existing Peschiera phase folds (HAFNER, 1993). Therefore, the timing of Peschiera phase folding, discussed later in a larger context (Fig. 14), is well constrained by magmatic events.

PESCHIERA PHASE SHEAR SENSES

Shear sense determinations in the BDZ were carried out in areas of high syn-D3 strain (southern-

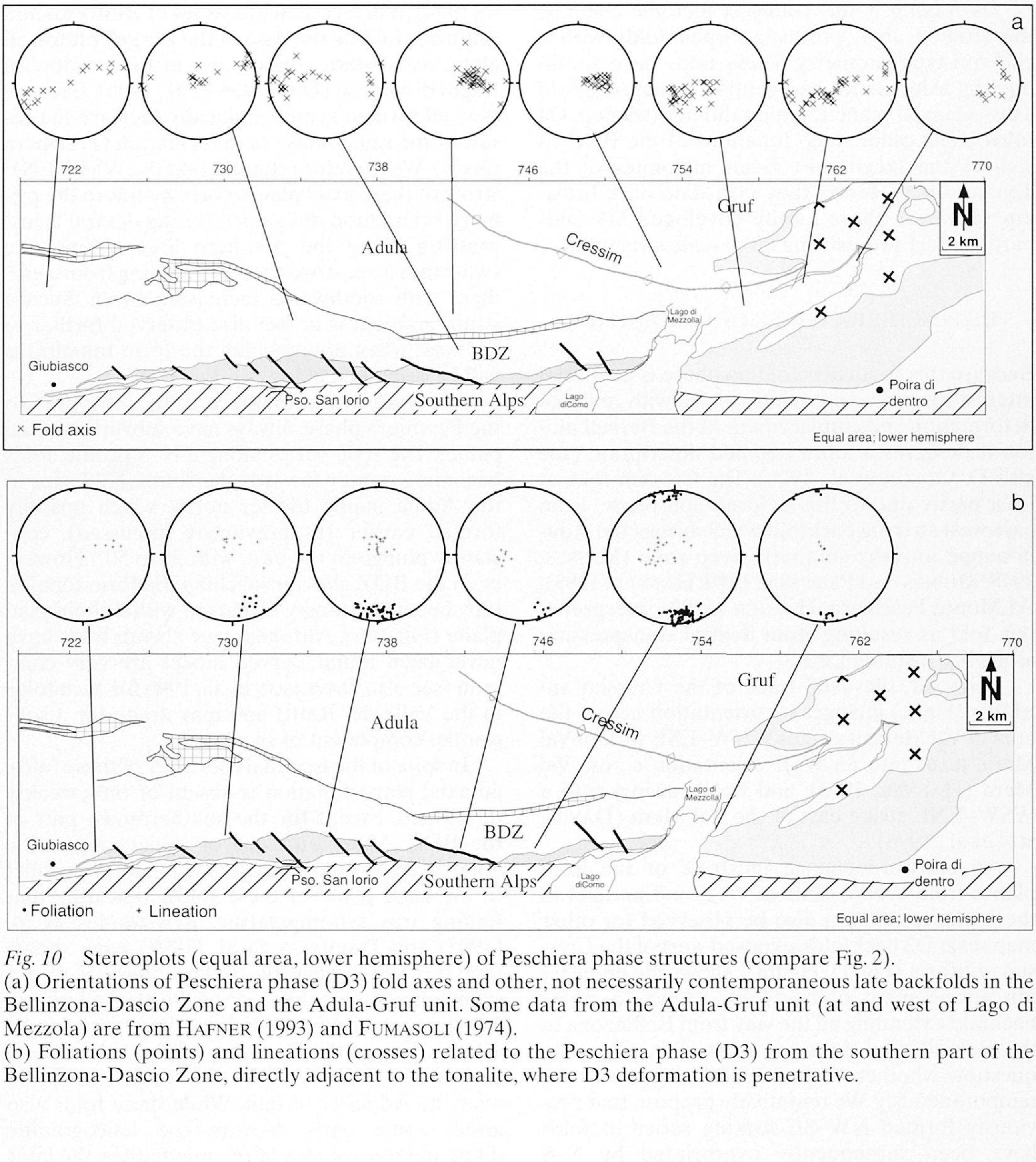

Fig. 10 Stereoplots (equal area, lower hemisphere) of Peschiera phase structures (compare Fig. 2).
(a) Orientations of Peschiera phase (D3) fold axes and other, not necessarily contemporaneous late backfolds in the Bellinzona-Dascio Zone and the Adula-Gruf unit. Some data from the Adula-Gruf unit (at and west of Lago di Mezzola) are from HAFNER (1993) and FUMASOLI (1974).
(b) Foliations (points) and lineations (crosses) related to the Peschiera phase (D3) from the southern part of the Bellinzona-Dascio Zone, directly adjacent to the tonalite, where D3 deformation is penetrative.

most BDZ), where D3 folding is completely overprinted by an S3 foliation. Both north side up and south side up shear senses occur, but the north side up shear senses largely dominate (75% of all the observed kinematic indicators), suggesting that these shear senses are related to backthrusting of the Penninic nappes, which however does not occur by simple shearing, but rather by a combination of simple and pure shear. This is compatible with a similar conclusion made earlier in regard to deformation within the Iorio tonalite (Fig. 4).

While subvertical stretching predominates within the BDZ (Fig. 10b) the stretch becomes dominantly orogen-parallel during the Peschiera phase at the western margin of the main Bergell intrusion, where senses of shear are conflicting, suggesting near-coaxial E–W stretching (DAVIDSON et al., 1996). Hence it appears that strain partitioning between N–S shortening and E–W extension is extremely complicated, as is also observed for the Niemet-Beverin phase north of the Bergell intrusion (BAUDIN et al., 1993; NIEVERGELT et al., 1996).

THE RELATIONSHIPS OF PESCHIERA-PHASE FOLDING WITH VERTICAL EXTRUSION AND BACKTHRUSTING

The Peschiera phase structures are primarily an expression of ongoing N–S compression during the postcollisional stage in the Central Alps, associated with strike-parallel E–W extension, particularly pronounced in the area of the main intrusion. This demonstrates, that there is no pause in deformation nor is there a general extensional phase at the time of the Bergell intrusion.

Because the Peschiera-phase folds also affect the synmagmatically deforming pluton, they must have formed prior to its complete solidification. DAVIDSON et al. (1996) regard this folding as part of the final emplacement of the Bergell pluton (their stage 2). Stage 1 of the final emplacement of the pluton, associated with the tectonic emplacement onto the Adula-Gruf unit and the BDZ, predates this folding. Therefore, the early synmagmatic stages of Peschiera phase folding are related to vertical extrusion of the pluton, rather than to backfolding and backthrusting.

As shown in figures 1 and 5, the vertical axial plane of the Cressim fold gradually becomes north-dipping at deeper structural levels, as it approaches the Insubric mylonites. This suggests that the Cressim antiform east of Val Mera originally formed with a vertical axial plane, and that subsequent deformation related to backthrusting rotated its axial plane into an orientation corresponding to that of a backfold in a strict sense. Consequently it appears that, strictly speaking, backthrusting post-dates the formation of the Cressim antiform in the area of the Bergell intrusion. Hence, the Peschiera phase, closely related to internal deformation of the Iorio tonalite, is considered partly contemporaneous with vertical extrusion of the tonalite, but lasts until the early stages of backthrusting.

THE TRANSITION FROM VERTICAL EXTRUSION TO BACKTHRUSTING

At some instant in time, vertical extrusion, which was considered as a likely mechanism to explain geometry, kinematics and strain values in the Bergell tonalite, must have given way to backthrusting of the Central Alps, including the Bergell pluton, as a more or less rigid entity (at the time of backthrusting!) over the Southern Alps (compare MERLE, 1994) who distinguishes an "extrusion phase" from a later "exhumation phase". Backthrusting, combined with rapid erosion, leads to the exhumation of the Bergell pluton and the entire Lepontine dome. Tentatively, we suggest that the onset of backthrusting and rapid exhumation coincides with the time of complete solidification of the pluton.

Vertical extrusion within a narrow and long tabular body, such as the Iorio and southern Bergell tonalite, leads to considerable overpressure above lithostatic pressure at the bottom centre of this tabular body (Fig. 4) which has to be considered as a channel of viscous material flowing between two rigid plates. ROBIN and CRUDEN (1994, their equation 10), based on an equation by JÄGER (1962), gave the following simple relationship between such an overpressure ΔP as a function of viscosity η within the channel, strain rate de/dt across the channel, and the normalized height Z (length of the channel divided by its half width):

$$\Delta P \approx {}^3/_2\, \eta \;\; de/dt\; Z^2$$

For the case of the Bergell area we estimate a maximum strain rate of 1.6×10^{-13} sec^{-1}, based on a north-south convergence rate across the Alps of 0.5 cm/a (SCHMID et al., 1996b), assumed to be taken up across the present day width of the Bergell tonalite tail (assumed to correspond to its present thickness of 1 km). The vertical length of the extruding channel is taken to be 30 km (see Fig. 7e in SCHMID et al., 1996b). Allowing for a very moderate overpressure of 10 MPa at the base of the channel, a viscosity of about 10^{16} Pa sec is derived. This is a reasonable figure for the viscosity of partially molten tonalite. However extrusion of the tonalite in the solid state, assumed to have a viscosity of 10^{20} Pa sec, would yield a totally unrealistic overpressure of about 10^5 MPa (1000 kbar!). Hence, it is reasonable to assume that vertical extrusion did not operate once the tonalite passed through its solidus over the entire width of the Bergell tonalite.

The Preda Rossa shear zone

Turning back to the southeastern margin of the pluton and looking at plate 1, it is seen that the aspect ratios of mafic enclaves do again indicate high strains near the contact of the southern Bergell tonalite with the country rocks as this contact crosses Val Masino. This belt of high strains, referred to as the Preda Rossa shear zone, follows that part of the southeastern margin of the Bergell pluton which is located north of the intrusive and discordant contact described in an earlier section. The shear zone follows remnants of the Suretta nappe and the Malenco-unit over much of its distance (Fig. 11). In plate 1 this high strain zone is seen to cut across the southern Bergell tonalite towards the west, where it follows the northern part of the tonalite tail. Hence the western continuation of the Preda Rossa shear zone is to be looked for within the tonalite and no longer follows its southern or southeastern margin. To the northeast, on the other hand, this high-strain zone can be followed as far as Valle Sissone, where it ends within granodiorite stocks which intruded after most of the deformation in the tonalite (BERGER and GIERÉ, 1995) related to the Preda Rossa shear zone. There, and further to the NE enclave strains change orientation and no longer record regional deformation but rather record strains related to ballooning (see BERGER and GIERÉ, 1995).

STRUCTURAL OBSERVATIONS

Across Val Masino, the contact of the southern Bergell tonalite strikes WSW–ENE into Valle di Preda Rossa, foliations within both tonalite and country rocks run parallel to the contact and dip steeply to the SSE (Fig. 11). In the Valle di Preda Rossa, the foliations at the southern margin of the tonalite slightly turn into a SE-dipping orientation, again parallel to the bending of the contact itself. The foliations within small remnants of the Suretta nappe (GIERÉ, 1985), preserved between tonalite and the Malenco unit (PFIFFNER and WEISS, 1994) in Valle di Preda Rossa, are also parallel to the contact of the pluton. This, however, is not the case for the foliations in the Malenco unit itself, which have a different orientation (Fig. 11).

Directly at the contact with the country rocks, the tonalite shows very intense solid state deformation. The intensity of solid state deformation rapidly decreases away from the contact, where a small amount of solid state overprint can only locally be recognized. The sense of shear related to the steeply south plunging stretching lineations (Fig. 11), inferred from small scale shear zones, shear bands and quartz-textures (BERGER, 1995), indicates northwest-side-up shearing, i.e. uplift of the pluton in respect to the country rocks. Hence, kinematically speaking, the Preda Rossa shear zone represents a normal fault.

Away from the contact, no shear sense indicators could be found within the tonalite. However, a magmatic fabric with a lineation parallel to the

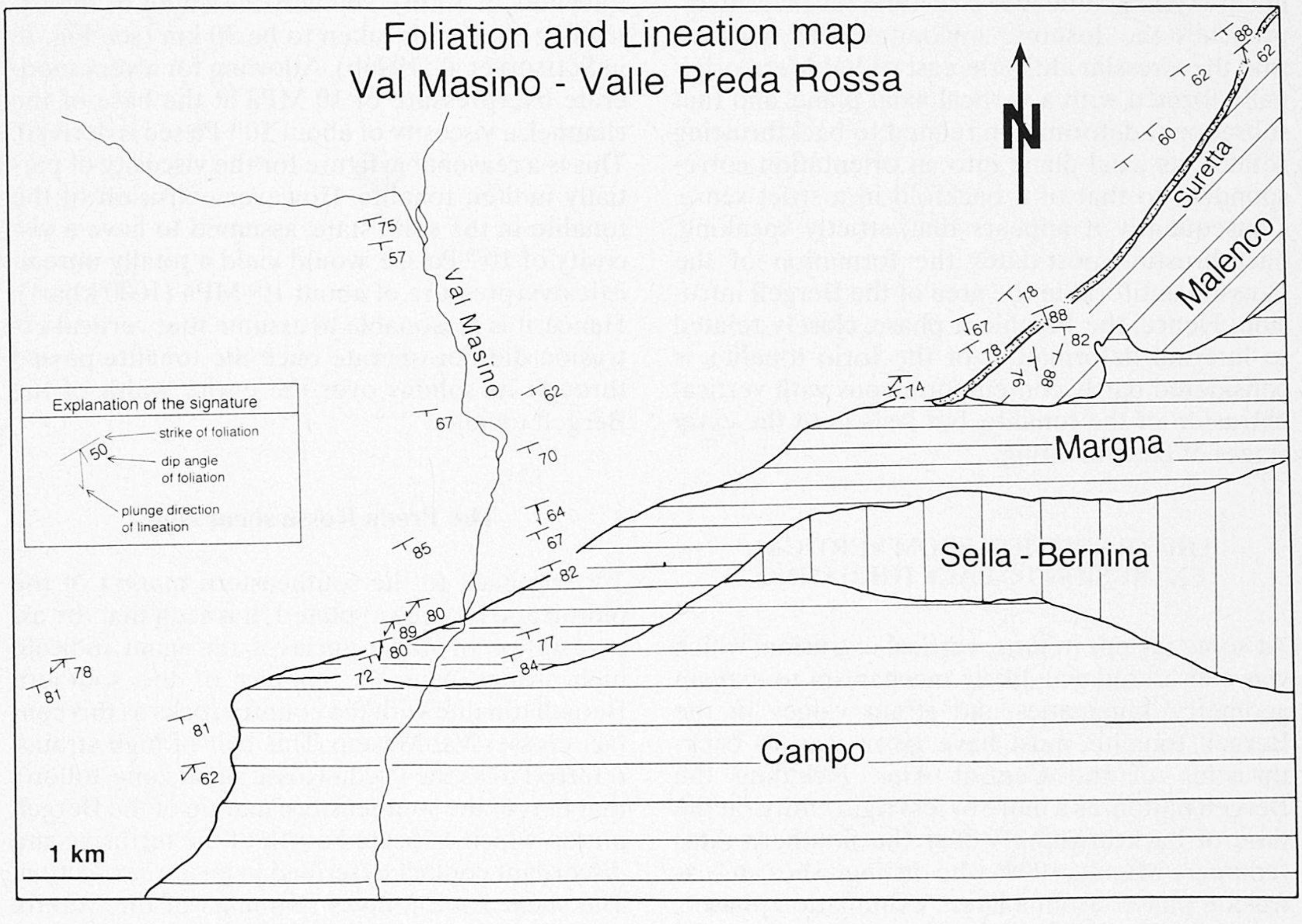

Fig. 11 Representative orientations of foliations and lineations, representing average values, along the SE margin of the Bergell pluton (Preda Rossa shear zone).

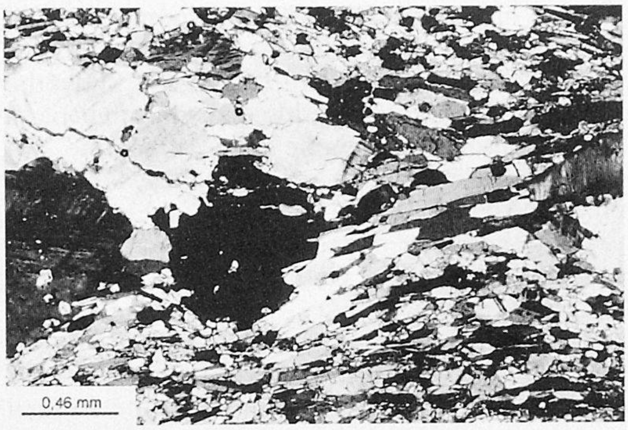

Fig. 12 Micrograph (crossed polarizers) showing contact-metamorphic wollastonite, synkinematically grown in the neck of a boudinaged feldspar; calc-silicate rock of the Suretta nappe in Valle Preda Rossa.

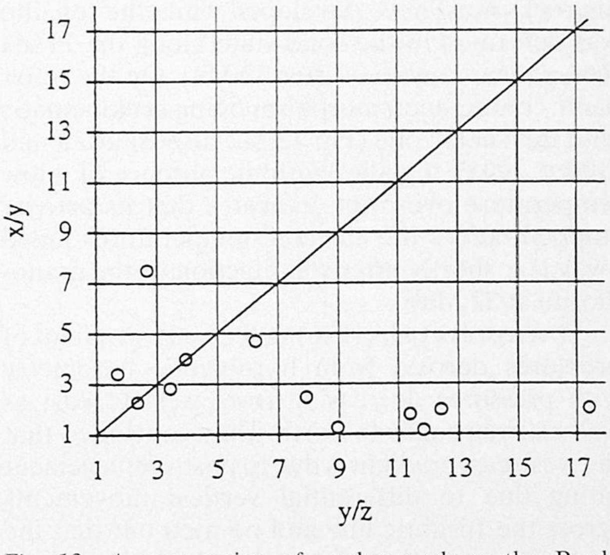

Fig. 13 Aspect ratios of enclaves along the Preda Rossa shear zone, plotted in a linear Flinn diagram.

one at the contact can be observed approximately 1 km away from the contact. This suggests that solid state deformation along the contact is contemporaneous with submagmatic and magmatic deformation away from the country rocks and within the pluton, according to the same kinematics. The shear sense in a Suretta quartzite, coming from a higher structural level of the Preda Rossa shear zone also affecting the country rocks, is the same as that found in the tonalite. High-temperature deformation observed in these country rocks (BERGER, 1995) is not compatible with the grade of Tertiary regional metamorphism prevailing within the country rocks, which never exceeded greenschist facies conditions (TROMMSDORFF and NIEVERGELT, 1983). These elevated temperatures are related to syn-kinematic contact metamorphism near the Bergell pluton. This finding is confirmed by the microstructures of some calc-silicates of the country rocks: wollastonite fibres have grown in the necks of boudinaged K-feldspar clasts (Fig. 12). These wollastonite fibres, together with the K-feldspar clasts, define a south-east-dipping stretching lineation, parallel to the lineation in the tonalite. This prooves that the Preda Rossa shear zone was active during the final emplacement of the Bergell pluton.

The aspect ratios of the enclaves reach 1 : 40 at the contact (plate 1), indicating pronounced apparent flattening. In two cases, away from the contact (≈ 750 m) and at low strains, the shape of the enclaves indicates apparent constriction (Fig. 13). This constrictional strain is related to a fabric which shows microstructures indicative for dominant magmatic flow, while the enclaves indicating flattening strain are found in the area of intense solid state deformation near the contact to the country rocks. The same trend from constriction or plane strain at low strains to flattening at high strains was already described along the Iorio tonalite.

DISCUSSION

Along the Preda Rossa shear zone, which kinematically represents a normal fault, pluton and country rocks were affected by the same deformation event. The amount of differential vertical movements due to shearing may be inferred from pressure estimates. In Valle di Preda Rossa the crystallization pressure in the tonalite is approximately 6.5 kb (REUSSER, 1989; DAVIDSON et al., 1996) and a pressure of merely 3 ± 1 kb is indicated for the contact-metamorphic aureole (TROMMSDORFF and NIEVERGELT, 1983, and citations therein; for discussion see BERGER, 1995). Therefore, the pressure difference between pluton and country rocks of about 3.5 ± 1 kb amounts to a vertical component of exhumation of the pluton in respect to its country rocks in the order of 10.5 ± 3 km in this area. The pressure estimates from the tonalite further north (Valle Sissone) decrease to 5 kb, hence the offset also must decrease to the north. In Valle Sissone this shear zone terminates (BERGER and GIERÉ, 1995), being cut by the granodiorite intrusion. There relative uplift of the intrusion only amounts to some 3–5 km due to NNE-striking flexuring of the country rocks (D 5 of SPILLMANN, 1993; see also Fig. 14 in BERGER and GIERÉ, 1995) related to ballooning of the granodiorite.

Because the "Al in Hornblende" barometer records the pressure at the solidus of the tonalite, the estimated offset between pluton and enclosing rocks must have developed while the tonalite was deformed in the solid state along the Preda Rossa shear zone (i.e. after 32 Ma). On the other hand, contact-metamorphism being synkinematic with this shear zone (Fig. 12, see also BERGER and GIERÉ, 1995), together with the absence of a low temperature overprint, indicates that its activity stopped before the elevated temperatures faded away (i.e. shortly after solidifaction of the granodiorite at 32 Ma).

DAVIDSON et al. (1996) described a gradient of pressures derived from hornblende barometry with pressures decreasing from west to east as well as from south to north. They concluded that the west-east gradient is due to post-emplacement tilting due to differential vertical movements across the Insubric line and pointed out that the north-south gradient must be partly explained by non-contemporaneous solidifaction of the tonalite, the depth of solidification decreasing to the north. In the light of our data this north-south gradient may well be related to the stage of vertical extrusion, of which the Preda Rossa shear zone is an integral part.

Discussion and conclusions

TIMING OF REGIONAL DEFORMATION IN THE BERGELL PLUTON AND SURROUNDING AREAS

The timing of regional deformation phases uses information on absolute ages dating magmatic events and is summarized in figure 14. At the eastern contact of the Bergell pluton VON BLANCKENBURG (1992) dated the tonalite at 31.88 ± 0.09 Ma and gave an age of 30.03 ± 0.17 Ma for the granodiorite. Because the crystallization is relatively fast in the east, these ages approximately date solidification of the two rock types in this region. However, it is important to emphazise that these solidus ages are not expected to be valid further to the west, i.e. at deeper crustal levels. Substantial differences in the cooling rate are expected from east to west, the temperatures of the country rocks being vastly different at the time of intrusion. In fact, new U–Th–Pb isotope measurements from the western part of the Iorio tonalite (OBERLI et al., 1996) indicate a much longer time-span from 33 Ma to 28 Ma for the crystallization of zircon and allanite in tonalite. This indicates slow cooling of a crystal mush which did not reach the solidus before approximately 28 Ma ago (OBERLI et al., 1996), leaving a substantial time gap of 5 Ma between liquidus and solidus over the entire area of the pluton.

The intrusion of the Novate granite is still poorly dated at around 26 Ma (KÖPPEL and GRÜNENFELDER, 1975). GEBAUER (1996) finds the same age for late pegmatitic dikes in other parts of the southern Lepontine dome. Since the Novate granite cross-cuts synmigmatitic Peschiera phase folding (HAFNER, 1993) we take this event to mark the end of a longlasting period of migmatization within the country rocks below the Bergell intrusion.

Structurally, the emplacement of the Bergell pluton was divided in two stages by DAVIDSON et al. (1996). Tectonic emplacement of the Bergell pluton on top of the underlying Penninic country rocks along a former nappe boundary (stage 1) was followed by still synmagmatic folding of that tectonic contact (stage 2). This second stage is correlated with the onset of Peschiera phase folding which started while the tonalite at the western margin of the Bergell pluton was still above its solidus. Note that, according to the timing proposed in figure 14, the tonalite at the eastern margin of the pluton, dated by VON BLANCKENBURG (1992) at 32 Ma, reached its solidus earlier, i.e. at the onset of the Peschiera phase folding. Contemporaneity of this stage 2 with ballooning of the pluton according to ROSENBERG et al. (1995) is crucial for the timing. This ballooning certainly predates the solidification of granodiorite at the eastern margin (30 Ma). It is infered to start at around 32 Ma, because this represents a late-stage mobilization of a granodioritic melt (BERGER and GIERÉ, 1995), discordant to and across the already solidified tonalite rim at the eastern contact. Note, that according to the timing proposed in figure 14 the synmagmatically deformed tonalite at the western contact cannot have reached its solidus before 30 Ma, i.e. 2 Ma after the solidus was reached at its eastern margin. Stage 1 tectonic emplacement of the pluton above the Penninic units started at an unknown instant of time before 32 Ma.

The movements along the Preda Rossa shear zone are assumed to start at around 33 Ma, i.e. shortly before the tonalite reached its solidus at the eastern margin, due to unroofing in the footwall of this shear zone. It lasted until 30 Ma at most, because the Preda Rossa shear zone is cut by the granodiorite intrusion. Hence, this shear zone is roughly contemporaneous with folding of the base of the pluton and ballooning at the northeastern margin.

Peschiera phase folding is well constrained between 32 Ma (onset of synmagmatic folding at the western margin of the pluton) and the Novate intrusion (26 Ma). The early stages of this folding are contemporaneous with vertical extrusion of

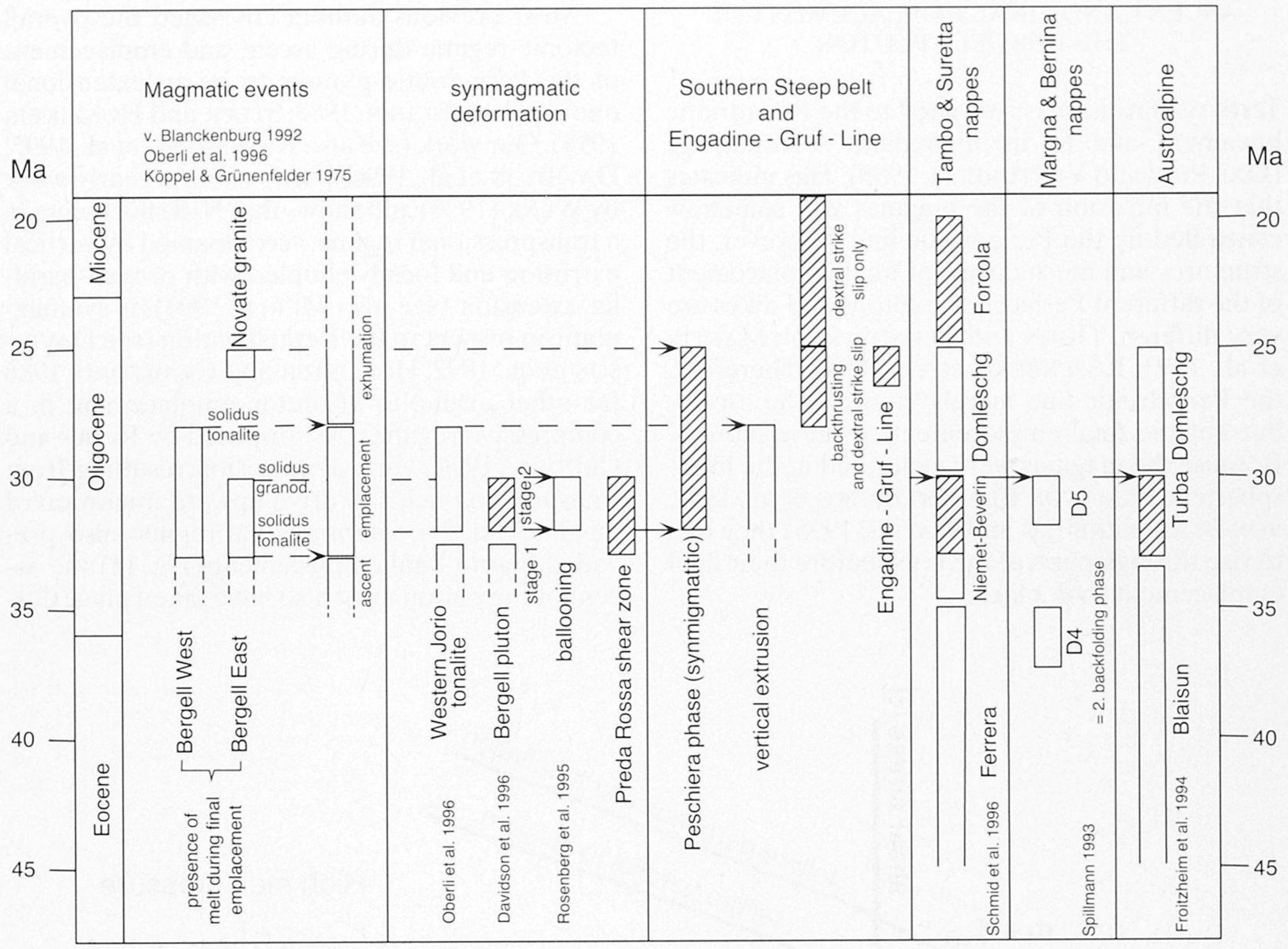

Fig. 14 Timing of magmatic and tectonic events in the Southern Steep Belt and adjacent Penninic and Austroalpine units. Diagonal ruling indicates deformation phases characterized by orogen-parallel stretching during ongoing N–S compression.

the Iorio and the southern Bergell tonalite. Vertical extrusion terminates no later than 28 Ma ago (i.e. when the solidus is reached in the westernmost part of the pluton, i.e. in the Iorio tonalite (OBERLI et al., 1996). Post-28 Ma backthrusting of the Central Alps is a short-lived event, assumed to have ended near 25 Ma ago, in order to allow for rapid cooling and exhumation of the entire Bergell area (GIGER, 1991; GIGER and HURFORD, 1989). The Engadine line certainly post-dates the metamorphic aureole of the Bergell and was proposed to be Late Oligocene by SCHMID and FROITZHEIM (1993).

Timing relationships between the Bergell pluton and deformation phases established further to the north are documented at the northern end of the Bergell pluton, where the Turba normal fault (NIEVERGELT et al., 1996) is contact-metamorphosed by the 30 Ma old granodiorite (LINIGER, 1992). As seen from figure 14 this normal fault is roughly contemporaneous with the Preda Rossa shear zone. Hence, we propose that the two fault zones are kinematically linked. The Turba normal fault represents the final stage of the Niemet-Beverin phase in the Tambo- and Suretta- and Schams-nappes (SCHMID et al., 1990, 1996a). This phase, bracketed between 35 Ma and 30 Ma by SCHMID et al. (1996b), appears to be contemporaneous (Fig. 14) with the tectonically driven synmagmatic emplacement of the Bergell pluton over the underlying Penninic nappes, and, ultimately, with vertical extrusion.

Backfolding of the Austrolapine units was shown to pre-date the final emplacement of the Bergell pluton. Hence, it pre-dates 32 Ma by some unknown time interval (see also WERLING, 1992). The fact that the Cretaceous metamorphic isograds are folded (SPILLMANN, 1993) implies a post-Cretaceous age for this backfolding. K/Ar biotite/chlorite cooling ages of 40–30 Ma in the Margna nappe outside the contact aureole (HUNZIKER et al., 1992) point to early Oligocene cooling and uplift. Hence, we follow SPILLMANN (1993) and place this event in the 37 Ma to 34 Ma interval.

ASCENT AND FINAL EMPLACEMENT OF THE BERGELL PLUTON

Tertiary plutonism is restricted to the Periadriatic lineament and to its immediate surroundings (DAL PIAZ and VENTURELLI, 1983). This indicates that the intrusion of the magmas was somehow controlled by the Periadriatic line. However, the structures and mechanisms of final emplacement of the different Periadriatic plutons and dikes are very different (JOHN and BLUNDY, 1994; MARTIN et al., 1993; ROSENBERG et al., 1995). Therefore, the Periadriatic line merely controls the ascent, but not the final emplacement of these plutons. Because the magmas were generated in the lithospheric mantle (VON BLANCKENBURG et al., 1991; VON BLANCKENBURG and DAVIES, 1995) they had to rise through parts of the crust before their final emplacement took place.

Most previous authors envisaged the overall tectonic regime during ascent and emplacement of the Periadriatic plutons to be an extensional one (i.e. LAUBSCHER, 1983; STECK and HUNZIKER, 1994). Our work (see also ROSENBERG et al., 1995; DAVIDSON et al., 1996) partly confirms early work by WENK (1973) and shows that N–S shortening in a transpressional regime, accompanied by vertical extrusion and locally coupled with orogen-parallel extension (see also MERLE, 1994), is synmagmatic in respect to the Bergell pluton (see DAVIDSON et al., 1992; HOLLISTER and CRAWFORD, 1986 for other examples of pluton emplacement in a compressive regime). As proposed by ROBIN and CRUDEN (1994) vertical extrusion resulting from transpression helps to drive upward migration of magma. Since a compressional regime also prevailed before final emplacement (Fig. 14) the ascent of the pluton must also have taken place dur-

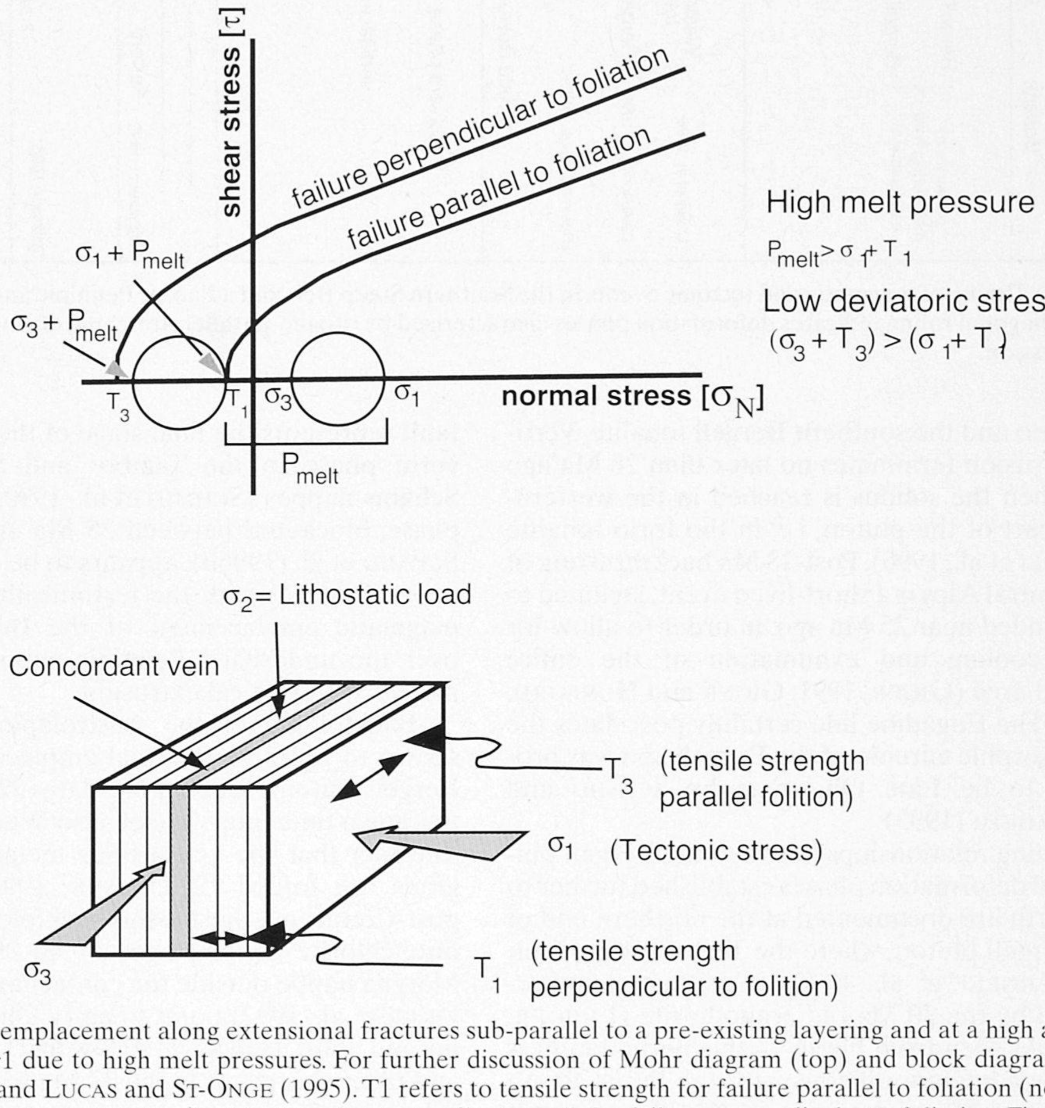

Fig. 15 Vein emplacement along extensional fractures sub-parallel to a pre-existing layering and at a high angle to the regional σ1 due to high melt pressures. For further discussion of Mohr diagram (top) and block diagram (bottom) see text and LUCAS and ST-ONGE (1995). T1 refers to tensile strength for failure parallel to foliation (note that σ1 is perpendicular to foliation), while T3 refers to tensile strength for failure perpendicular to foliation. Figure taken from LUCAS and ST-ONGE (1995).

ing lithospheric convergence, associated with slab break-off according to von BLANCKENBURG and DAVIES (1995). The steep fabric in the easternmost part of the Tonale series north of the mylonites of the Tonale line points to the existence of a precursor of the Insubric line. This precursor controlled the position of the Periadriatic intrusions by favouring magma ascent. Note however, that this pre-existing steep zone is not identical with the Penninic Southern Steep Belt which formed later and during final emplacement of the Bergell pluton.

The Iorio tonalite is interpreted as the feeder of the pluton (see also ROSENBERG et al., 1995; DAVIDSON et al., 1996) although this steeply N-dipping tabular body of tonalite is oriented perpendicular to the maximum shortening direction. At first sight this orientation of a feeder dike only contradicts emplacement of the tonalite during N–S shortening. However, WICKHAM (1987), and LUCAS and ST. ONGE (1995) showed that rocks with a pre-existing anisotropy (foliation, layering) oriented perpendicular to $\sigma1$ (maximum principal stress), tensionally fail along foliation-parallel fractures if certain conditions are met (Fig. 15). The deviatoric stress ($\sigma1 - \sigma3$) has to be lower than the difference in tensile strength of a rock parallel and perpendicular to the foliation. Additionally, the melt pressure (P melt) has to exceed the sum of $\sigma1$ and the foliation-parallel tensile strength of the rock. Such fractures give way to dikes at high angles to $\sigma1$. This mechanism may well apply to the intrusion of the tonalites of the southern Bergell intrusion, since these tonalites intruded into a simultaneously active crustal shear zone with evolving planar fabrics, and, additionally, steep planar anisotropies inherited from backfolding of the Austroalpine root zone (Fig. 16a). Very low differential stresses prevailing during ductile deformation of the country rocks are a corollary of this hypothesis which implies melt-enhanced embrittlement during dike-propagation (DAVIDSON et al., 1994). The fact that the partially molten pluton deforms conformably with the solid state deformed country rocks independently supports solid state ductile deformation at very low differential stresses.

STRUCTURAL RELATIONS BETWEEN FINAL EMPLACEMENT AND REGIONAL DEFORMATION

Directly north of the Insubric line backfolding affects the Bergell pluton including its country rocks. Structural data along the eastern and western contacts of the Bergell pluton indicate that backfolding occurred before, during and after emplacement of the pluton. The evolution of this deformation in space and time is characterized by westward migration over a time interval of some 8 Ma (Fig. 14): the Malenco- and Margna units have been backfolded before the intrusion of the Bergell pluton (Fig. 14; SPILLMANN, 1993), while backfolds in the eastern Penninic zone affect the Bergell pluton late during its final emplacement.

The upwards directed flow in the Southern Steep Belt was found to be contemporaneous with the Niemet-Beverin phase (Figs 14 and 16b). This phase is associated with differential N-wards emplacement of the Tambo- and Suretta nappes leading to large-scale nappe refolding of the Schams nappes (SCHREURS, 1996; MERLE, 1994; MERLE and GUILLER, 1989; SCHMID et al., 1990). Note that there is no root of the Tambo and Suretta nappe preserved within the Southern Steep Belt (Fig. 1). This differential north-directed movement reaching the earth's surface in the northern foreland of the Alps (Fig. 16b) may create part of the room which had to be provided for the emplacement of the pluton. Due to ongoing N–S compression, folds developed at the floor of the pluton during step 2 of the final emplacement (Fig. 16c). Locally, this north-directed movement is associated with very pronounced east-west extension (BAUDIN et al., 1993; NIEVERGELT et al., 1996), particularly during the closing stages of this phase (Turba normal fault). Interestingly, synmagmatic folding at the base of the pluton is also associated with east-west extension (DAVIDSON et al., 1996). Orogen-parallel stretching during ongoing N–S shortening seems to characterize the tectonic scenario of a large region during emplacement of the Bergell pluton, but also immediately afterwards (SCHMID and FROITZHEIM, 1993).

Upwards directed magma flow, differential north directed thrusting of Tambo and Suretta, folding of the base of the pluton and orogen-parallel stretching develop as part of a continuous process, because syn-magmatic structures related to all these events are found within the Bergell pluton. The continuity of these deformation steps is in full agreement with modelling of MERLE and GUILLER (1989). In this model, continuous N–S shortening induces the development of the southern steep belt as well as a N-directed escape of material (Tambo and Suretta) which can no longer vertically extrude as it reaches the base of the rigid orogenic lid (Austroalpine). The Bergell pluton is an excellent marker, defining the exact timing of all the stages of this evolution, its geometry encompassing the Southern Steep Belt as well as the flat lying parts of the Penninic nappes.

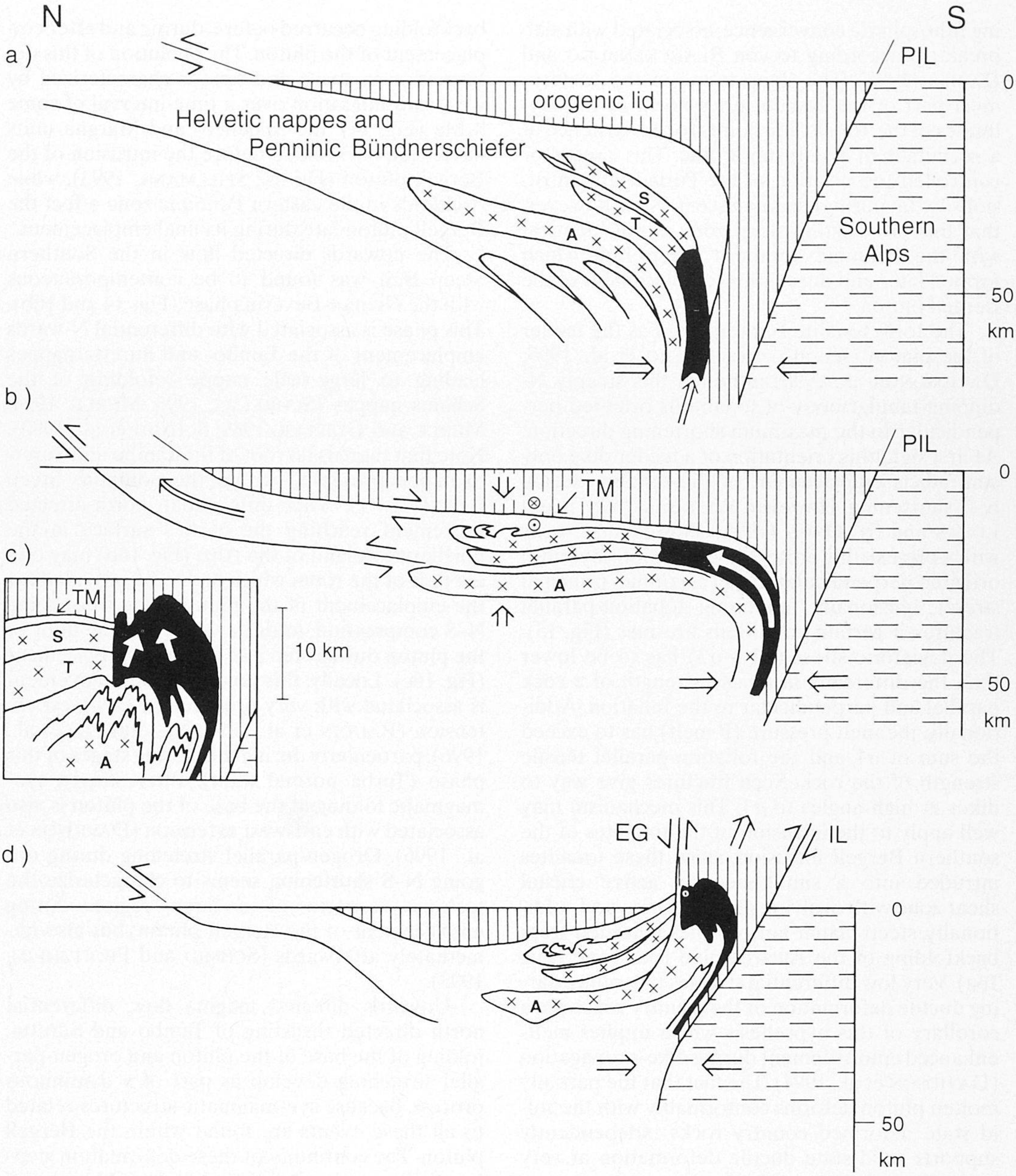

Fig. 16 Schematic profiles illustrating ascent, emplacement and exhumation of the Bergell pluton (after SCHMID et al., 1996b and DAVIDSON et al., 1996). (a) Ascent into a pre-existing steep zone north of a precursor of the Insubric line (PIL) at around 35 Ma. (b) Situation and the end of stage 1 of the final emplacement (see Fig. 14), i.e. at around 32 Ma. Stage 1 is characterized by the differential northwards emplacement of the Tambo and Suretta nappes, in combination with top to the east normal faulting along the Turba mylonite zone (TM). (c) Inset (note different scale) illustrating the effects of stage 2 of the final emplacement, terminating at around 30 Ma (see Fig. 14). Stage 2 is associated with syn-magmatic shortening at the base of the intrusion which is contemporaneous with ballooning of the granodiorite near the roof of the intrusion (ROSENBERG et al., 1995). (d) Sketch of the situation in the Early Miocene (19 Ma). Exhumation due to differential uplift of the Bergell area between the Engadine-Gruf (EG) and Insubric (IL) lines led to a high relief and rapid erosion.

Intense deformation within the Iorio tonalite was shown to be associated with substantial flattening strains (Fig. 3). Hence, we propose that the southern Bergell area, including the roots of the Tambo and Suretta nappes, was vertically (and to some extent laterally) extruded before being simply "backthrusted" along the Insubric mylonitic belt. Although the existing data do not allow an exact quantification, the pure shear component of deformation associated with vertical extrusion recorded in the southern Bergell, may (in combination with E–W extension and erosion) be the cause of the very rapid exhumation of these rocks and the early redeposition of Bergell boulders in the Gonfolite Lombarda molasse (GIGER and HURFORD, 1989; GIGER, 1991). This vertical extrusion is associated with orogen-parallel extension north of the Bergell area (Turba normal fault) as well as within the pluton and normal faulting at its margins (Preda Rossa shear zone) during pluton emplacement. This supports very similar conclusions proposed by MERLE (1994) in regard to syn-convergence exhumation of the entire Central Alps (in particular the Lepontine dome).

POST-EMPLACEMENT EXHUMATION OF THE BERGELL AREA

While much of the relative vertical movement of the Bergell pluton in respect to its country rocks and part of its exhumation is associated with final emplacement, particularly at the eastern margin of the pluton (Preda Rossa shear zone), pluton and country rocks together have been differentially exhumed due to movements along important fault zones north and south of the pluton after final emplacment (Fig. 16d), leading to an overthickened relief and rapid cooling and erosion.

Together with the underlying originally deep-seated Adula-Gruf unit the Bergell pluton was differentially uplifted along a vertical ductile fault (Gruf fault) situated between the Chiavenna ophiolite and the Adula-Gruf unit (Fig. 5). This fault zone is still poorly investigated from a structural point of view. However, it is clear that faulting is associated with a very substantial metamorphic field gradient across the Chiavenna ophiolite complex (SCHMUTZ, 1976; TROMMSDORFF, 1980), which is similar to a contact metamorphic aureole. The existence of this steep gradient implies that the Gruf complex probably was still partially molten during its differential uplift. Therefore, this displacement is likely to predate 25 Ma. Displacements along the SW–NE trending Engadine line also result in substantial differential uplift of the Bergell pluton in respect to the country rocks, due to block rotation under brittle conditions prevailing at higher structural levels and post-dates the granodiorite intrusion (SCHMID and FROITZHEIM, 1993). Since it is highly probable that both lines are kinematically linked, this differential uplift has to post-date solidifation of the granodiorite also along the Gruf fault.

Backthrusting and dextral strike slip along the western Tonale line south of the pluton are contemporaneous with the Gruf fault and the Engadine line. The amount of relative movement across the Tonale line decreases from west to east as inferred from the orientation of the lineations in this mylonite belt (SCHMID, 1987 and 1989). Hornblende barometry (REUSSER, 1987; DAVIDSON et al., 1996) quantifies this variation by revealing pressure differences corresponding to eastward tilting of the entire pluton by some 7°, as inferred from an east-west profile through the tonalite close to the Insubric line (ROSENBERG, 1996). Note however, that substantial tilting had to occur already during the vertical extrusion stage, hence the 7° represent a minimum estimate of total tilting. Over a distance of some 50 km, measured between the western end of the Iorio tonalite and the eastern margin of the intrusion, this minimum angle leads to an excess uplift of the westernmost Bergell pluton by at least 6 km in respect to its eastern end related to backthrusting.

As pointed out by SCHMID and FROITZHEIM (1993), the combined activity of dextral shearing along the Tonale line and sinistral shearing, associated with block rotation along the Engadine line, leads to relative uplift and eastward escape of the entire area between the two fault zones as a result of ongoing N–S shortening. This late-stage scenario is very similar to that invoked earlier for the Niemet-Beverin phase associated with the emplacement of the Bergell pluton.

GENERAL CONCLUSIONS REGARDING PLUTON EMPLACEMENT IN COMPRESSIONAL REGIMES

While HOLLISTER and CRAWFORD (1986) provided evidence for pluton emplacement in compressional regimes some time ago, this hypothesis has met with considerable scepticism due to the widely held belief that pluton emplacement is restricted to extensional or strike slip scenarios. The following main conclusions emerging from this study and related work on the Bergell intrusion (ROSENBERG et al., 1995; BERGER and GIERÉ 1995; DAVIDSON et al., 1996) may be of general interest:

1. Deformation of the partially molten Bergell pluton at great crustal depth (20–30 km) during final emplacement is an integral part of regional deformation, affecting the country rocks at the same time. North-directed escape of surrounding units (Tambo and Suretta nappes) elegantly solves the room problem inherent to pluton emplacement at this great depth.

2. At higher structural levels, near the orogenic lid, pluton emplacement associated with ballooning may appear unrelated to regional deformation, although ballooning may be driven by ongoing shortening at deeper levels, reaching the earth's surface a long way from the site of the intrusion (in the northern foreland in case of the Alps) rather than by diapirism related to buoyancy.

3. Ascent and emplacement of plutons along compressional or transpressive crustal megashears oriented at a high angle to the maximum compressive stress is feasable if the existence of a pre-existing anisotropy (foliation) is taken into account. Mechanical considerations regarding magma ascent and concordance of deformation within and outside the pluton point to very low differential stresses prevailing during ductile solid-state flow in the country rocks at deep crustal levels characterized by an elevated geotherm.

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