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Structural observations at the eastern contact of the Bergell Pluton

by *Alfons Berger*[1] and *Reto Gieré*[2]

Abstract

Macro-, meso- and microstructures indicative of syn-intrusive deformation are very prominent at the eastern contact of the Bergell pluton (between Val Forno and Valle Sissone). This deformation is documented, for example, by boudinaged intrusive sills and folded dikes. On a larger scale, the syn-intrusive deformation produced foliations that are concordant with the general trend of the contact between pluton and country rocks. Mafic, microgranitoid enclaves in both tonalite and granodiorite reveal a strain concentration towards the contact of the pluton. In all cases these enclaves point to a flattening type of strain.

Deformation related to the emplacement of the Bergell pluton is further indicated by microstructures exhibited by contact metamorphic minerals. In some cases, the textural relationships suggest that the contact metamorphism can be subdivided into two stages, an older static event followed by a younger kinematic stage.

In order to link these observations with the western part of the Bergell, we constructed a NE–SW profile through the entire pluton. This profile confirms that, due to regional tilting of the Central Alps and block rotation along the Engadine line, a significantly higher crustal level is exposed in the east relative to that exposed in the west. Furthermore, the construction suggests that the outcrops in Val Forno represent upper levels of the side rather than the roof of the pluton.

Keywords: contact metamorphism, deformation, strain distribution, magmatic enclaves, Bergell/Bregaglia pluton, Central Alps.

1. Introduction

The history of the Bergell pluton and the surrounding rocks has been a controversial issue for at least one hundred years. During this period, various mechanisms have been proposed in order to interpret all field and laboratory observations in terms of the timing between intrusion and deformation. Suggested mechanisms include post-tectonic intrusion (e.g., STAUB, 1918), in-situ granitization (DRESCHER-KADEN and STORZ, 1926), syn-tectonic intrusion (i.e., a nappe-like structure; WENK, 1973), and ballooning (CONFORTO-GALLI et al., 1988). TROMMSDORFF and NIEVERGELT (1983) give a thorough review of the historical evolution of ideas concerning the origin of the Bergell Alps, and summarize many of the important field relationships. Moreover, they emphasize the strikingly different appearance of the western and eastern parts of the pluton.

Recent studies of DAVIDSON and ROSENBERG (in press) show that along its western contact, the Bergell pluton exhibits characteristics of syn-magmatic deformation and records a common history for the two main rock types, i.e., tonalite ("serizzo") and granodiorite ("ghiandone"). In order to compare these results with the structural elements exposed in the eastern parts of the Bergell, we studied the deformation along the eastern contact of the pluton.

2. Geological setting

The Bergell calc-alkaline intrusion represents one of a few major igneous complexes of Tertiary

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age in the Alps. It is composed of four distinct rock types: 1) several small bodies of hornblendites and hornblende gabbros occurring at the margin of the intrusion, 2) a 32 Ma old hornblende-bearing tonalite in the south, southwest and southeast, 3) a 30 Ma old granodiorite with characteristic K-feldspar phenocrysts in the center of the intrusion, and 4) several types of granitic pegmatite to aplite stocks and dikes (for comprehensive descriptions, see e.g., GYR, 1967; TROMMSDORFF and NIEVERGELT, 1983; REUSSER, 1987; DIETHELM, 1989; BLANCKENBURG, 1992). The pressure conditions at the time of intrusion of the tonalite were estimated at 5 ± 1.5 kbars in the east, and 8.4 ± 0.2 kbars in the west (hornblende equilibration with the tonalite solidus; REUSSER, 1987; DAVIDSON and ROSENBERG, in press). Two major tectonic units are found in contact with the Bergell pluton at its eastern margin, namely the middle Penninic Suretta nappe, and the upper Penninic Monte del Forno unit (Fig. 1; see also TROMMSDORFF and NIEVERGELT, 1983).

The Suretta nappe comprises different basement rocks (granitic porphyries, metapelites, amphibolites, various schists and gneisses) and a Mesozoic sedimentary cover which, from bottom to top, consists of quartzites, metacarbonate rocks, calcareous schists, and calc-schists (Averser Schiefer; e.g., PFIFFNER et al., 1990; LINIGER, 1992). In the Northern part of the studied area, the Suretta nappe occurs in the form of isolated xenoliths of various sizes (10 cm to 100 m) embedded within the margin of the pluton, whereas to the South, this nappe can be continuously traced along and parallel to the intrusive contact (from Monte Disgrazia to Valle di Preda Rossa, see Fig. 1 and Plate 1).

In the basement of the Suretta nappe one can distinguish between porphyritic granitoids of Permian age and units that underwent Variscan metamorphism. The southern part of the Suretta basement consists mainly of gneisses and amphibolites, which were subjected to a pre-Alpine amphibolite facies metamorphism and a later Alpine regional metamorphism in greenschist facies (cf. WENK et al., 1974; GIERÉ, 1985; PFIFFNER and WEISS, 1994). The Mesozoic cover underwent Alpine regional metamorphism at approximately 35–40 Ma, as documented outside the Bergell contact aureole (HURFORD et al., 1989); close to the Bergell pluton, the rocks were subsequently overprinted by contact metamorphism. Along the eastern contact of the Bergell pluton, cover rocks, predominantly marbles, are much more abundant than basement rocks (Plate 1). The presence of characteristic layers at the base of the Mesozoic cover allows to correlate the regional metamorphic Suretta sediments north of Val Bregaglia with the metasedimentary rocks occurring within the Bergell contact aureole (from Val Forno to Valle di Preda Rossa, see Plate 1; GIERÉ, 1985).

The Monte del Forno unit is an ophiolite sequence which consists of amphibolites (former pillow lavas, pillow breccias, and basalts) and various metasedimentary rocks comprising quartzites (interpreted as metamorphosed radiolarian cherts), metaarkoses, metapelites, and metacarbonates with associated concentrations and deposits of Mn and Fe–Cu–Zn (cf. MONTRASIO, 1973; FERRARIO and MONTRASIO, 1976; PERETTI, 1985). This unit strikes parallel to the northeastern contact of the Bergell pluton, and is cut off to the north by the Engadine line. The metasedimentary units are abundant in the north, but disappear towards the south, where the Monte del Forno unit is represented almost exclusively by amphibolites. Further south, ultramafic rocks of the Malenco unit predominate (Plate 1). Two folding phases have been recognized in the Monte del Forno unit (PERETTI, 1985): the first is documented by isoclinal folds (F1) with an intense axial plane cleavage, which represents the main foliation in these rocks. This deformation took place under upper greenschist facies conditions, and is probably related to the westward thrusting and nappe stacking during the upper Cretaceous (LINIGER and GUNTLI, 1988; SPILLMANN, 1993). Relics of this metamorphism are found, for example, as actinolitic cores of amphiboles that were overprinted by the later contact metamorphism induced by the intrusion of the Bergell; the contact metamorphic overprint is represented by pargasitic rims around the actinolitic cores (GAUTSCHI, 1980). The second deformation phase, described in the area North of Passo del Muretto only, is characterized by open and irregularly shaped folds (F2 generation of PERETTI, 1985).

In his excellent summary of the deformation history of this area, SPILLMANN (1993) distinguished five deformation phases in the Malenco unit and the Margna nappe: phases D1 to D4 are of pre-Bergell age and are documented in a large area of the western Austroalpine units. Deformation phase D5, on the other hand, is restricted to the Bergell area, and is characterized by folds with NNW–SSE trending axial planes. The most prominent structure is the Muretto monocline, which can be described as an asymmetric synform (also called Chiesa synform).

The northeastern part of the Bergell pluton is surrounded by two cataclastic fault zones, i.e., by the Engadine line in the north (SCHMID and

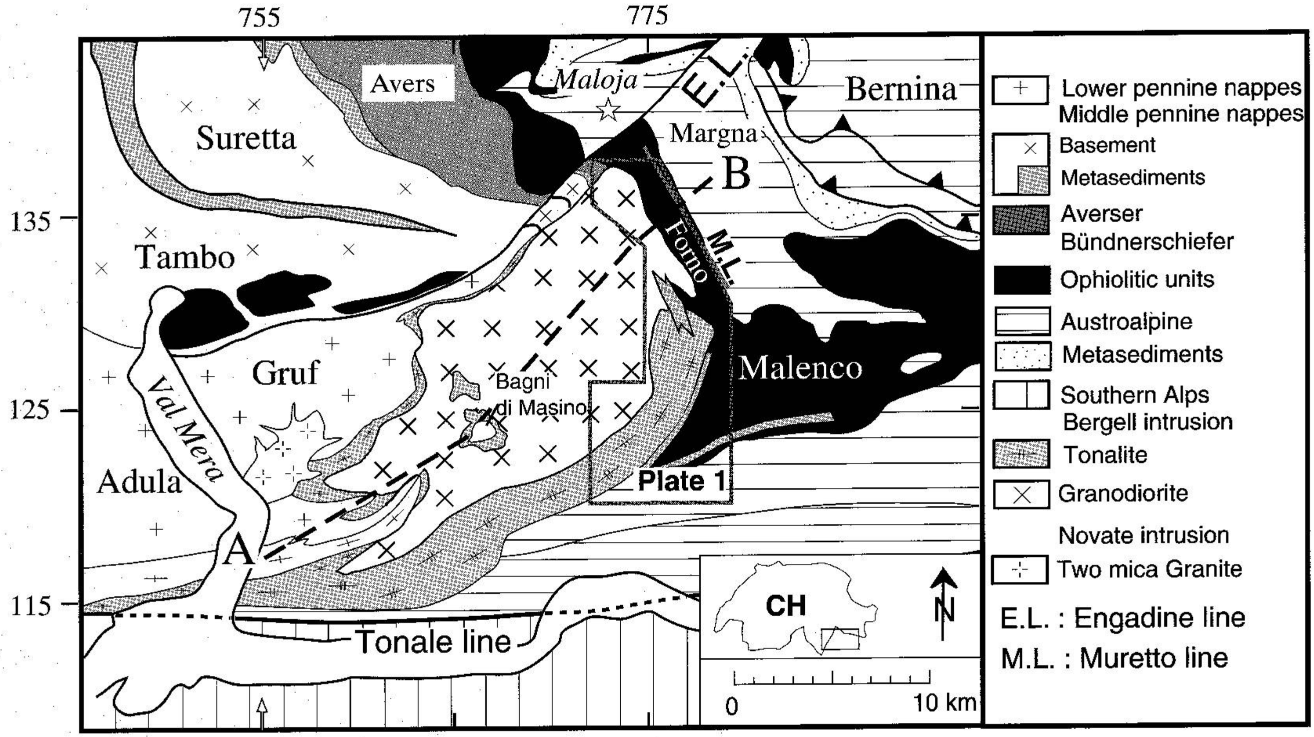

Fig. 1 Tectonic map of the Bergell pluton and the surrounding units. Area shown in plate 1 is outlined.

FROITZHEIM, 1993) and by the Muretto line in the east (SPILLMANN, 1993; RING, 1994; see Fig. 1). The Muretto line is very distinct, both morphologically and mineralogically (calcite, dolomite, various iron oxides and sulfides; PERETTI, 1985), and is accompanied by numerous smaller parasitic faults. The latter displace and deform the amphibolites and metasedimentary rocks of the Monte del Forno unit, but also the Bergell intrusive rocks. Therefore, the development of the Muretto line is, without doubt, a post-Bergell event. SPILLMANN (1993) suggested that the Muretto line produced offsets of approximately 200 m at Passo del Muretto, and 600 m near Alpe Vazzeda (Plate 1). The Engadine line overprints contact metamorphic rocks and thus is also of post-Bergell age (SCHMID and FROITZHEIM, 1993).

3. Structural geology along the eastern margin

In the studied area, two different types of planar fabrics can be distinguished within the Bergell pluton: (1) a foliation developed during magmatic flow, and (2) a foliation resulting from solid-state deformation.

Magmatic flow can be recognized as a shape preferred orientation of crystals whereby the individual grains show no internal plastic deformation (PATERSON et al., 1989). In our field area, magmatic flow produced at various localities a compositional layering and a shape preferred orientation of elongate minerals. The layering is documented in the granodiorite by bands of accumulated K-feldspar megacrysts, which often show a preferred orientation parallel to the layering. These layers, usually with thicknesses in the order of several centimeters, stand out by their light color from the darker, biotite-rich layers with only few K-feldspar phenocrysts; in some cases a gradual change in the amount of megacrysts has been observed (Fig. 2).

Fig. 2 Boudinaged granodiorite sill (south of Monte Rosso). Note the magmatic layering of the K-feldspars. Knife is 10 cm long.

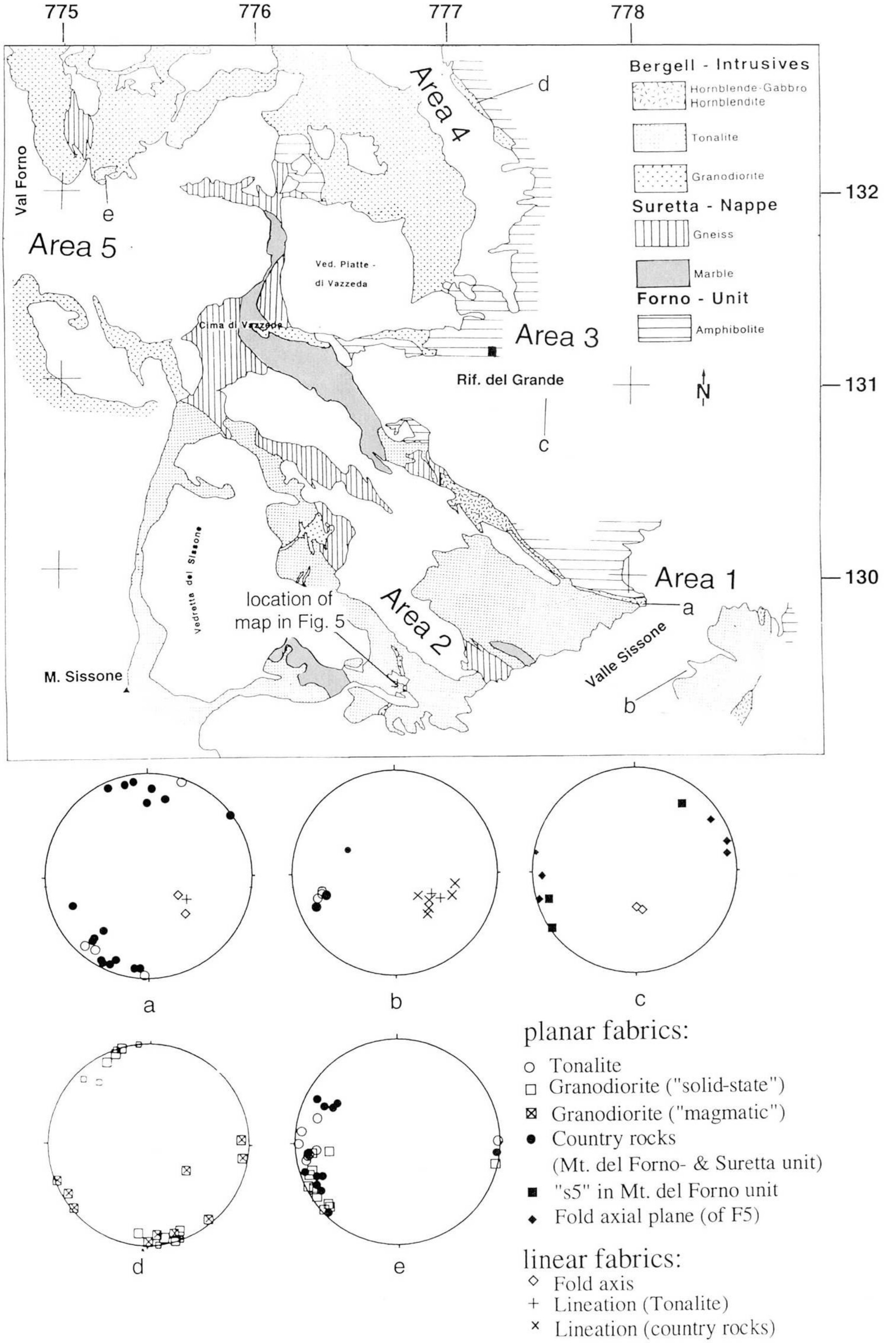

Fig. 3 Structural elements from different localities in the northeastern part of the Bergell pluton. The numbered areas are referred to in the text. Stereograms are lower hemisphere, equal area projections.

Evidence for solid-state deformation can also be gathered in the field: it is provided by small tails around K-feldspar megacrysts in the granodiorite, and by lenticular hornblende crystals in the tonalite. In thin section, solid-state deformation is indicated by recrystallized grains of feldspars and quartz.

In order to establish the relationship between the emplacement of the Bergell pluton and the deformation in the country rocks, we analyzed areas where country rocks and intrusives are spatially closely associated. Best suited were outcrops where magmatic rocks and country rocks occur in alternating layers. We also investigated the orientation of contact metamorphic minerals in relation to the deformation of their host rocks. Other indications of the relationship between intrusion and deformation are given by thin intrusive dikes which are folded and exhibit axial planes parallel to the foliation in the country rock.

3.1. NORTHERN END OF THE TONALITE IN VALLE SISSONE

The tonalite body ends in the lower Valle Sissone (cf. Plate 1). In this area (Area 1 in Fig. 3), a special situation is encountered, because the contact between tonalite and country rocks strikes approximately E–W, i.e. perpendicular to the general trend in the studied area (Plate 1, and Figs 3, 4).

This E-W orientation of the contact is accompanied by a zone of approximately E–W-striking foliations (Fig. 4a). In the Monte del Forno unit, these foliations can be observed only locally and are restricted to within 1–2 meters from the contact. The tonalite exhibits a fabric that results from both intense solid-state and magmatic deformation; this fabric is parallel to the contact as well as to the foliation in the Forno amphibolites within the contact zone (Fig. 3, stereogram a). Moreover, the axial planes of folded aplitic dikes within the tonalite are strictly parallel to the foliations in this area. Further away from the contact, the foliation in the tonalite changes from its E–W orientation into a SE–NW direction (Area 2) and, towards the interior parts of the tonalite, into a SSE–NNW direction (see Figs 3, 4a, and below).

The contact is additionally complicated, because it is associated with bulky hornblendites which show no internal fabric (Fig. 3). North of the hornblendites, however, some intrusive contacts between amphibolites and tonalite are preserved. Several tonalite dikes and sills, usually a few centimeters thick, occur in the amphibolites and thus demonstrate that the tonalite intruded directly into the Monte del Forno unit. These sills and dikes are often folded or boudinaged, and therefore provide evidence for simultaneous deformation of tonalite and amphibolites.

Foliations parallel to the contact are also observed along the contact exposed on the eastern side of Valle Sissone. In this area, however, the foliations dip steeply to the east, and a constant SE-dipping lineation is additionally prominent both in the tonalite and in the country rocks (Fig. 3, stereogram b). The structural elements found in the eastern part of Valle Sissone can be traced into Valle di Preda Rossa (cf. Fig. 4b). In Valle di Preda Rossa and further to the west, a shear zone has been detected along the contact of the pluton (BERGER and GIERÉ, 1993). This shear zone was active during the emplacement of the tonalite, and led to the uplift of the tonalite relative to the country rocks (BERGER, 1995). North of Valle Sissone, however, there is no evidence for the existence of such a shear zone along the contact between intrusives and country rocks; moreover, such a shear zone has not been detected within the country rocks either. In the area north of Valle Sissone, the contact is characterized by features indicative of ballooning rather than shearing (see below). These observations suggest that the shear zone, so prominent in Valle di Preda Rossa, is ending somewhere in Valle Sissone (see Fig. 4b).

3.2. STRUCTURES INSIDE THE TONALITE AND THEIR RELATIONSHIPS TO GRANODIORITE DIKES

In the interior parts of the tonalite, the foliations generally exhibit a SSE–NNW orientation (Area 2 in Fig. 3). The foliation in the tonalite can be traced continuously from the upper Valle Sissone to the Monte del Forno (Fig. 4a). Between Rifugio del Grande and Monte del Forno, the foliation strikes parallel to the intrusive contact. In the Suretta nappe, the layering within the marbles, probably a sedimentary bedding, as well as the foliations observed in the gneisses follow the same trend. Moreover, this trend is also exhibited by the orientation of the long axis of numerous xenoliths in the tonalite. In the upper Valle Sissone, some Suretta marbles are folded together with the tonalite (Fig. 5, lower left). The foliation found in the enclosing intrusive rocks is concordant with that in the xenoliths, and is also parallel to the axial planes of the folded contact (Fig. 5, lower left).

Within the Suretta gneisses, boudinaged tonalite sills can be recognized (BUCHER-

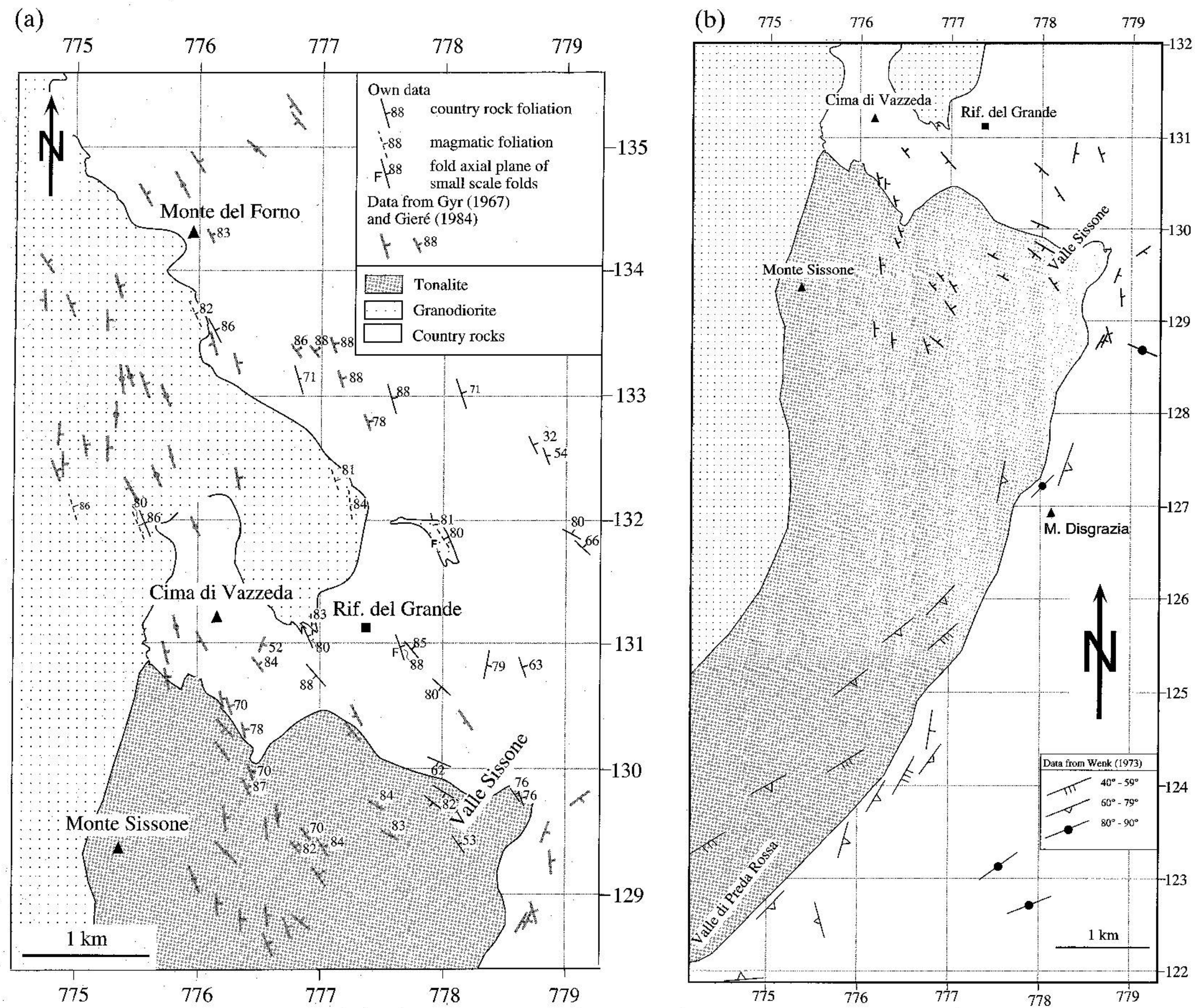

Fig. 4 a) Map of foliations between Valle Sissone and Monte del Forno. The map includes our own measurements as well as data compiled from the literature. Note the trend parallel to the contact between pluton and country rocks.
b) Map of foliations between Valle Sissone and Valle di Preda Rossa. The foliations in Valle Sissone are drawn from figure 4a, and the foliations in the southern part are redrawn from WENK (1973). Note the continuity along the contact from Valle di Preda Rossa to Valle Sissone.

NURMINEN, 1977; GIERÉ, 1984). This indicates that the solidification of the tonalite predates this deformation (gneisses are less competent). In the eastern part of Valle Sissone, however, boudins of gneiss within the tonalite can also be found: in these cases, the tonalite flows into the boudin necks, where no macroscopic fabric is observed. Similarly, some larger xenoliths of country rocks have the shape of boudins. These last examples imply that gneisses and other country rocks are more competent than tonalite, suggesting that the tonalite was partially molten at the time of deformation. These apparently contradictory observations on boudinage indicate that deformation started during the magmatic stage and continued under solid-state conditions in the intrusives.

3.3. AREA AROUND RIFUGIO DEL GRANDE

The deformation of the Monte del Forno amphibolites in the area around Rifugio del Grande (Area 3 in Fig. 3) is characterized by two folding phases. The first phase is documented by a folded s_0 which probably represents a primary layering within the amphibolites. The layers in the amphibolites now consist mainly of epidote, and are boudinaged at several localities. The folding of s_0 is related to the main foliation (s_1), and it can be

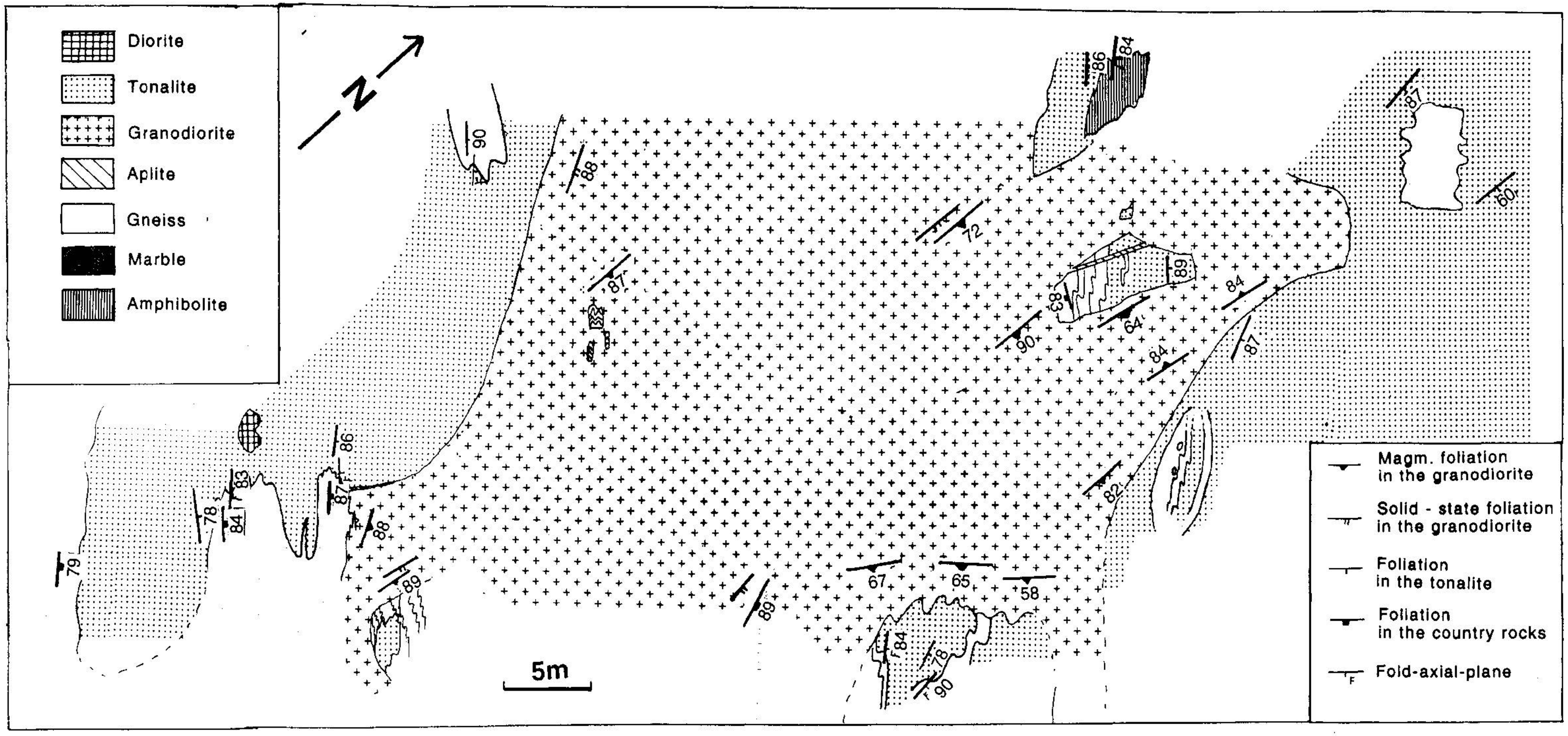

Fig. 5 Detailed map of a granodiorite dike in upper Valle Sissone. Locality of the outcrop is marked in figure 3.

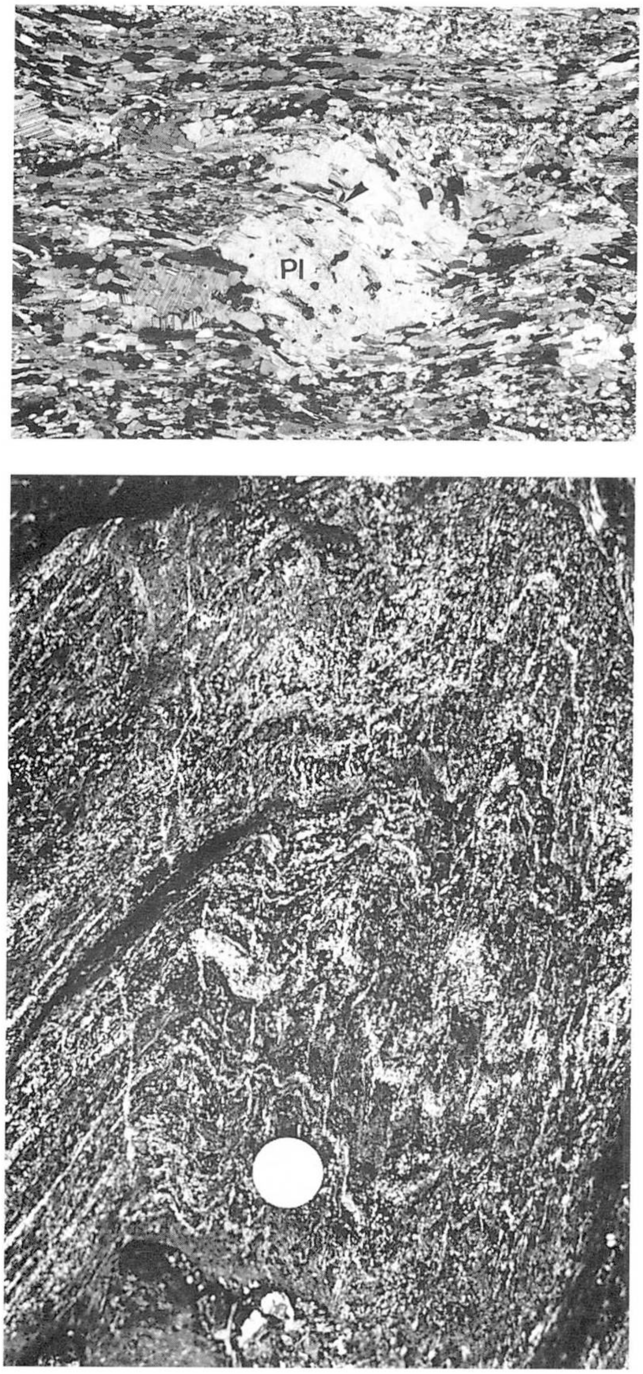

Fig. 6 a: Rotated plagioclase blast (Pl) in the Monte del Forno unit near Rifugio del Grande. The matrix consists of plagioclase and pargasitic hornblende. Arrows point to amphibole inclusions. Long side of the photograph is parallel to s_5, and it is 5.2 mm long. Plane polarized light.
b: Field photograph showing the relationship between s_1 and s_5, whereby s_5 is the axial plane foliation of the folded s_1 foliation. Near Rifugio del Grande.

correlated to F1 of PERETTI (1985), the main deformation phase in this area (probably upper Cretaceous in age; SPILLMANN, 1993). The s_1 foliation is folded or crenulated during a second deformation event, and a new foliation may be observed locally. After the formation of s_1, growth of porphyroblastic plagioclase occurred; these neoblasts were sometimes rotated (see Fig. 6a) during the development of the new foliation. The plagioclase porphyroblasts have an anorthite content of approximately An_{30} (GYR, 1967) and, because they contain inclusions of pargasite, probably grew under amphibolite facies conditions. In the Monte del Forno unit, the peak regional metamorphic conditions, attained during the upper Cretaceous metamorphism, are upper greenschist facies, whereas amphibolite facies conditions are restricted to areas within the Bergell contact aureole. These observations suggest that the plagioclase porhyroblasts are of contact metamorphic origin. This conclusion, in turn, implies that the rotation of these plagioclase crystals as well as the development of the new foliation are related to a syn-intrusive deformation at the Bergell contact.

A similar deformation event is described by SPILLMANN (1993): he observed that one deformation phase, D5, is only documented close to the contact with the Bergell, and therefore, he interpreted it as a syn-intrusive deformation. By analogy, we infer that the observed second foliation developed during D5, even though we did not recognize the other deformation phases (D2 through D4 of SPILLMANN, 1993) in our study area. Hence, we refer to this younger foliation as "s_5" in the following discussion. This s_5 foliation is mainly found around Rifugio del Grande, where it commonly intersects s_1 at a high angle. In this area, small-scale folds of the old s_1 foliation are often related to the development of s_5 (Fig. 6b), as indicated by the axial plane of these folds which represent the s_5 foliation.

Further to the north, however, the angle between s_1 and s_5 decreases, until s_1 and s_5 cannot be distinguished anymore. Here, the old s_1 foliation is parallel to the axial plane of folded intrusive rocks, and therefore, the foliation must have been reactivated by the deformation related to the intrusion of the Bergell. From these observations we infer that the main foliation here represents a composite one, i.e. produced during D1 and D5.

The reasons for the very localized development of a distinct s_5 and for the folding during D5 may be sought in the peculiar geometry of the intrusive contacts in the area around Rifugio del Grande. A distinct new foliation (s_5) may have developed due to the primary orientation of s_1 in the amphibolites. It appears that in this area s_1 was at a small angle to the shortening direction during D5.

In a small granodiorite stock to the east of Rifugio del Grande, the relationship between granodiorite deformation and development of s_5 can be studied very well. In this outcrop (Fig. 7), the lithological boundary between amphibolite and granodiorite displays cuspate-lobate structures. Where s_1 is parallel to the shortening direction during D5, the s_1 foliation is folded and a new foliation, s_5, is found as the axial plane to these folds. These axial planes are particularly well visible (Fig. 6b) because they consist mainly of plagioclase. The folds, which deform s_1, are very tight directly at the contact to the granodiorite, but become open folds further away from the contact. In the limbs of the s_5 folds, where s_1 is perpendicular to the shortening direction, neither folds nor a distinct s_5 foliation can be observed. Hence, shortening during the folding event must have reactivated s_1, in accordance with the interpretation given above.

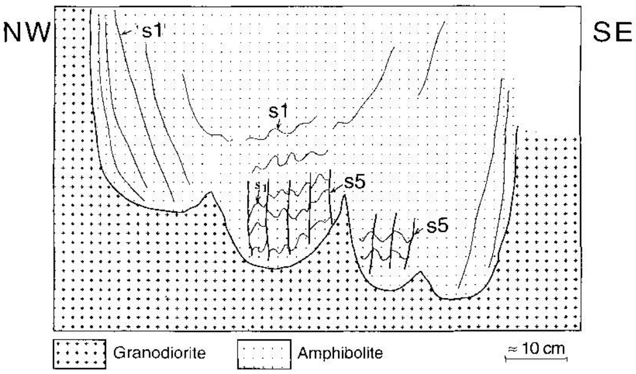

Fig. 7 Line drawing of an outcrop east of Rifugio del Grande, where s_1 and s_5 can be distinguished. See text for further explanation.

3.4. AREA TO THE NORTH OF RIFUGIO DEL GRANDE

In general, the foliations in both the intrusives and the Monte del Forno amphibolites strike SSE–NNW in the area below Vedretta Piatte di Vazzeda (Area 4 in Fig. 3; see also Fig. 4a). The foliation in the granodiorite displays some variation in its orientation; this variation, however, is restricted to the magmatic foliation (Fig. 3, stereogram d), and is mainly observed around xenoliths, which represent local inhomogeneities and thus probably caused the scattering. Small granodiorite dikes in the country rocks possess an internal magmatic layering, which has an orientation that is parallel to the dike contacts but different from the general SSE–NNW trend. Granodioritic and dioritic dikes are also occasionally folded. When only a few centimeters wide, the granodiorite dikes exhibit folds with amplitudes of approximately 10 cm, whereas wider dikes commonly display cuspate-lobate structures at the dike margin. The granodiorite always represents the competent layer during this folding, thus indicating that the dikes were solid during deformation. In all cases, we observed that the main foliation in the country rocks (s_1) is parallel to the axial plane of these folds. The shortening in the amphibolites, therefore, had to be accommodated by the already existing foliation (s_1). This interpretation, however, is difficult to prove because the good alignment of the contact metamorphic pargasitic hornblendes in the amphibolites can be explained in two different ways: the growth of pargasitic hornblende could represent a topotactic replacement of older amphiboles, which were already aligned during an older deformation (D1), or alternatively, both growth and alignment of the pargasitic hornblendes could have occurred during the contact metamorphism and related deformation (cf. chapter 5). The field observations imply that the folds involving intrusive rocks must be either syn- or post-intrusive; therefore, they can be correlated to the same tectonic event that leads to the development of s_5 in the Monte del Forno amphibolites further south (see above).

3.5. VAL FORNO

The contact between intrusion and country rocks is very irregular in the lower Val Forno (Plate 1). On the one hand, many large xenoliths are found within the granodiorite, and on the other hand, a network of granodiorite dikes is present in the country rocks. The contact thus is better described in terms of a wide boundary zone. In this boundary zone, a foliation can be observed both in the granodiorite (slight alignment of K-feldspar phenocrysts) and in the country rocks. The relationship between the foliation measured within the xenoliths of the Suretta nappe and the granodiorite is shown in figure 3 (stereogram e; measurements from the uppermost Val Forno, area 5 in Fig. 3). The foliations are parallel in both rock types in this area as well.

Granodiorite dikes that are oriented parallel to the foliation in the country rock are boudinaged (GIERÉ, 1984). Boudinage has been observed on a scale ranging from a few centimeters to tens of meters. The boudinage of granodiorite implies that the intrusives were solid during deformation, but the lenticular shape of the boudins (Fig. 2) points to a low viscosity contrast between intrusives and country rocks. Like in area 4 (Fig. 3), the granodiorite dikes with orientations perpendicular to the main foliation have been folded in the Val Forno, and the main foliation in the country rock always represents the axial plane of these folds.

4. Aspect ratios of enclaves

In the studied area, aspect ratios of enclaves have been measured in order to obtain a relative criterion for estimating the intensity of deformation. No country rock xenoliths, but only mafic, microgranitoid enclaves have been used for these determinations. Wherever possible, the aspect ratios have been determined parallel to the main structural elements (foliations and lineations of the intrusive rocks). This was possible only in the tonalite exposed in lower Valle Sissone (Area 1 in Fig. 3). Where no lineation could be recognized, measurements were performed in a horizontal plane. In a few cases, we were able to estimate the three-dimensional strain ellipsoid from measurements on two perpendicular planes in a single outcrop. The Flinn diagram shown in figure 8 contains all available data regarding the three-dimensional strain; all points plot in the field of general flattening (ruled area). The data with the largest aspect ratios were obtained from the tonalite contacts in Valle Sissone (Area 1 in Fig. 3), whereas aspect ratios of approximately 1: 3.5 (in the horizontal plane) were observed in the internal parts of the tonalite. The regional distribution of the analyzed enclaves, displayed in figure 9, reveals a strain concentration towards the contact with the country rocks (cf. upper Val Forno and Valle Sissone). In the case of the upper Val Forno, the Cima di Vazzeda, a large "block" of country rock, acted as the local border of the intrusion. In Valle Sissone, the strain is concentrated directly at the contact, as shown by aspect ratios that range from 1 : 25 to 1 : 39. These values are in sharp contrast to those found inside the intrusion (approximately 1 : 4).

Strain inhomogeneities can also be caused by the presence of xenoliths. The size and the rock types (amphibolites, gneisses, marbles) of the xenoliths are important in determining the amount of strain inhomogeneity. The different rheological behavior of these rocks produces different structures within and around the xenoliths. Figure 10 shows an example of strain concentration around a gneiss xenolith occurring in the tonalite in upper Valle Sissone: the xenolith itself has been deformed into a lens-shaped body with its long axis parallel to the foliation of the tonalite. This particular shape can be attributed to conditions of boudinage with relatively low viscosity contrast between tonalite and gneiss. At the northern end of the xenolith, fish mouth-like structures are present. These relationships imply that the gneiss is more competent than tonalite, and thus, that the deformation occurred during the magmatic stage. The enclaves around the xenolith reflect a strain concentration at those sides of the xenolith that are parallel to its long axis.

The mentioned observations regarding the aspect ratios of enclaves suggest that two factors controlled the strain distribution in this part of the intrusion: 1) on a regional scale, the distance from the contact, and 2) on a smaller scale, the presence of local, isolated inhomogeneities such as xenoliths.

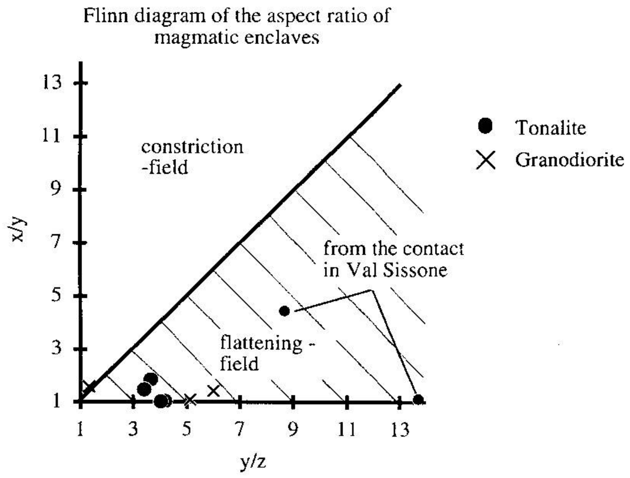

Fig. 8 Aspect ratio of enclaves displayed in a Flinn diagram. The measurements at the contact exposed in Valle Sissone are emphasized.

5. Relationship between contact metamorphism and deformation

All the units along the eastern margin of the Bergell were affected by contact metamorphism which overprinted an older regional metamorphism (e.g., TROMMSDORFF and EVANS, 1972, 1977; RIKLIN, 1978; TROMMSDORFF and NIEVERGELT, 1983; GIERÉ, 1984; DIETHELM, 1984). In the studied region, the contact aureole is approximately 1.5 km wide, and the highest metamorphic grade is recorded by the parageneses enstatite + forsterite in ultramafic rocks and corundum + K-feldspar in metapelites (TROMMSDORFF and NIEVERGELT, 1983).

In some places the mineral growth is typically post-kinematic, as documented, for example, by randomly oriented crystals overgrowing an older

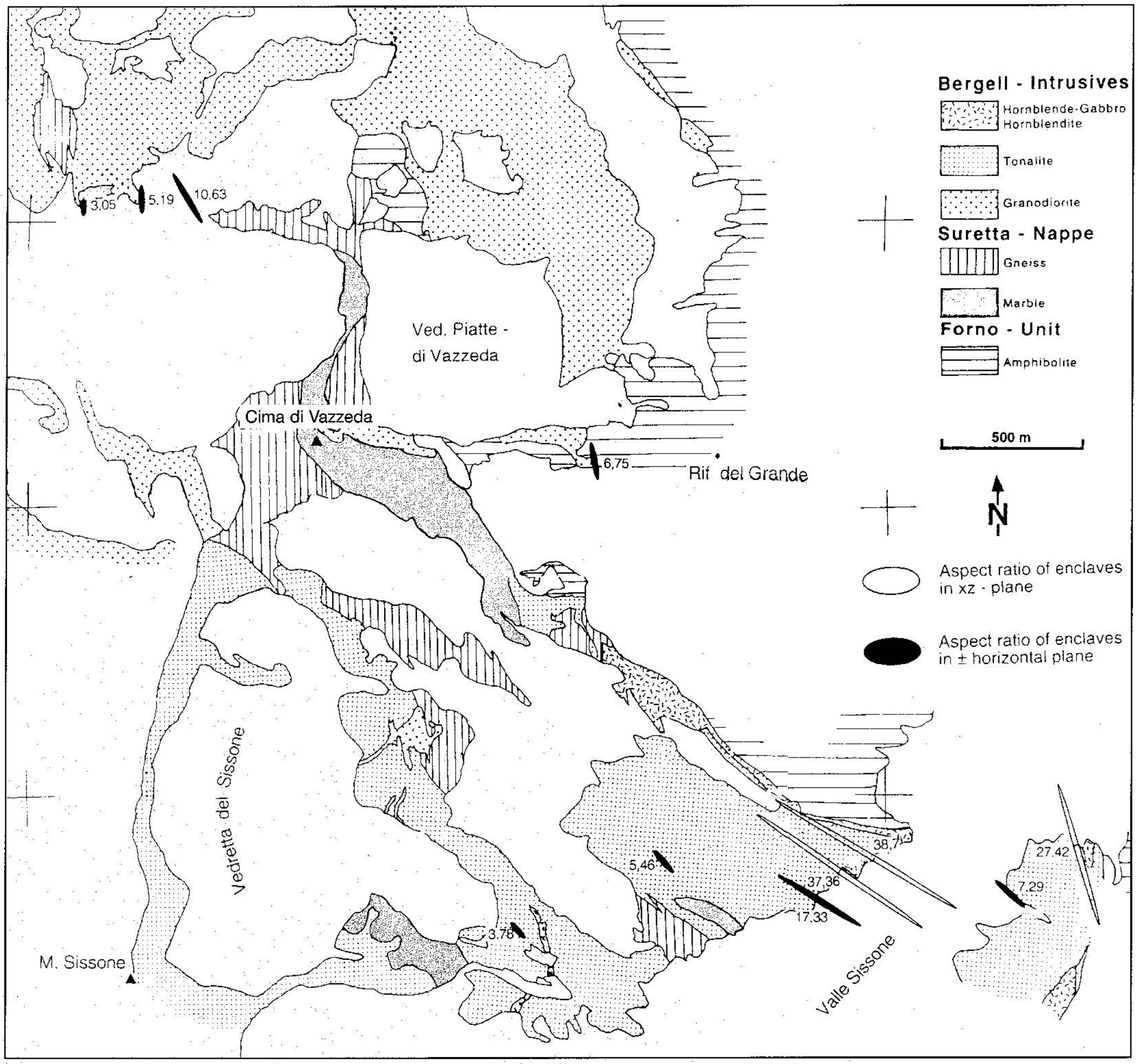

Fig. 9 Aspect ratio of enclaves in the investigated area. The ratios were measured in the xz plane (open symbols) or in a subhorizontal plane (full symbols). The numbers represent the actual value of the aspect ratios.

foliation in ultramafic rocks (e.g., olivine in Val Ventina) and in metapelites (e.g., andalusite at Lägh da Cavloc and Passo del Muretto). Similarly, pargasitic hornblendes of contact metamorphic origin are found to randomly grow over an older fabric in the Monte del Forno amphibolites (Fig. 11); this observation was made only locally in the lower Val Muretto. In almost all other parts of the Monte del Forno unit, however, the amphiboles exhibit a well developed preferred orientation. In the northeastern part of the amphibolites, old actinolitic cores are surrounded by a pargasitic rim (GAUTSCHI, 1980), whereas in the areas closer to the pluton, the amphiboles are almost entirely pargasitic in composition. It thus appears that the pargasite of contact metamorphic origin completely replaced the older amphiboles. This apparently topotactic replacement does not necessarily destroy an already existing fabric, and in such a case it becomes difficult to distinguish between pre- and syn-Bergell fabrics in the amphibolites (see above).

Similar complications are encountered in the basement of the Suretta nappe, because relics of a pre-Alpine amphibolite facies metamorphism may be preserved. In contrast to the basement gneisses, the Mesozoic sedimentary rocks provide a better opportunity to distinguish between contact and regional metamorphism, because they were subjected to only one regional meta-

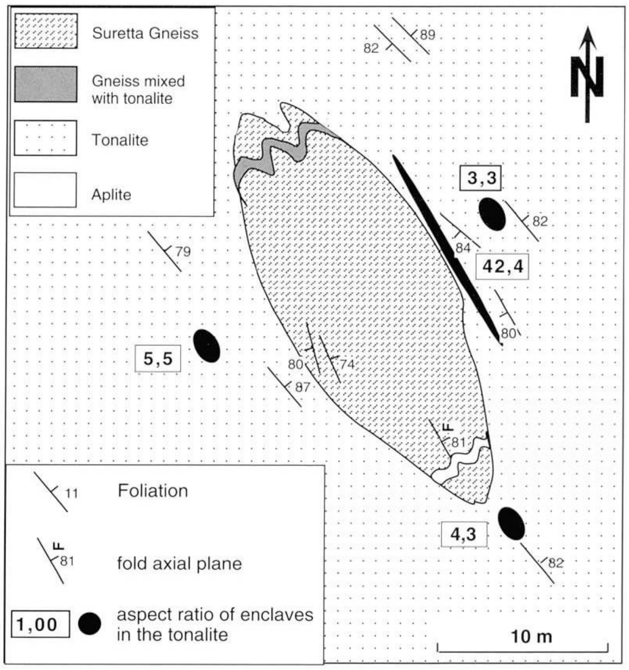

Fig. 10 Structural details around a xenolith of Suretta gneiss in the tonalite, upper Valle Sissone. Note the different aspect ratios of the enclaves.

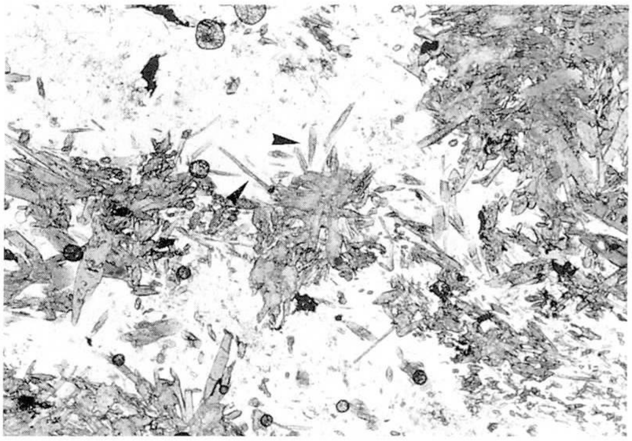

Fig. 11 Photomicrograph of amphiboles grown randomly over an old fabric. The long side of the photograph is parallel to the foliation, and it is 3.25 mm long. Plane polarized light.

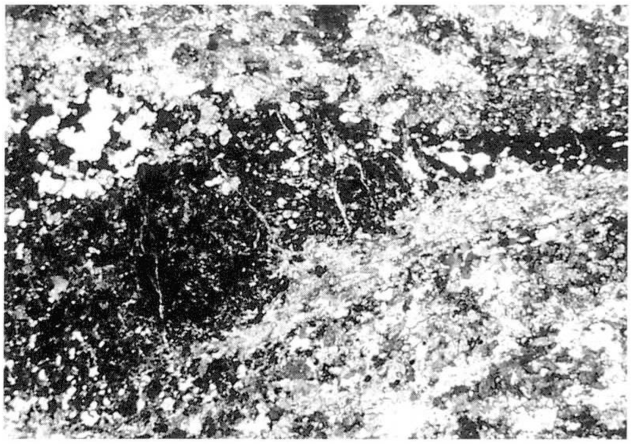

Fig. 12 Photomicrograph of a deformed andradite-rich grossular with a tail containing numerous small andradite-rich grossulars. Calc-silicate rocks of the Suretta nappe. Long side of photograph is 5.2 mm. Crossed polarizers.

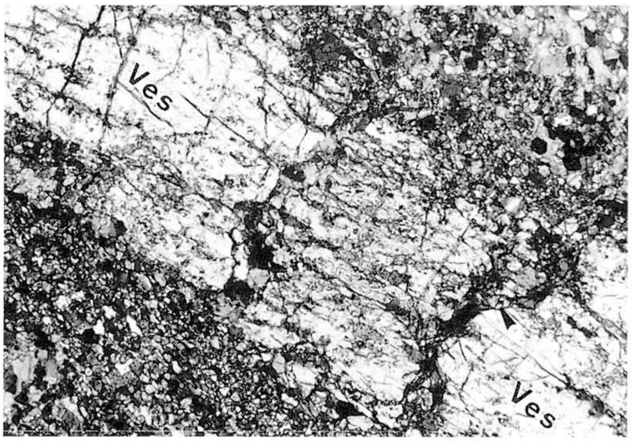

Fig. 13 Photomicrograph of fractured vesuvianite (Ves). Fractures contain diopside (indicated by the arrow). Long side of photograph is 5.2 mm. Crossed polarizers.

morphic event prior to the contact metamorphism. Therefore, we have investigated these rocks with particular emphasis on deducing the relationship between contact metamorphism and deformation.

In diopside-bearing calc-silicate rocks of the Suretta nappe asymmetric garnet tails occur around garnet porphyroblasts indicating that the tails grew during the deformation (Fig. 12). Both tails and porphyroblast have very similar compositions, containing 35–36 mol% andradite component (Tab. 1). Mineral assemblages containing andradite-rich garnet, diopside, quartz, and calcite are common at contacts of many plutons, and are typical for relatively high temperatures (e.g., TRACY and FROST, 1991). Moreover, garnet-diopside assemblages (analyses in Tab. 1) have not been documented in the regional metamorphic carbonate rocks of the Suretta nappe outside the Bergell contact aureole. These assemblages, therefore, are most likely of contact metamorphic origin. Furthermore, the andradite-rich tails indicate that the contact metamorphism was at a later stage associated with deformation, i.e. that it was not purely static.

In the upper Valle Sissone, vesuvianite-bearing calc-silicate rocks are quite common constituents of the Suretta metasediments. In these rocks two different fabrics can usually be distinguished: 1) an old layering which may represent the original sedimentary bedding and which is overgrown

Tab. 1 Electron microprobe analyses of contact metamorphic garnet and diopside occurring in calc-silicate rocks from upper Valle Sissone (sample 2A.153). *Abbreviations:* adr = andradite, alm = almandine, grs = grossularite, prp = pyrope, sps = spessartite. Analytical conditions: 15 kV, 20 nA, JEOL JXA-8600 (University of Basel).

	Garnet			**Diopside**	
wt%	Tail	Clast	Clast		
SiO_2	38.3	38.0	37.9	SiO_2	53.9
Al_2O_3	15.22	15.36	15.10	Al_2O_3	0.17
TiO_2	0.26	0.43	0.60	TiO_2	0.04
$FeO_{(calc)}$	0.8	0.0	0.0	$FeO_{(tot)}$	4.85
Fe_2O_3	11.7	11.0	11.1	Fe_2O_3	
MgO	0.07	0.1	0.1	MgO	14.25
MnO	1.01	0.82	0.62	MnO	1.27
CaO	33.5	34.3	35.8	CaO	24.6
Na_2O	0.01	0.02	0.02	Na_2O	0.08
Total	100.9	100.0	101.3	Total	99.2
	Numbers of cations based on:				
	24 O	24 O	24 O		6 O
Si	3.0588	3.0462	3.0157	Si	2.0091
Al	1.4325	1.4511	1.4160	Al	0.0075
Ti	0.0156	0.0259	0.0359	Ti	0.0011
Fe^{2+}	0.0555	0.0000	0.0000	Fe^{2+}	0.1512
Fe^{3+}	0.7031	0.6643	0.6660	Fe^{3+}	
Mg	0.0083	0.0120	0.0119	Mg	0.7919
Mn	0.0683	0.0557	0.0418	Mn	0.0401
Ca	2.8663	2.9457	3.0517	Ca	0.9824
Na	0.0015	0.0031	0.0031	Na	0.0058
x_{alm}	0.0185	0.0000	0.0000	x_{Fe}	0.1538
x_{prp}	0.0028	0.0040	0.0038	x_{Mg}	0.8055
x_{sps}	0.0228	0.0185	0.0134	x_{Mn}	0.0408
x_{grs}	0.9555	0.9765	0.9817		
x_{adr} 1)	0.3594	0.3451	0.3510		

1) $x_{adr} = (Fe^{3+} + Ti)/2.0$

by vesuvianite, and 2) folds that result from deformation of the old layering during contact metamorphism. Due to the folding event vesuvianite is commonly cracked, and the cracks are filled with diopside which is most likely also of contact metamorphic origin (Fig. 13). This observation again points to a two-stage contact metamorphic evolution[1].

This conclusion is further supported by a third type of microstructures observed in other calc-silicate rocks of the Suretta nappe: this rock type is characterized by a pronounced layering that consists of alternating bands of wollastonite + calcite and diopside + wollastonite + plagioclase + vesuvianite, respectively. The mineralogically different layers are folded, and the following textural relationships can be observed: the poikiloblastic vesuvianite crystals contain abundant inclusions of diopside, wollastonite, plagioclase and calcite, suggesting that vesuvianite formation may be descibed by the reaction

$$9 \text{ calcite} + 5 \text{ anorthite} + 3 \text{ diopside} + \\ 2 \text{ wollastonite} + 5\ H_2O = \text{vesuvianite} + 9\ CO_2.$$

According to this decarbonation reaction vesuvianite could be formed only after crystallization of wollastonite, a mineral that is undoubtedly of contact metamorphic origin. Wollastonite, however, also occurs outside the vesuvianite crystals where it commonly exhibits a preferred orientation. These wollastonite crystals are either aligned parallel to the axial plane of the folded layering or they are wrapped around vesuvianite. These microstructures clearly indicate that contact metamorphism was associated with deformation. The best examples for these very distinct rocks are found in upper Valle Sissone close to the contact with the tonalite (Area 2 in Fig. 3).

Another indication for deformation of contact metamorphic features is provided by RIED (1994) who described metasomatic veins which were formed by fluids derived from the intrusives and which were subsequently folded and boudinaged.

In summary, these observations allow to differentiate between a static and a kinematic contact metamorphism associated with the Bergell intrusion. The static contact metamorphism, as observed, for example, at Passo del Muretto and in the Malenco ultramafics, is characterized by random growth of new minerals over an older tectonic fabric. This feature is mainly found at greater distances from the contact. The static stage is in some cases clearly older than the kinematic stage, as indicated e.g. by the occurrence of diopside in fractures of vesuvianite. From these observations, we conclude that the kinematic contact metamorphism is directly related to the final emplacement of the Bergell pluton.

6. Relationship between tonalite and granodiorite

The temporal as well as the structural relationships between the two main lithologic units of the Bergell pluton are important for the discussion of the ascent and the emplacement history of the intrusion. The significant age difference (tonalite in

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[1] Similar observations are reported also for metapelitic rocks (cracked andalusite crystals of contact metamorphic origin; see PERETTI, 1983; KUBLI, 1983).

Valle Sissone: 31.88 ± 0.09 Ma; granodiorite east of Val Forno: 30.13 ± 0.17 Ma: see BLANCKENBURG, 1992) and the clear structural relationships at the eastern contact may be interpreted in terms of two magmatic events.

In the studied area at the eastern margin of the pluton, tonalite and granodiorite can easily be distinguished in the field. In the southern and southwestern parts of the intrusion, however, a transition zone, the so-called "Uebergangszone" (MOTICSKA, 1970; WENK and CORNELIUS, 1977; see also Plate 1) exists between these two rock types. This transition zone probably formed by both mingling and mixing processes: mingling processes could explain the macroscopic appearance of the zone, often characterized by alternating bands of tonalitic and granodioritic rocks. Mixing, on the other hand, is indicated by the chemical composition that is intermediate between those of the tonalite and the granodiorite (REUSSER, 1987). These observations in the south and southwest of the intrusion suggest that tonalite and granodiorite had, at least in this area, a common magmatic stage. In our study area, however, granodiorite dikes and stocks, are found to crosscut the tonalite in the upper Valle Sissone (DIETHELM, 1984; GIERÉ, 1984). Figure 5 displays a map of one of these outcrops (east of Vedretta del Sissone), and shows that Suretta marbles and gneisses have been deformed together with the tonalite (see Chapter 3.2.). The granodiorite, however, is clearly discordant to these structures, and exhibits a magmatic fabric which is parallel to its contact to tonalite and country rocks (see Fig. 5, lower right corner). Irregularly shaped xenoliths containing folded tonalite/gneiss contacts occur within this granodio-rite (Fig. 5, upper right); the intense deformation recorded in the xenoliths, however, cannot be observed in the granodiorite. A large tonalite enclave within granodiorite is also described in the upper Val Forno (Area 5 in Fig. 3; cf. GYR, 1967), and further demonstrates that in the eastern part of the pluton the intrusion of tonalite is undoubtedly older than that of granodiorite.

The distinctly different observations in the different parts of the Bergell pluton are only apparently contradictory (cf. TROMMSDORFF and NIEVERGELT, 1983). Mixing and mingling (within the Uebergangszone) is exclusively developed in the southern and southwestern parts of the Bergell, where the common history of the ascent of tonalite and granodiorite may have been preserved, because this area represents a deeper level of the intrusion. In contrast, the discordant structures described above have been observed at the eastern margin only, where a higher crustal level is exposed. The discordant structures described above, therefore, were produced most likely during the final stages of emplacement of the pluton.

7. Relationship between the eastern and western contacts on a regional scale

In the previous chapters we have described the meso- and microstructures at the eastern contact of the pluton. The structural and petrological differences between the eastern and western contacts of the Bergell have already been pointed out, and additional information may be found in TROMMSDORFF and NIEVERGELT (1983). In order to correlate our data from the east with observations made at the deeper crustal level exposed along the western contact, a NE–SW profile has been constructed. The line of profile (A–B in Fig. 1) starts in the Margna nappe to the east, cuts through the Forno unit and the Bergell pluton, and reaches the Gruf complex in Val Mera, underlying the Bergell pluton. The profile terminates in the west at the Swiss coordinate 755.000, and thus, intersects with the N–S cross section constructed by SCHMID et al. (in press; see our Fig. 14a). In the western part, the profile follows the hinge line of a major antiform, which was constructed from structural contour maps for the tonalite/Gruf and tonalite/granodiorite contacts (DAVIDSON and ROSENBERG, in press).

The position of the base of the Margna nappe at the western end of our profile (point 1 in Figs 14a and 14b) was taken from the mentioned N–S profile, where the altitude of point 1 corresponds to that of the base of the Margna nappe just south of the Engadine line. In the N–S profile, the altitude of point 1 was obtained by projecting structural contour maps of the Penninic nappes north of the Engadine line into the plane of our profile and by using the known vertical offset along the Engadine line (SCHMID and FROITZHEIM, 1993).

North of the Engadine line, the Suretta and Tambo nappes gently dip to the east, and a regional plunge of 22° E has been constructed from structural contour maps (PFIFFNER et al., 1990) and from seismic models (LITAK et al., 1993). In the NE–SW profile, this regional plunge has an apparent dip of 13°, and an extra 10.5° must be added in order to account for the rotation of the southern block during the uplift along the Engadine line (SCHMID and FROITZHEIM, 1993). The resulting angle of 23.5° was used to project the base of the Margna nappe from point 1 (Fig. 14b) towards northeast. According to this construc-

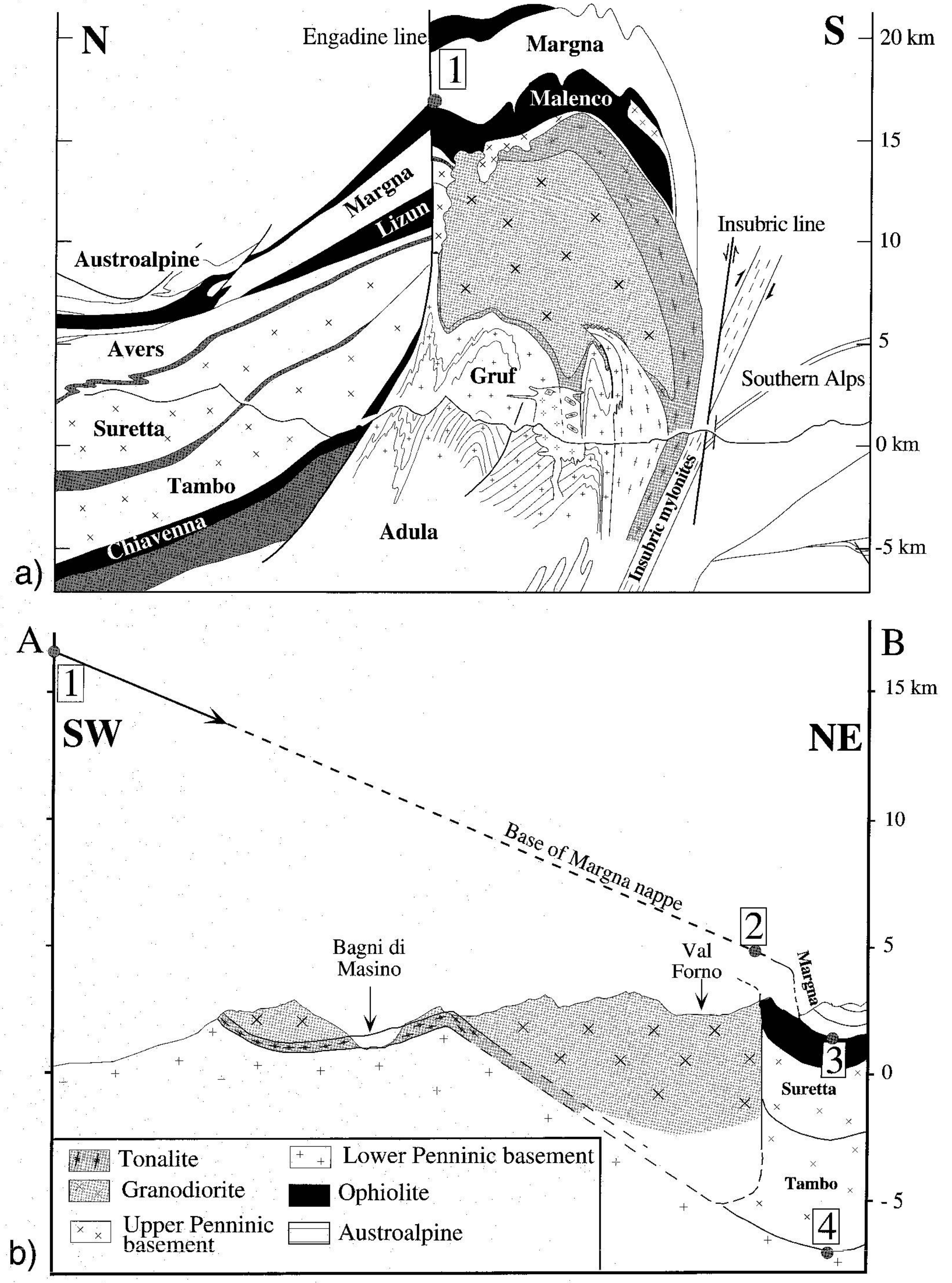

Fig. 14 a: N–S profile constructed along the Swiss coordinate 755.000 (see small arrows in Fig. 1) redrawn from SCHMID et al. (in press).
b: NE–SW profile along A–B in figure 1 (trace along major hinge line in the west). See text for explanation.

tion, the base of the Margna nappe would come to lie 2 km above the eastern margin of the Bergell pluton (point 2 in Fig. 14b). From this result, it follows that the roof of the intrusion would lie at least 0.5 km above today's surface, if 1.5 km are taken as the thickness of the Forno unit beneath the Margna nappe. The eastern contact of the Bergell pluton is associated with a synform related to the intrusion. Development of this so-called Muretto monocline (equivalent to the Chiesa synform of SPILLMANN, 1993) resulted in a steep orientation of the Forno unit. Naturally, we have no direct evidence for the exact geometry of the Margna and Forno nappes above today's topography, but our construction suggests, in combination with the existence of the Muretto steep zone, that the eastern contact represents the side rather than the top of the intrusion.

In order to construct the base of the pluton in the east, the thicknesses of the Penninic Tambo, Suretta and Forno nappes, as measured in the N–S profile of SCHMID et al. (in press) at the Swiss coordinate 150.000, have been added downwards from point 3 (Fig. 14b), where the base of the Margna nappe is lying flat and is not affected by the mentioned synform related to the intrusion. This operation yields point 4, which defines the base of the Tambo nappe (Fig. 14b). If we assume that the floor of the pluton follows the top of the Gruf-Adula unit, as observed in the west (DAVIDSON and ROSENBERG, in press), point 4 can be connected with the base of the intrusion in the middle part of the profile (near Bagni di Masino). Here, the floor of the intrusion is located at the top of the Gruf-Adula unit (see Fig. 1; e.g. DAVIDSON and ROSENBERG, in press), and the cross section can be directly constructed from geological and contour maps. The resulting average NE plunge of the base of the pluton is very similar to the constructed plunge for the base of the Margna nappe.

The profile shows that the combination of regional tilting and block rotation along the Engadine line resulted in the base of the Bergell pluton in the western part being presently at a topographic level similar to that of the top in the eastern part (Fig. 14b).

8. Summary and conclusions

Our observations along the eastern contact of the Bergell pluton indicate that syn-intrusive deformation occurred. The foliations in the intrusive rocks document a continuous transition from magmatic flow to high temperature solid-state deformation. In the contact area, deformation of dikes is significant, and is documented by folds and cuspate-lobate structures at discordant contacts. The axial planes of these folds are always parallel to the general trend of the intrusive contact. Furthermore, the foliation in the country rock represents an axial plane cleavage in these situations. Dikes parallel to the foliation are boudinaged during the same deformation event. The shape of some boudins point to a low viscosity contrast between intrusives and country rocks. Deformed contact metamorphic minerals in the country rocks suggest deformation at high temperature. Furthermore, microstructures exhibited by contact metamorphic minerals suggest that the contact metamorphism can be subdivided into two stages, an older static event followed by a younger kinematic stage.

Between Valle Sissone and the lower Val Forno, the main part of the studied area, the intrusive contact strikes SSE–NNW in a map view. The foliations observed in both intrusion and country rocks define the same general trend (cf. Fig. 4). In the granodiorite we found primary magmatic foliations represented by aligned megacrysts, but solid-state overprint can also be recognized locally. The mesostructures described along this contact (boudinage, folding, foliation parallel to the contact) point to a deformation event related to the final emplacement of the pluton. This deformation, however, does not eliminate all the primary discordant contacts between pluton and country rocks; such contacts can still be recognized in the studied area. On a larger scale, the Muretto (Chiesa) synform, with its axial plane parallel to the contact, is also related to the deformation during emplacement of the Bergell pluton (SPILLMANN, 1993). In addition to the deformation structures at various scales, the aspect ratios of the enclaves serve as a criterion for the intensity of deformation, and reveal increasing strain towards the contact.

Features such as parallel foliations in the pluton and the country rocks, weak flattening-type of deformation, strain increase towards the contact, and continuous deformation from magmatic to solid state are mainly described around ballooning plutons (CASTRO, 1987; PATERSON et al., 1991). Therefore, the observed structures probably result from ballooning of the Bergell pluton. Although these observations are restricted to the northeastern part, i.e. the upper level, of the pluton, it appears that ballooning was an important mechanism during the final emplacement of the Bergell pluton (for details, see ROSENBERG et al., 1995).

Acknowledgements

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References

BERGER, A. (1995): Magmatic and solid state flow during the syntectonic emplacement of the Bergell pluton southeastern part: field studies and microstructural analysis. Ph. D. Thesis, Universität Basel.

BERGER, A. and GIERÉ, R. (1993): Kinematics of emplacement of the Bergell Intrusion along its southeastern margin. Terra Abstracts, Vol 5, 1, p. 302.

BLANCKENBURG, F. (1992): Combined high precision chronometry and geochemical tracing using accessory minerals applied to the Central-Alpine Bergell Intrusion. Chem. Geol. 100, 19–40.

BUCHER-NURMINEN, K. (1977): Die Beziehung zwischen Deformation, Metamorphose und Magmatismus im Gebiet der Bergeller Alpen. Schweiz. Mineral. Petrogr. Mitt. 57, 414–434.

CASTRO, A. (1987): On granitoid emplacement and related structures: A review. Geol. Rdsch. 76, 101–124.

CONFORTO-GALLI, C., SPALLA, M., GOSSO, G. and MONTRASIO, A. (1988): Synintrusive foliation of the Masino-Bregaglia Tonalite and its roof pendants in Val Sissone (Val Malenco, Central Alps, Italy). Rend. Soc. ital. Mineral. Petrol. 43, 509–516.

DAVIDSON, C. and ROSENBERG, C. (in press): Evidence for syntectonic intrusion from the Western margin of the Bergell pluton, Central Alps. Tectonophysics.

DIETHELM, K.H. (1984): Geologie und Petrographie des Bergeller Ostrandes II. Unpublished Diploma thesis, ETH Zürich.

DIETHELM, K.H. (1989): Petrographische und geochemische Untersuchungen an basischen Gesteinen der Bergeller Intrusion. Ph. D. Thesis, ETH Zürich 8855.

DRESCHER-KADEN, F.K. and STORZ, M. (1926): Ergebnisse petrographisch tektonischer Untersuchungen im Bergeller Granit. N. Jb. Mineral. 54 Abt. A, 284–291.

FERRARIO, A. and MONTRASIO, A. (1976): Manganese ore deposits of Monte del Forno; its stratigraphic and structural implications. Schweiz. Mineral. Petrogr. Mitt. 56, 377–386.

GAUTSCHI, A. (1980): Metamorphose und Geochemie der basischen Gesteine des Bergeller Ostrands. Ph. D. Thesis, ETH Zürich.

GIERÉ, R. (1984): Geologie und Petrographie des Bergeller Ostrandes. Unpublished Diploma thesis, ETH Zürich.

GIERÉ, R. (1985): Metasedimente der Suretta-Decke am Ost- und Südostrand der Bergeller Intrusion: Lithostratigraphische Korrelation und Metamorphose. Schweiz. Mineral. Petrogr. Mitt. 65, 57–78.

GYR, T. (1967): Geologische und petrographische Untersuchungen am Ostrande des Bergeller Massivs. Ph. D. Thesis, ETH Zürich.

HURFORD, J., FLISCH, M. and JÄGER, E. (1989): Unravelling the termo-tectonic evolution of the Alps: a contribution from fission track analysis and mica dating. In: COWARD, M.P., DIETRICH, D. and PARK, R.G. (eds): Alpine Tectonics. Geological Society Special Publication 45, 369–398.

KUBLI, TH. (1983): Geologie und Petrographie der Fornoserie im unteren Val Forno. Unpublished Diploma thesis, ETH Zürich.

LINIGER, M.H. (1992): Der ostalpin-penninische Grenzbereich im Gebiet der nördlichen Margna-Decke (Graubünden, Schweiz). Ph. D. Thesis, ETH Zürich.

LINIGER, M.H., and GUNTLI P. (1988): Bau und Geschichte des zentralen Teils der Margna-Decke. Schweiz. Mineral. Petrogr. Mitt. 68, 41–54.

LITAK, R.K., MARCHANT, R.H., PFIFFNER, O.A., BROWN, L.D., SELLAMI, S., LEVATO, L., WAGNER, J.-J. and OLIVIER, R. (1993): Crustal structure and reflectivity of the Swiss Alps from three dimensional seismic modeling: 2. Penninic nappes. Tectonics 12, 925–935.

MONTRASIO, A. (1973): Strutture a pillow nelle anfiboliti del M. Forno (Pennidico medio – Alpi Retiche). Rend. Accad. Naz. Lincei, Cl. Sci. Fis. Mat. Nat. 54, 114–123.

MOTICSKA, P. (1970): Petrographie und Strukturanalyse des westlichen Bergeller Massivs und seines Rahmens. Schweiz. Mineral. Petrogr. Mitt. 50, 355 pp.

PATERSON, S.R., VERNON, R.H. and FOWLER, T.K. (1991): Aureole Tectonics. In: KERRICH, D.M. (ed.): Contact Metamorphism. Mineral. Soc. Am. 26, 673–714.

PATERSON, S.R., VERNON, R.H. and TOBISCH, O.T. (1989): A review of criteria for the identification of magmatic and tectonic foliations in granitoids. Journ. Struct. Geol. 11, 349–363.

PERETTI, A. (1983): Geologie und Petrographie der Fornoserie. Piz dei Rossi. Unpublished Diploma thesis, Universität Zürich.

PERETTI, A. (1985): Der Mt. del Forno-Komplex am Bergell-Ostrand: Seine Lithostratigraphie, alpine Tektonik und Metamorphose. Eclogae geol. Helv. 78, 23–48.

PFIFFNER, A.O., KLAPER, E.M., MAYERAT, A.M. and HEITZMANN, P. (1990): Structure of the basement-cover contact in the Swiss Alps. In: Deep structure of the Alps (Ed. by Soc. Geol. Suisse, m.). 1, 247–262.

PFIFFNER, M. and WEISS, M. (1994): Strukturelle und petrographische Untersuchungen im Grenzbereich Penninikum-Unterostalpin am Südostrand des Bergell-Plutons (Val Masino, Italien). Schweiz. Mineral. Petrogr. Mitt. 74, 245–264.

REUSSER, E. (1987): Phasenbeziehung im Tonalit der Bergeller Intrusion. Ph. D. Thesis, ETH Zürich.

RIED, F. (1994): Titanmobilität: Metasomatische, titanreiche Adern am Kontakt von Dolomitmarmoren zur Bergeller Intrusion. Ph. D. Thesis, ETH Zürich.

RIKLIN, K. (1977): Geologisch-Petrographische Untersuchungen am Bergell-Ostrand, nördlich der Valle Sissone (Prov. di Sondrio, N-Italien). Unpublished Diploma thesis, ETH Zürich.

RIKLIN, K. (1978): Strukturen und Metamorphose im Bereich der südlichen Moretto-Linie. Schweiz. Mineral. Petrogr. Mitt. 58, 345–356.

RING, U. (1994): The kinematics of the late Alpine Muretto fault and its relation to dextral transpression across the Periadriatic line. Eclogae geol. Helv. 87, 811–832.

ROSENBERG, C., BERGER, A. and SCHMID, S.M. (1995):

Observations from the floor of a granitoid pluton: Inferences on the driving force of final emplacement. Geology 23, 443–446.

SCHMID, S.M. and FROITZHEIM, N. (1993): Oblique slip and block rotation along the Engadine line. Eclogae geol. Helv. 86, 569–594.

SCHMID, S.M., FROITZHEIM, N., KISSLING, N., PFIFFNER, A. and SCHÖNBORN, G. (in press): Integrated cross section and tectonic evolution of the Alps along the Eastern transect. In: HEITZMANN, P. (ed.): Deep structure of the Swiss Alps – Results from NFP/PNR 20. Birkhäuser AG, Basel.

SPILLMANN, P. (1993): Die Geologie des penninisch-ostalpinen Grenzbereichs im südlichen Berninagebirge. Ph. D. Thesis, ETH Zürich.

STAUB, R. (1918): Geologische Beobachtungen am Bergeller Massiv. Vjschr. Natf. Ges. Zürich. 63, 1–18.

TRACY, R.J. and FROST, B.R. (1991): Phase equilibria and thermobarometry of calcareous, ultramafic and mafic rocks, and iron formations. In: KERRICK, D.M. (ed.): Contact Metamorphism. Mineral. Soc. Am. 26, 207–289.

TROMMSDORFF, V. and EVANS, B.W. (1972): Progressive metamorphism of antigorite schists in the Bergell Tonalite aureole. Am. J. Sci. 272, 423–437.

TROMMSDORFF, V. and EVANS, B.W. (1977): Antigorite Ophicarbonates; Contact Metamorphism in Val Malenco. Contr. Mineral. Petrol. 62, 301–312.

TROMMSDORFF, V. and NIEVERGELT, P. (1983): The Bregaglia (Bergell) Iorio Intrusive and its field relations. Mem. Soc. geol. ital. 26, 55–68.

VENZO, S., CRESPI, R., SCHIAVINATO, G. and FAGNANI, G. (1971): Carta geologica-petrografica delle Alpi Insubriche Valtellinesi tra la Val Masino e la Val Malenco (Sondrio). In: Mem. Soc. It. Sci. Nat. e del Museo di Storia Naturale, Milano 1; Vol. 19.

WENK, H.R. (1973): The structure of the Bergell Alps. Eclogae geol. Helv. 66, 255–291.

WENK, H.R. and CORNELIUS, S.B. (1977): Geologischer Atlas der Schweiz, 1 : 2500 Blatt 70 Scoria, Schweiz. Geol. Komm.

WENK, H.R., WENK, E. and WALLACE, J. (1974): Metamorphic mineral assemblages in pelitic rocks of the Bergell Alps. Schweiz. Mineral. Petrogr. Mitt. 54, 507–554.

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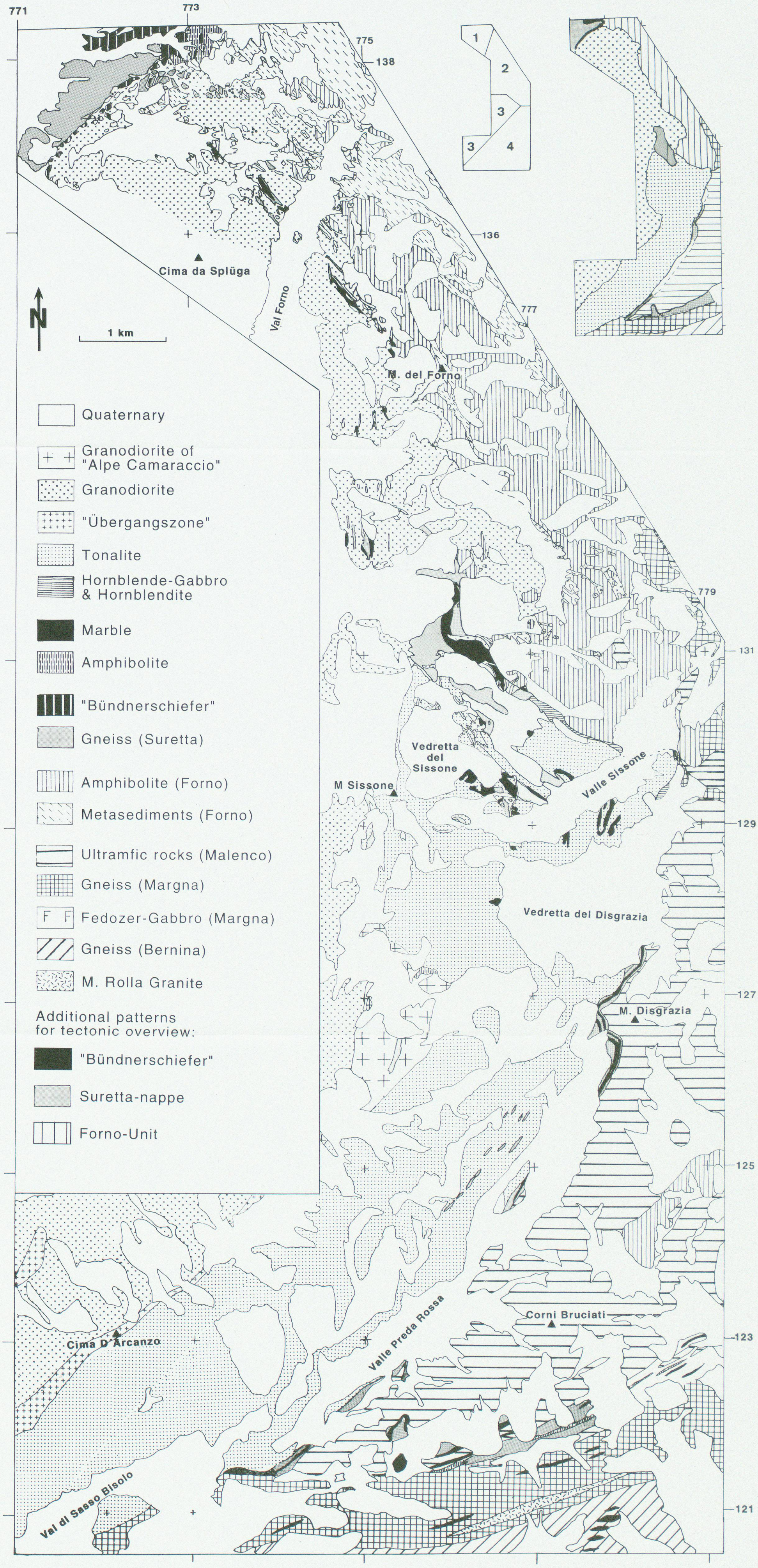
Plate 1 Geological map of the Eastern Bergell area. A tectonic overview of the same area is given in the upper right corner. The map was compiled from various sources (cf. small inset), i.e.

1 = GYR (1967)
2 = RICKLIN (1977), KUBLI (1983), PERETTI (1983), GIERÉ (1984), DIETHELM (1984, 1989); see also compilation of SPILLMANN (1993)
3 = WENK and CORNELIUS (1977)
4 = VENZO et al. (1971), PFIFFNER and WEISS (1994).



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