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The Structure of the Bergell Alps[1])

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ABSTRACT

The Bergell granite in the Central Alps has always been viewed as a postalpine massif. A new concept is now proposed that the granite was mobilized early in the Alpine orogeny (Oligocene ~30 million years) and intruded volcanic and sedimentary deposits of the Alpine geosyncline. It may have been the Lepontine metamorphism that initiated remelting of older granitic material but more likely the Lepontine regional metamorphism (~25 million years) is younger than the Bergell granite. The crystallizing granite and its contact were then thrust northeastward as a plate-shaped mass in the same strainfield in which the upper and middle Pennine nappes were emplaced. Deformation produced foliation parallel to the one in the country rock, strong preferred orientation of alkalifeldspar megacrysts, elongation of xenoliths, and mylonitic recrystallization of quartz. The granitic material was more ductile in the SW than in the NE where the granite and some contact material were emplaced as a rigid unit ("a large boudin") forming anticlinal structures in the surrounding nappes (Muretto and Gruf anticlines). Most likely the granite was deformed throughout the entire duration of crystallization ending with the formation of shear zones and anticlines in the Forno area, that may be some of the youngest movements of the Alpine folding (not considering more recent faults such as the Insubric and the Engadine Line). This model which is based on new field evidence (e.g., windows of Bagni Masino, V. di Ferro and Albigna), linear and planar structures, microscopic textures and crystal structure properties of wollastonite is consistent with new isotope data, especially U/Pb ages of zircons.

CONTENTS

[1]) Part 3 of *Geological Observations in the Bergell Alps*.

Introduction

The Bergell Alps are defined topographically as the region between the Bernina group to the northeast, the Lepontine Alps to the west (W of Valle della Mera), bordered to the south by the Veltlin Valley (Valtellina), and to the north by the Bergell Valley[2]). Tectonically they belong to the Pennine realm of the Central Alps. The Bergell granite, the main theme of this paper, is situated along the southside of the Bergell Valley (V. Bregaglia). The granite, an attraction for tourists and climbers, is also of interest to geologists and has recently become the subject of controversial discussions. Two incompatible viewpoints are illustrated in Figure 1. This paper attempts to supply evidence that Figure 1 bottom should replace the generally ac-

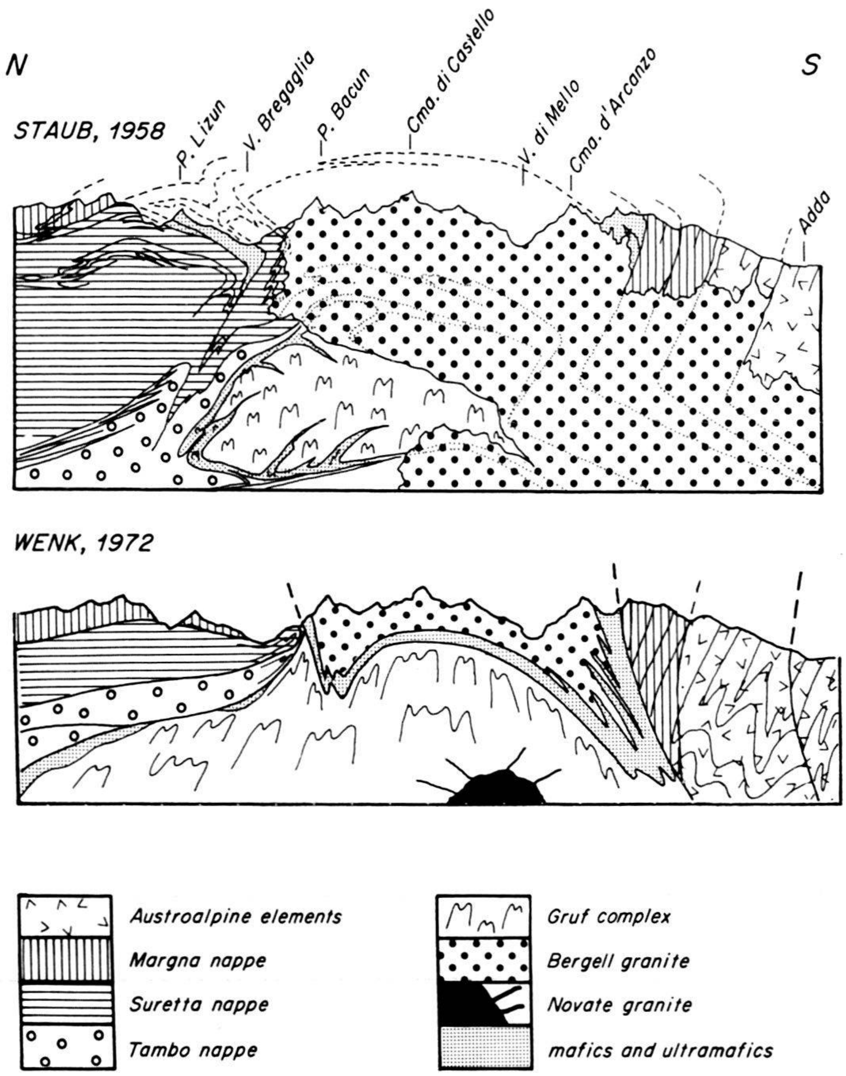

Fig. 1. Schematic N-S cross sections through the Bergell Alps. Top: STAUB (1958), bottom: WENK (1972).

[2]) Geographic names in this paper refer to the Swiss national topographic maps (especially the quadrangles 1:25,000, 1275, 1276, 1296; 1:50,000, 267, 268, 277, 278; 1:100,000, 43, 44). Most of the names used in the text are to be found on the maps in Plate I (towns) and Plate II (mountains and rivers). Local names are avoided. Geological maps are listed in the reference section at the end of the paper.

cepted model 1 top of STAUB (1924, 1956). The Bergell granite has long been presented as a textbook example of a young post-tectonic intrusion that penetrates the nappe structures like a cancerous tumor. Under the influence of this concept, an unquestioned credo for Alpine geologists, important observations have been overlooked and ignored. DRESCHER and STORZ (1926) published a structural map of the northern part of the granite which indicates that foliations and lineations in country rocks and granite are parallel. GRÜNENFELDER and HAFNER (1962) comparing thin sections of Bergell and Rotondo granite (Gotthard) found to their surprise that the seemingly postkinematic Bergell granite appears much more deformed than they expected. Only very recently has detailed structural work been done in this area (MOTICSKA 1970; WENK 1970), and the results are used to outline a new tectonic concept for the Bergell Alps. The main purpose of this paper is to study the *emplacement* of the granite as derived from macro- and microscopic deformation features. The question of formation is left open. In addition, this paper supplies structural data that are important for the interpretation of the regional geology of the area, and also contributes to the understanding of deformation of granite under metamorphic conditions, a subject which has so far received little attention. Results from X-ray petrofabric analysis and discussion of the metamorphic history will be presented later. For a more complete review of previous geological work in the Bergell Alps the reader is referred to WENK (1970).

Macroscopic structures

The Bergell Alps display a great variety of metamorphic minerals. Stilpnomelane and chloritoid occur in the northeast, andalusite and Fe/Mg-cordierite in the east and Mg-cordierite, sillimanite and hypersthene in the west, just to name a few contrasting assemblages. They indicate a variety of temperature-pressure conditions under which the style of deformation changes from horizontal thrusts of rigid masses in the east (Austroalpine and Upper Pennine nappes) to plastic deformation of highly mobile and ductile material at high temperatures and pressures in the west (Lepontine gneisses). The general structure can best be explained with maps of planar and linear directions. Foliations, lineations and foldaxes have been measured and a statistically valid selection of these measurements is shown in Plates I and II. (Some data from BLATTNER 1965, CORNELIUS 1972, GYR 1967, MOTICSKA 1970, SCHMUTZ 1971, WEBER 1966 and E. WENK 1956 are incorporated.) Both lineations and foliations indicate a complex history. In many places more than one phase of deformation has left imprints in the rocks and occasionally two systems of linear structures can be seen in the same outcrop. However, it has not been possible to separate distinct episodes of deformation, and it appears that most of these structures have been formed continuously during the main phase of deformation in the Central Alps. Lineations in the central part dip fairly uniformly to the east, perhaps indicating the eastern prolongation of the Ticino culmination, but this dip is accentuated by a subsidiary dome-like structure just east of Valle della Mera. The gentle east dip of 15° averaged over 25 km and the difference in elevation result in a difference of tectonic level of over six kilometers (~2 k bars) between the granulite-resembling sillimanite gneisses at Novate (200 m) and the andalusite schists of M. del Forno (3,000 m).

The general structural trend in the Bergell Alps is outlined by the contact between the Bergell granite composing the central part and the metamorphic rocks surrounding it. The WSW-ENE strike in the west turns SE in the east and bends SW in the southeast with steeply dipping fold axes in the Preda Rossa area. The different styles of deformation which are displayed in the structural maps can best be seen in the diagrams in Figure 2. They are used to divide the region into tectonic units (see Figure 3 which is a good visual reference for the following discussion). The most conspicuous characteristics of each unit, especially their relation to the Bergell granite, will be discussed consecutively, beginning with the highest unit. To aid in visualizing the *geometry*, a sequence of profiles has been constructed from petrographic maps (Sciora quadrangle: WENK 1973), evidence from water tunnels of the hydroelectric power plants, and by extrapolation using structural trends as indicators (Pl. III).

Higher Pennine nappes

The *Higher Pennine nappes* (Sella, Margna and Suretta) are characterized by rocks of low metamorphic grade even in the vicinity of the Bergell granite. All plagioclase is albite, chlorite is common, stilpnomelane, chloritoid and glaucophane occur occasionally. Prasinitic chlorite schists (Lizun) and muscovite augengneisses (Maloja) are the predominant rock types. Limestone bands mark thrust contacts between nappes ("Deckenscheider"). Foliations dip gently to the east. The *Margna nappe* rests above the Bergell granite though not in direct contact with it. Some folding and bending has been produced in it during emplacement of the granite, which can best be observed between the Maloja and Muretto passes. This relationship between the granite and the Margna nappe will be treated in more detail during discussion of the granite contact (p. 266). To the east the Margna nappe forms a large anticlinal structure partly enveloping the Bergell granite, and almost completely surrounding the Disgrazia-Malenco ultramafics. South of these units, it roots.

The *Suretta nappe* is composed of muscovite gneisses and metamorphic rocks in its lower portion, and of metasedimentary rocks in the higher portion. The latter in the eastern part are in greenschist facies with some possibly early Alpine glaucophane, and the western part is in an early or prealpine amphibolite facies (WENK 1974).

The lowest strata are bands of limestone and quartzite, presumably originally Triassic sediments. The higher units are Jurassic shales, sandstone, and chert, all of them metamorphic (Piz Duan). The Suretta nappe crosses the Bergell Valley at Pranzaira and appears as an extremely deformed sequence in the bottom of Lavinair Crusc. It may surround the granite as a strongly sheared anticlinal structure to the north and east (compare profiles in Fig. 7), but several thrust faults obliterate any direct evidence that these petrographically similar structural units belong together. Diagram 1 in Figure 2 shows that fold-axes and lineations are less regular than the foliation, and these linear structures presumably must be attributed to more than one tectonic episode. The Suretta as well as the Margna nappe appear to have been emplaced as rather rigid blocks and the heterogeneity in structure and metamorphic grade – apart from structures close to the Bergell granite – reflects imprints from older geological events.

The *Tambo nappe* (according to STAUB 1924, the eastern equivalent of the Monte Rosa nappe) extends from P. Tambo in the north almost to the Bergell granite. It is composed of rocks of predominantly granitic composition with muscovite-biotite granites and augengneisses (GANSSER 1937, WEBER 1966), of Hercynic age (GULSON

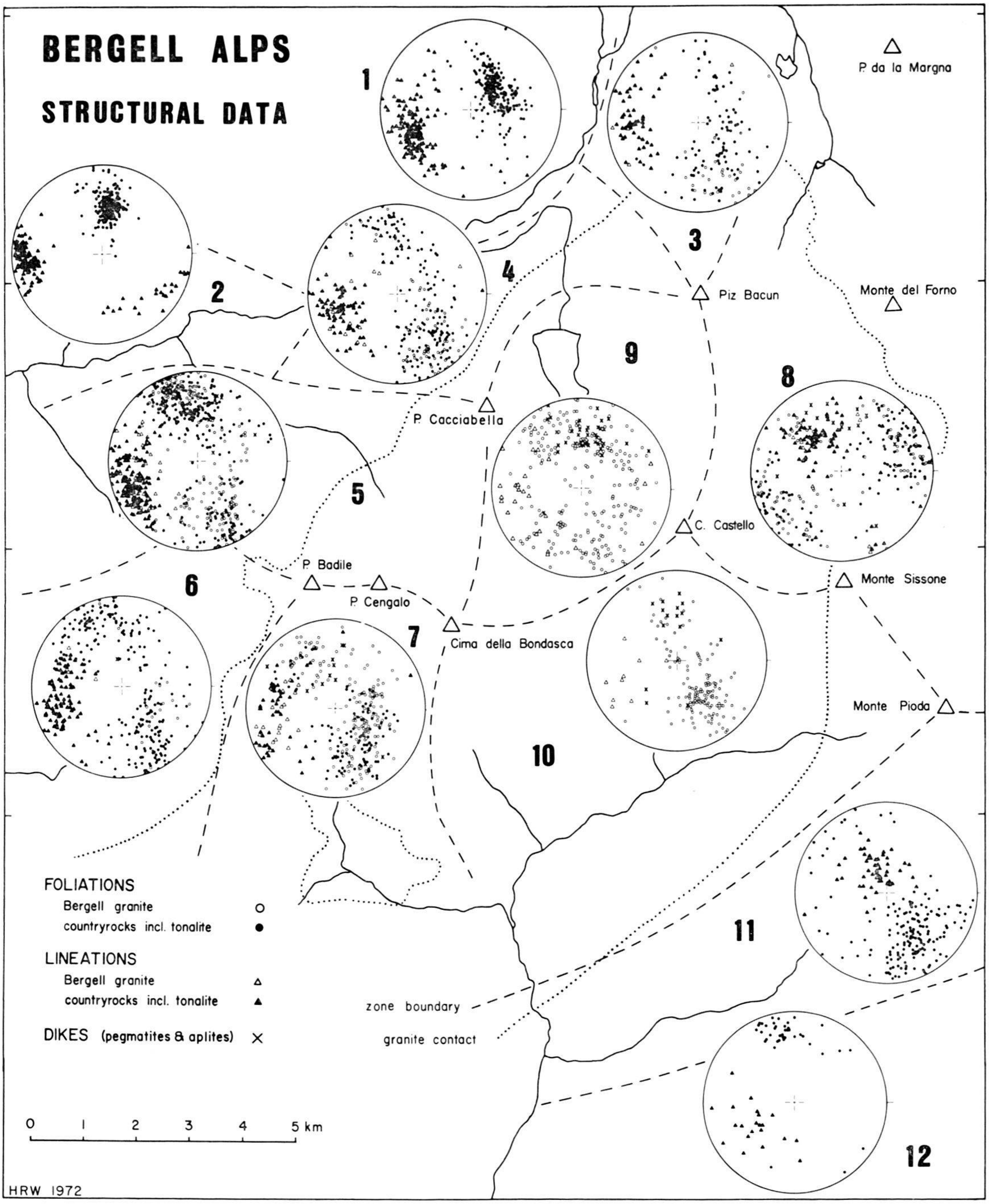

Fig. 2. Map of the central Bergell Alps divided into 12 zones for which orientation diagrams of structural elements (foliations, lineations, fold axes) are displayed. 1:25,000. Diagrams are equal-area projections on upper hemisphere.

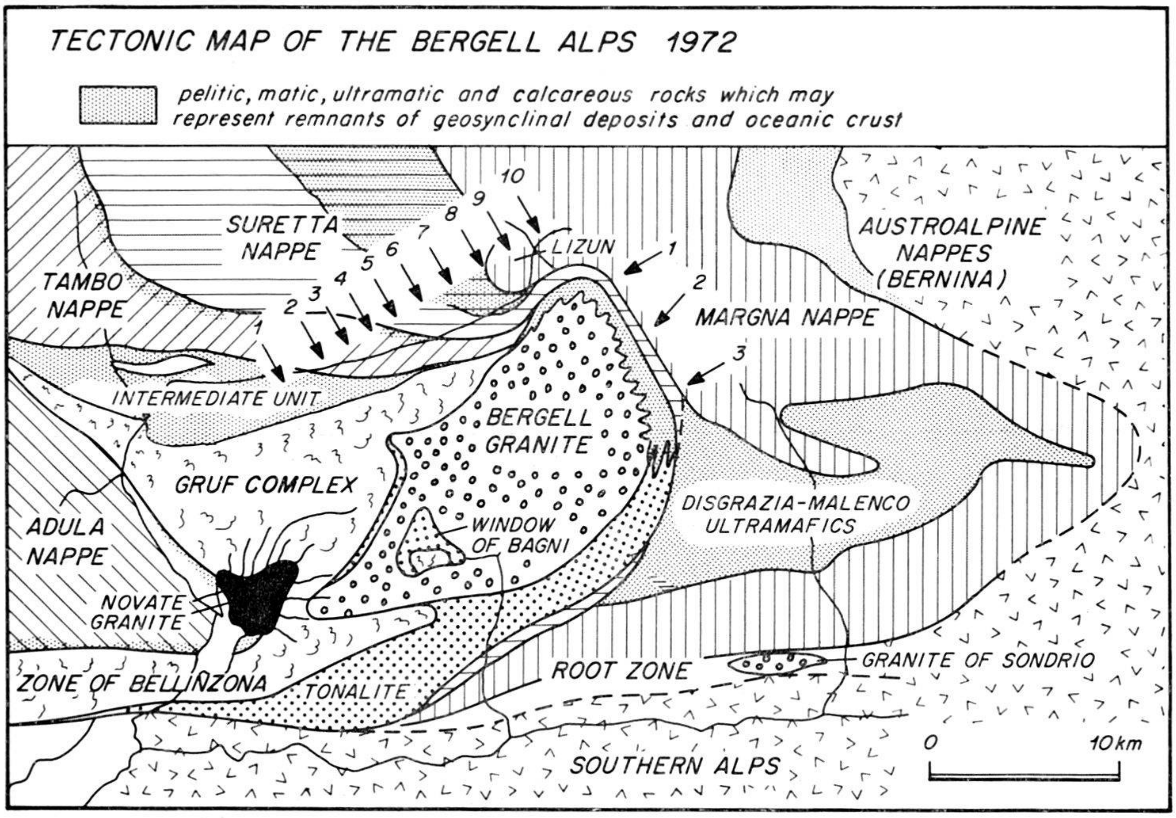

Fig. 3. Tectonic map of the Bergell Alps, schematic. Profile traces are indicated with arrows (compare Pl. III and Fig. 7, bottom).

1971, 1973). The large body of megacrystic granite of Truzzo (grading into augengneisses in the Bergell Valley) is separated from the smaller megacrystic Chiavenna granite by metamorphic rocks (biotite-muscovite-garnet schists, chlorite-muscovite schists, oligoclase amphibolites, rare ultramafics and calc-silicate rocks). The megacrystic granites of Truzzo and Chiavenna and local granitic rocks near Castasegna and in Val Bondasca resemble in many aspects the Bergell granite. Isotropic granite, however, is rare. Most of the rocks are augengneisses and in the east platy gneisses (Soglio, Promontogno). The strain during deformation was in certain localities very heterogeneous, which is excellently demonstrated in the Liro River outcrops below San Giacomo. Granite with spherical dark inclusions changes within a few meters into augengneisses with dark thin bands marking elongated inclusions which reflect the strain (Fig. 4). The granite layer is about 2 km thick in the Chiavenna area bu- thins rapidly eastward and disappears strongly sheared east of Vicosoprano. Lineat tions in the lower units of the Tambo nappe dip ENE. In the higher parts they turn around and dip WNW (Pl. II). Foliations in the gneisses dip uniformly, about 45° to the north (Diagram 2, in Fig. 2). Only in the vicinity of the granite does the inclination become steeper and beds are overturned north of Stampa and Vicosoprano (Pl. III). The root zone which is composed of rocks belonging to the Margna, Suretta and Austroalpine nappe, does not contain any Tambo gneisses and therefore the Tambo nappe may have never extended as far to the south. The thrust contact with the underlying Gruf migmatites is marked by fine-grained mylonites. A metasedimentary

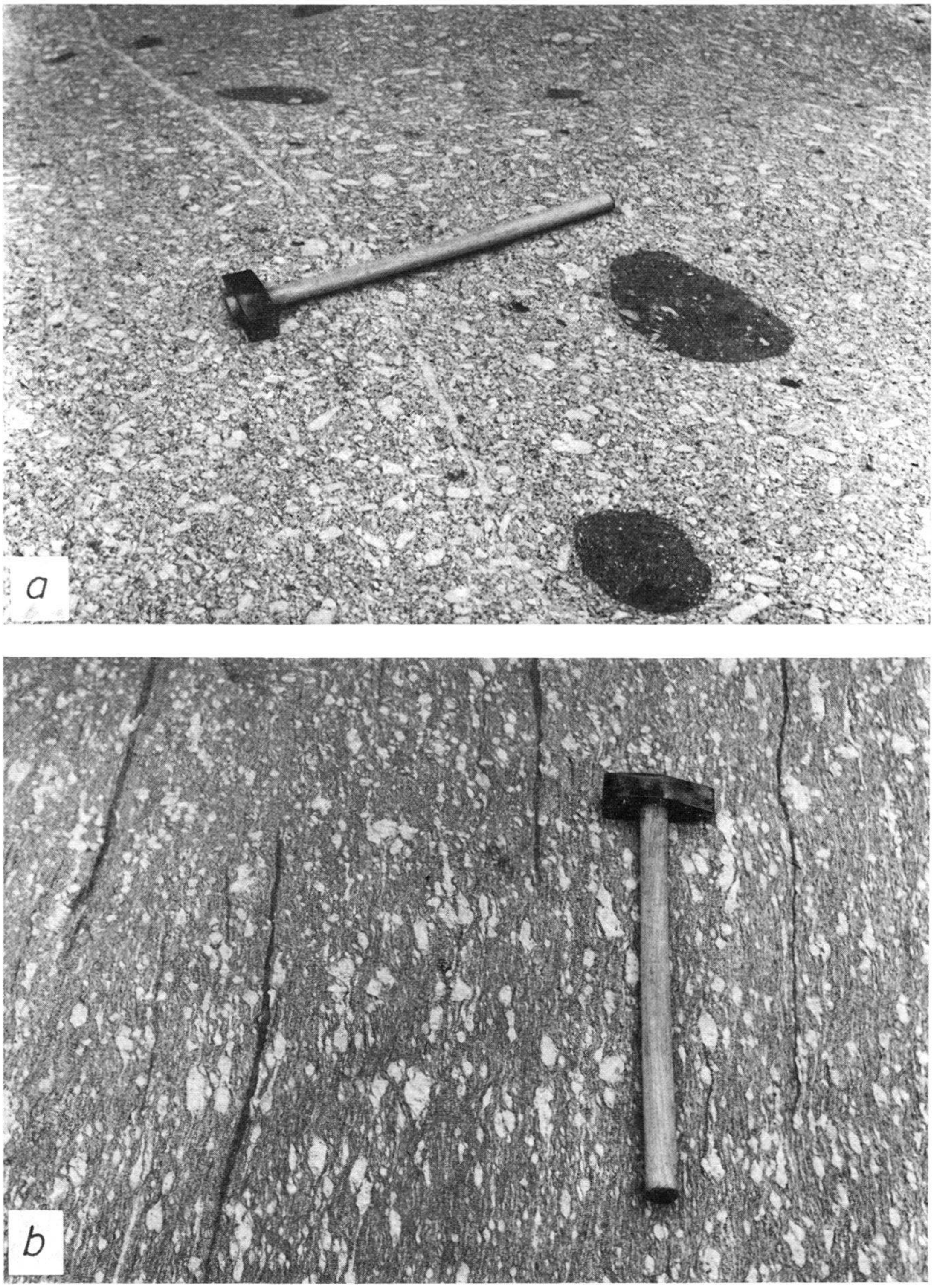

Fig. 4. Outcrop of Chiavenna-granite (Tambo-nappe) in Liro-riverbed between Bette and San Giacomo. a) Megacrystic granite with dark inclusions. b) Highly strained augengneiss. Dark bands represent deformed inclusions. 30 meters from a.

layer, probably Triassic, with strongly deformed marbles, quartzites and rauhwackes defines the contact with the overlying Suretta nappe.

Gruf complex s. l. (named after Monte Gruf), including Zone of Bellinzona

An entirely different style of deformation begins underneath the Tambo nappe. The *Gruf complex*, composed predominantly of migmatitic gneisses, is characterized by isoclinal folding (Fig. 5a; Diagrams 4, 5, 6 and 7 of Fig. 2). The orientation of lineations and foldaxes is sharp. On an average they are dipping 15° to the NE (Pl. II). Poles to the foliation lie on a great circle around the lineations (Fig. 6b). This is in marked contrast to structures in the higher nappes (Diagrams 1 and 2 in Fig. 2). To the west, the isoclinal belt forms a broad anticlinorium that narrows into an antiform bordering the Bergell granite to the north. The anticlinal structure is outlined in the internal part of the Gruf complex in upper Val Codera by the metasomatic Sivigia diorite. This rock – appearing locally as ultramafic breccia (Fig. 5b), elsewhere as massive diorite (Fig. 5c) – is easily recognized because of its conspicuous, large labradorite megacrysts and serves as an excellent structural marker in these overall fairly uniform gneisses. The Sivigia diorite is clearly formed by feldspathization of an ultramafic breccia, probably identical with the series found in Val Trubinasca (ARTUS 1959). A good section across the northeast part of the Gruf antiform is exposed in Val Bondasca.

Many of the isoclinally folded Gruf migmatites contain inclusions and some larger bodies of micaschist (garnet-rich biotite-sillimanite-cordierite gneisses occasionally with orthopyroxene and sapphirine), labradorite-amphibolites, ultramafics (olivine, enstatite, talc, ±antophyllite) and rarely calcsilicate rocks (garnet–wollastonite–diopside–vesuvianite–anorthite) indicating metamorphic conditions close to granulite facies. The ultramafic rocks occur in disconnected lenses that follow the general strike. There is only one larger complex of ultramafic rocks which extends from Chiavenna to Val Bondasca, resting on the northwest limb of the Gruf anticlinorium and underneath the Tambo augengneisses. The mesocratic rocks here display a zonation in metamorphic grade which is well exhibited in the mineral assemblages of the micaschists. They contain sillimanite-cordierite near the migmatite contact, kyanite, and staurolite, farther north, and chloritoid N of V. Bregaglia. In the south, in the Novate-V. dei Ratti area, the isoclinally folded migmatites change without a major unconformity into platy gneisses and injection gneisses of the type of Bellinzona (GUTZWILLER 1912, KNOBLAUCH 1934). Gruf complex and Zone of Bellinzona appear to be tectonically closely related judging from their petrographic composition, texture and occurrence. Several Gruf migmatites have been dated but the determined pre-hercynic age is somewhat controversial (Rb-Sr, total rock: GULSON 1971, 1973). Thus, lenses and zones of marble, pelitic schists, mafic and ultramafic rocks randomly distributed throughout Gruf migmatites may not be relics of the Mesozoic geosyncline.

The Gruf complex has many characteristics of an autochtonous basement massif and may actually represent some of the tectonically deepest rocks exposed in the Central Alps. Part of this series has been compared already by REPOSSI (1916) with the "Zona diorito-kinzigitica" = Ivrea Zone of the Southern Alps. Isoclinal folding in these crystalline rocks was produced under high confining pressure (tectonic depth) with constraints on all sides. Unterneath the Bergell granite and the Tambo gneisses, the migmatites were compressed during the Alpine deformation, in the frame of the root zone (to the south), the N-dipping Tambo nappe (to the north) and the Adula nappe (to the west), see Figure 3.

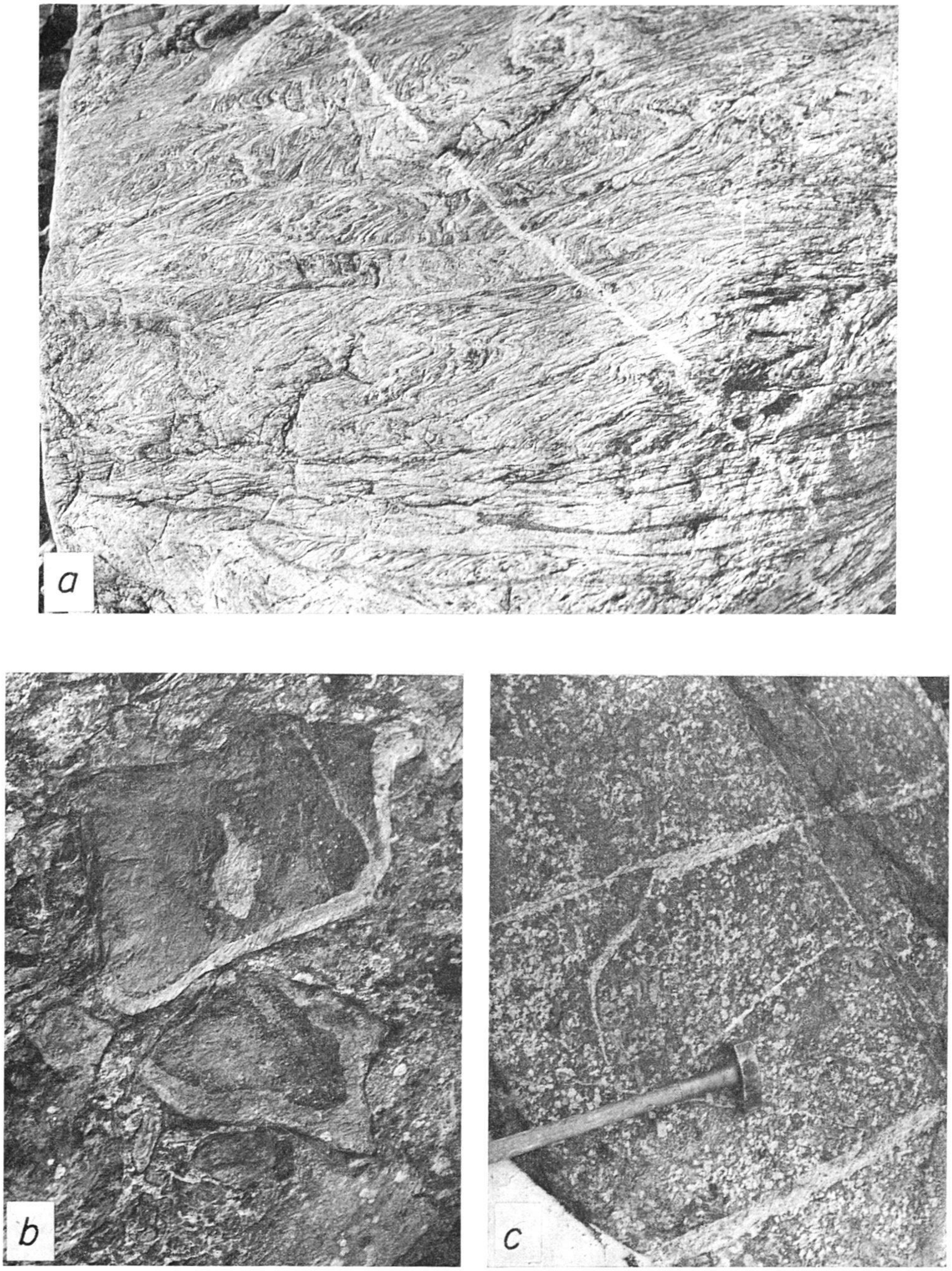

Fig. 5. Rocks of the Gruf complex. a) Isoclinally folded Gruf migmatite, crosscut by aplitic vein. Block in river from V. Codera at Novate. b, c) Ultramafic breccia (b) being transformed into megacrystic labradorite-"diorite" (c) Alpe Sivigia, upper V. Codera.

Lower Pennines

The Lower Pennine units that compose most of the Lepontine metamorphic zone in the Tessin form the western boundary of the Bergell Alps. Since their occurrence is rather limited east of Valle della Mera they will be discussed only briefly. The principal unit is the *Adula*, a nappe in the northwest (Adula, V. Calanca) but to the southeast a folded complex that has undergone structural and metamorphic transformation. It is represented in Valle della Mera by anticlinal structures of Val Bodengo (Soe, Garzelli; BLATTNER 1965) and has, progressing eastwards, increasingly steep fold axes (E. WENK 1956). The antiform disappears, steeply dipping, in the Novate area underneath the Gruf complex. Sporadic lenses of calcsilicates outline the boundary between Adula and Gruf complex. It appears that the easternmost portion of the Adula has been thrust down into the granulite-like migmatites and it is possible that, during this local subduction, remelting mobilized the *Novate granite*, centered at the steeply plunging eastern front of the Adula antiform.

The zone of Lepontine Gneisses extends northwards to the Mesozoic rocks of the Zone Mesocco–Forcola and southwards to the series of Tonale and tonalite. Gneisses of the Zone of Bellinzona, part of the Lepontine in the Tessin, extend through V. dei Ratti as far westwards as Bagni di Masino. There isoclinally folded gneisses are indistinguishable from Gruf migmatites and we think that the two units are identical. The exact tectonic relation between Adula, Gruf and Zone of Bellinzona is uncertain. They probably all represent reworked material of old crystalline basement.

Bergell Granite

The border of the *Bergell granite*[3]) is outlined by dots on the structural maps. Chemically the rock varies from granodiorite to granite (WEIBEL 1960). The granitic body is about 10 km in diameter and at least 2 km thick and the main purpose of this paper is to study the structural relations between it and surrounding rocks. Most of the granite contains conspicuous alkali feldspar megacrysts whose origin is unclear. DRESCHER-KADEN (1940, 1969) discussed the feldspar-quartz fabric which displays myrmekitic textures. A nonmegacrystic variety is confined to small bodies of younger, discordant microgranite along the eastern contact (SE Monte del Forno, Monte Rosso, Alpe Pioda) and a sheet of concordant granodiorite in the center of the main body. This sheet dips gently to the east and is only exposed in the high parts of the Cacciabella-Sciora and Pta. da l'Albigna-Cantun-Casnile area disappearing in the center of Forno Valley. It serves as an excellent marker for the structure within the granite. Another indication of the plate-like character of the Bergell granite is the geometry of the contact: The granite rests in the southwest on migmatites, the best evidence being in the window of Bagni Masino. A puzzling feature is the conformity of linear and planar structures in the granite and country rocks. This is obvious from Plates I and II and from the Diagrams in Figure 2 where different symbols were used for structures in the granite and the country rock. Strong preferred orientation of megacrysts and elongated inclusions are typical of rocks adjacent to the contact

[3]) The name "Bergell granite" is used in the same sense as the Italian term "ghiandone" and describes the granitic-granodioritic mainly megacrystic rocks in the central Bergell Alps. It does not include tonalite ("serizzo") nor Novate granite ("granito di San Fedelino").

(1 km) in V. Forno, V. Albigna, V. Bondasca, V. Codera, V. Masino and V. di Mello and are attributed to postmagmatic deformation (compare Fig. 9b). Strain features are less common, more heterogeneous and less pronounced in the central and eastern part of the Bergell granite but locally always present. Foliation and especially lineations are sometimes difficult to measure in the field, yet statistical sampling over many years shows remarkable orientation patterns even in the central massive portion of the granite (Diagrams 9 and 10 in Fig. 2). A quantitative comparison of all measurements in granite from zones 3, 4, 5, 6, 7, 9, 10 (Fig. 6a) with an equal number of

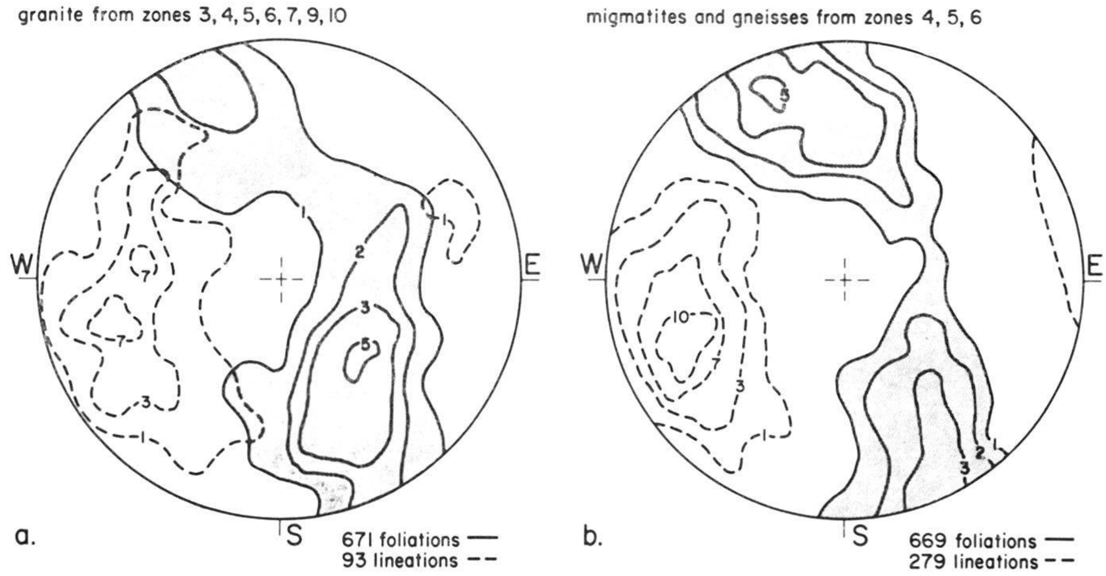

Fig. 6. Structural elements in Bergell granite (a) and Gruf migmatites (b) plotted in equal-area projection on upper hemisphere. Contoured using method of SCHMIDT (1925) showing percentage of poles per 1% area (compare Fig. 2). Notice that the two diagrams are almost identical.

measurements in migmatites and gneisses in zones 4, 5, 6 shows a striking similarity (Fig. 6b). There is no doubt that the migmatites and the granite have been deformed in the same strain field and that isoclinal folding may also be the dominant style of deformation in the granite despite its plate-like shape.

Contact relations around the Bergell granite are rather complicated and variable. The direct contact rocks are on the whole mesocratic or mafic, either tonalite (hornblende-quartz diorite) or amphibolite, often accompanied by lenses or bands of ultramafic and calcsilicate rocks, and biotite schists. Only rarely and locally is there a direct contact of granite with Gruf migmatites (V. Bondasca–Cengalo) or gneisses (Murtaira–Forno). None of the surrounding nappes display an eruptive contact with the Bergell granite. Anticlinal structures and thrust planes mark the offset between the nappes and the region containing both the granite and its immediate contact rocks. Emplacement of the granite as a comparatively rigid body mechanically influenced its environment. The granite body acted as a "large boudin" rather than as a "big porphyroblast" (DRESCHER 1969 in analogy to Purtscheller's concept of the Mont Blanc granite, 1963, 1964) and the intense deformation textures in the country rocks in the vicinity of the Bergell granite preclude in situ granitization of gneisses.

The lack of igneous contacts between Bergell granite and the Higher Pennine nappes removes the prime argument for the post-Alpine age of the granite. The evidence for the crosscutting relation between the granite and the Margna nappe, which influenced so deeply the geological literature, was based on the igneous contacts at Monte del Forno (CORNELIUS 1913). There is no evidence however, that these contact rocks belong to one of the higher Pennine nappes. In order to support the new structural concept it is necessary to describe in more detail the relationship between granite and contact rocks, and between the granitic body and the nappes. The contact is variable: to the east the granite disappears underneath the Muretto anticline and Margna nappe; on the northwest it extends to the Gruf antiform; to the southwest it rests on Gruf migmatites and to the south the granite terminates in a synclinal structure bordering an alkali feldspar bearing biotite-hornblende-andesine gneiss ("tonalite").

The eastern contact (Fig. 7) is well exposed and easily accessible at Sella del Forno–Monte Rosso (from Cap. Forno) and Ved. Piatte di Vazzeda and upper Val Sissone (from Chiareggio–Cap. del Grande). The country rocks immediately adjacent to the granite show features typical of igneous activity with crosscutting dikes, angular inclusions, roof pendants and contact minerals such as andalusite and $Fe_{0.5}Mg_{0.5}$-cordierite in pelitic schists, and diopside, wollastonite and anorthite in calcsilicate rocks (WENK and MAURIZIO 1970). These contact features, which are very local (Monte Rosso, Monte del Forno, Cima di Vazzeda), do not display a metamorphic gradient. The granite and contact rocks have been thrust NE, producing subvertical and west dipping shear zones in the granite and an anticline in the adjacent nappes well visible in the lower Forno valley. This anticline extends from Plan Canin to Muretto pass, separating the contact rocks from the Margna nappe. Composed of low grade rocks, it is quite conspicuous in the field (Fig. 7, top) and may represent squeezed relics of the Suretta nappe. The Margna nappe, which rests on the eastern limb of the anticline, has been bent up by emplacement of the Bergell granite. Deformation has been brittle in this area and cataclastic features indicate deformation at low temperature, the granite being much stronger than the surrounding rocks.

The area *Cima di Murtaira–Lavinair Crusc* is the only place where a large mass of country rock affected by the granite intrusion is exposed and pelitic schists contain large clusters of prismatic andalusite especially well exposed along the south shore of Lagh de Cavloc. Occasionally long andalusite prisms grow across the cleavage and are therefore younger. Pegmatite, aplite and granite veins and dikes extend as far as Piz Salacina to the northeast (Fig. 8). These contact metamorphic rocks are offset by a subvertical thrust fault from the low grade metamorphic rocks of the Suretta and Margna nappe. The tectonic position of the contact rocks is unclear. They underlie the Margna nappe and most likely also the Suretta nappe. They are closely related to the granite and quite distinctly separated from any of the surrounding nappe units.

Progressing towards the west, the sequence of metamorphic rocks becomes increasingly strained and diminishes into a thin band of cordierite–sillimanite–micaschists and amphibolites with occasional calcsilicate and ultramafic inclusions. The mineral assemblages indicate higher pressure than in the NE (Mg-cordierite). Strong effects of plastic deformation are visible in the granite. In many places strain is heterogeneous with blocks of augengneisses in macroscopically undeformed

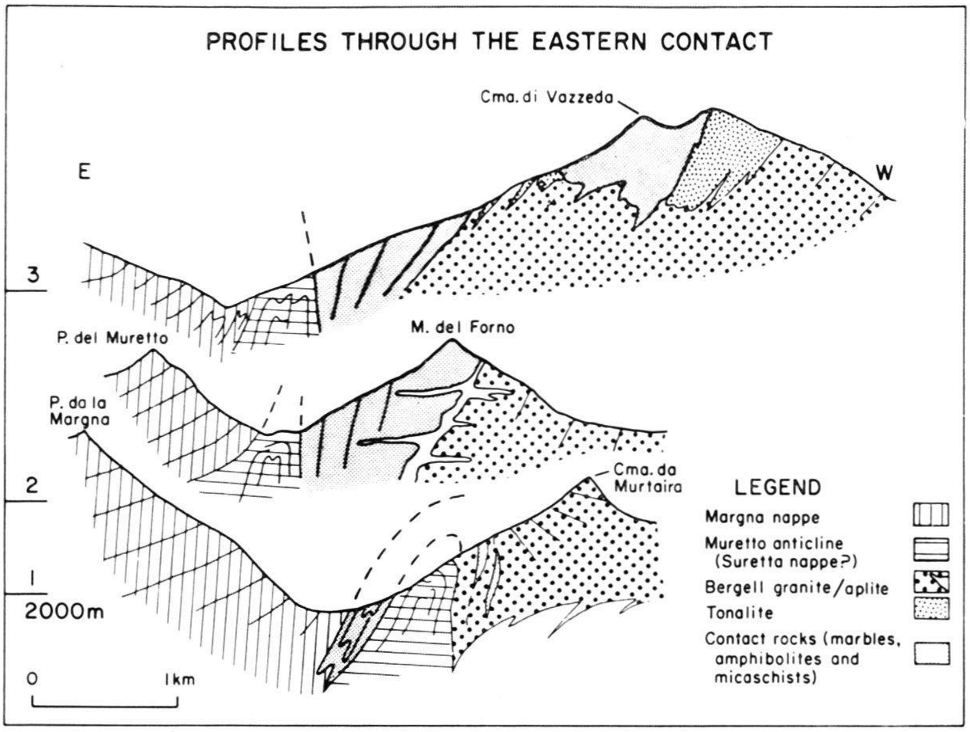

Fig. 7. Eastern contact of the Bergell granite. Top: View from Maloja pass towards Monte del Forno. Bergell granite (to the right) is separated from the Margna nappe (left) by Muretto anticline (photo Swissair). Bottom: E-W profiles through the eastern contact (for traces, see Fig. 3).

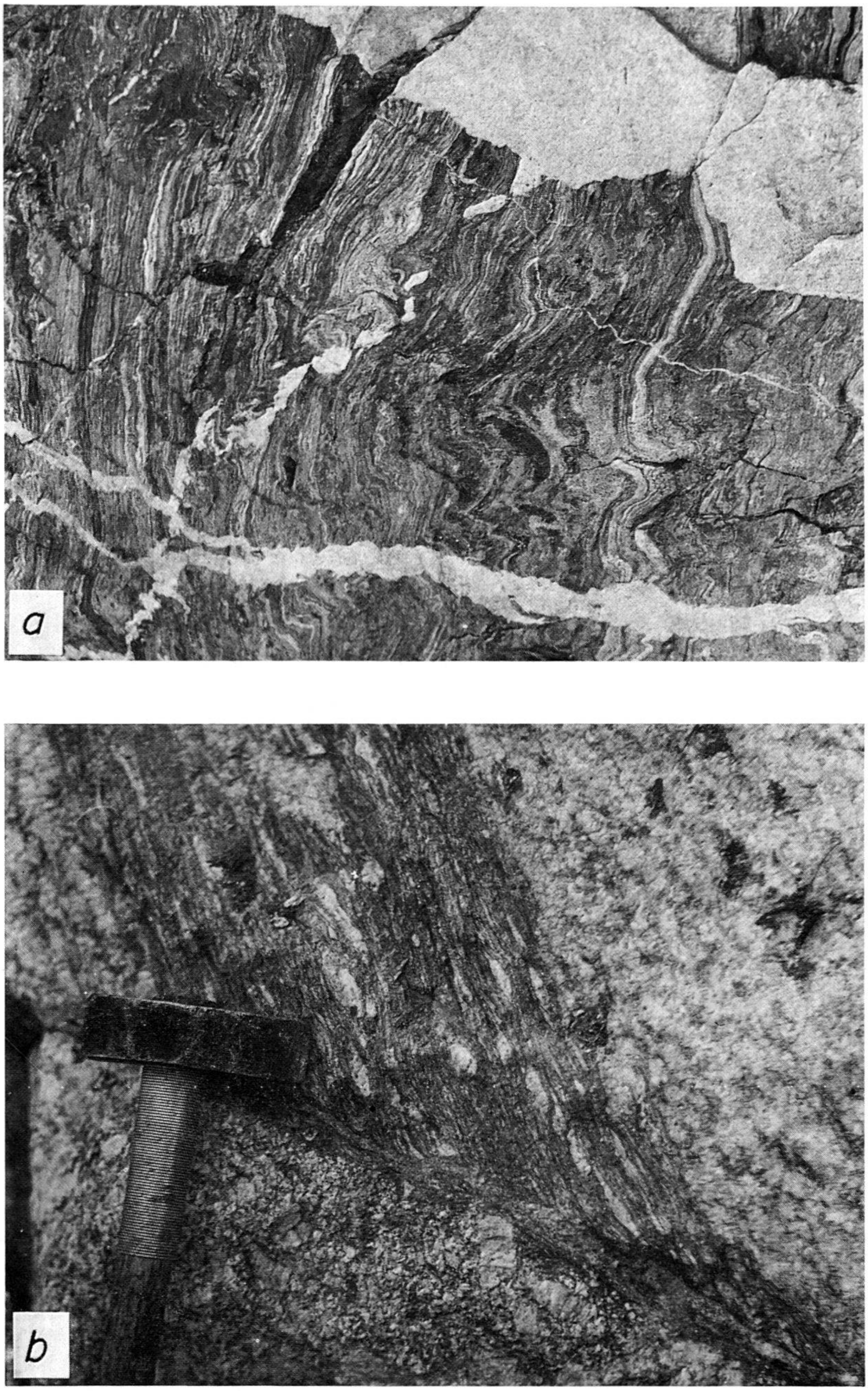

Fig. 8. Northern contact of the Bergell granite. a) Aplite dike crosscutting folded amphibolites close to granite contact. W. Cima di Murtaira. b) Strongly sheared granite in contact with undeformed granite. V. Albigna.

megacrystic granite (Fig. 8b). Deformation is more pronounced near the contact marked by stretching of dark inclusions and parallel alignment of alkalifeldspar megacrysts (Fig. 9a, b). Close to the contact hornblendite inclusions become abundant.

The rock units along the *northern border* of the Bergell granite form an anticline with sheared and strongly folded rocks. The isoclinally folded Gruf migmatites disappear east of Vicosoprano as does the Tambo nappe, thinning out at a constant rate east of Chiavenna. The Suretta nappe is equally sheared and folded near the contact and strongly reduced in thickness.

Some of the most spectacular outcrops of the contact are at Alpe Trubinasca (NW P. Badile), and in upper Val Codera. The granite plate rests as a horizontal plate on the isoclinally folded gneisses of the Gruf. A metasomatically, strongly altered ultramafic breccia (ARTUS 1959) on the thrustplane is obviously related to emplacement of the granite (Fig. 12c).

Apart from these outcrops in Val Bondasca and Val Codera, the *window of Bagni di Masino* and other smaller windows exposing rocks underneath the granite are the best evidence for the plate-structure of the Bergell granite. In the attractive valley of Bagni di Masino, known for its hot spring, tonalites, amphibolites, migmatites, mica schists, calcsilicates and ultramafic rocks – all indistinguishable from rocks in Val Codera and V. dei Ratti – appear below the granite in an anticlinal structure. The petrography of these rocks, heretofore regarded as roof pendants, has been described by CRESPI and SCHIAVINATO (1966). A subsidiary small window, only exposing hornblendites and amphibolites in upper Val di Ferro, is a direct continuation of the Masino rocks, expected from the regional 20° NE dip of the fold axes. Thus the plate structure extends towards the central part of the granite, possibly as far as Albigna. A window, presently covered by the glacier, may exist in the back part of Val Albigna. Two big moraines which reach the glacier surface at the junction of the Castello and Ferro glaciers contain large amounts of hornblendites and hornblende gabbros. In Albigna valley there are only very small outcrops of amphibolite lenses on the crest NE Passo di Zocca (P. 3,012 m) and at Sciora di Dentro, which do not account for this material. The source of the moraine blocks, which strongly resemble the amphibolite-hornblendites and tonalites of V. Masino is probably in the ice-covered bottom of the valley.

Further indication that horizontal structures dominate in the central Albigna-Forno area is the slab of nonmegacrystic granite mentioned above.

The *southern border* of the Bergell granite consists of a broad synclinorium in the fairly inaccessible mountains S of V. di Mello. A narrow syncline of megacrystic granite in upper V. della Spluga–Alpe Merdarola (Profile 2 in Pl. III) progresses eastwards into a broad isoclinally folded structure. Isoclinal folding of these rocks is documented by the gradational contact of Bergell granite with tonalite. The contact is represented by a mixed zone of variable composition and rich in inclusions of hornblende quartz diorite that show a strong preferred orientation. The nonmegacrystic granodiorite of A. Pioda is also part of this heterogenous transition zone (CORNELIUS 1972).

These macroscopic structures, ascertained from field evidence, are summarized in the cross-sections in Plate III and Figure 7, bottom. Excellent three-dimensional outcrops leave little freedom for the interpretation of the geological map. Profiles and

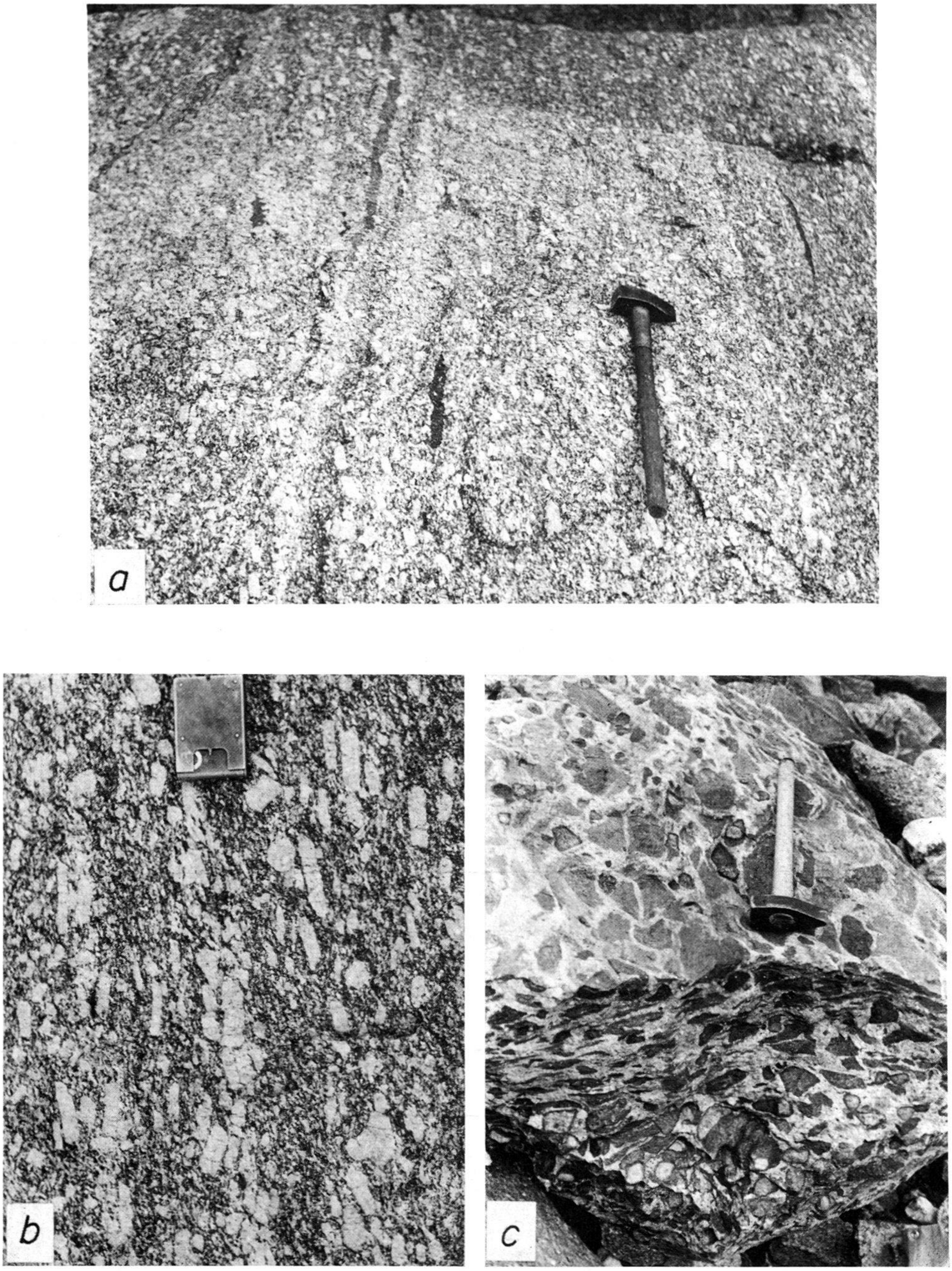

Fig. 9. Val Bondasca (upper Alpe Trubinasca). a) Foliated granite. Notice preferred orientation of the alkalifeldspar megacrysts and elongated inclusions. b) Preferred orientation of alkali-feldspar megacrysts in Bergell granite. c) Ultramafic breccia at base of the Bergell granite.

structural data (e.g. Fig. 6) indicate strongly that the Bergell granite is not a post-kinematic intrusion. Throughout, the granite has been deformed – less in the center than near the contact – in a similar strain field as the country rocks. Therefore, formation of the granite had to precede these tectonic events which are most likely connected with the main phase of the Alpine orogenesis in the area. Magmatic contacts in the Murtaira-Forno region are probably relics of the original pre-Alpine or early Alpine intrusion which have been dragged along during the mechanical emplacement.

Tonalite

An epidote- and alkalifeldspar-bearing hornblende-biotite-andesine gneiss (tonalite, "serizzo")[4]) envelopes the granite as a large body to the south and as a thin band to the west and northwest. The rock resembles in hand specimens the Tertiary tonalites of the Adamello. As already described the contact between granite and tonalite is rarely sharp; indeed a strongly oriented megacrystic granite changes over a distance of 50 to 200 m into tonalite. The complicated structures in this transition zone indicate isoclinal folding, although actual folds are rarely seen. An abundance of dark inclusions in a matrix enriched in alkalifeldspar megacrysts and many quartz-feldspar mobilisates are typical of this contact zone. In the center, the tonalite is quite homogeneous.

Alignment of hornblende *b*-axes (MOTICSKA 1970) produces a lineation that can be measured in the field and is parallel to the contact. The E dipping structures to the southwest and the S-dipping structures to the east join steeply SW-dipping in a vortex structure at Preda Rossa (Pl. II and Diagram 11 in Fig. 2). The contact with the Disgrazia ultramafic rocks is marked by a band of amphibolites and marbles and intensely folded pelitic schists which show strong retrograde metamorphism, clinozoisite and epidote replacing biotite and plagioclase. Occasionally the tonalite contains inclusions of hornblende-fels, more rarely of talc-olivine rock and calcsilicates. The tonalite grades into amphibolites in the Trubinasca-Bondasca area to the NW and in upper V. Sissone to the NE. In V. Sissone this transition is sharp; over a range of only 100 m, amphibolites gradually become coarse-grained, attain gabbroic character containing feldspathic mobilisates and grade into tonalites. There is no question in these places that tonalite originated from mobilization of amphibolites and that the two rocks formed from the same initial material.

On the southwest, close to the Insubric line, the tonalite forms a large body with N-dipping foliation. Internal structures and the varying thickness indicate that the extension there is produced by repetition through folding probably similar to the Bergell granite in a synform. The tonalite decreases markedly in thickness west of Valle della Mera and forms a thin zone of disconnected lenses just north of the Insubric line (WEBER 1957), extending as far as Bellinzona.

Root-zone

A thin sequence of high-grade metamorphic rocks of uncertain tectonic relationship borders the tonalite to the south. Farther south and adjacent to the above unit,

[4]) The term "tonalite" is in common usage among alpine geologists and therefore we apply it in this paper. It should be noted however that the Bergell tonalite is distinctly different from tonalite of the type-locality at Tonale Pass (Italy). "Serizzo", the Italian term, would be more appropriate.

in the north slopes of V. Sasso Bisolo and V. di Spluga, the root-zone begins. EW-striking foliations dip increasingly N towards south in a fanlike structure (Diagram 12 in Fig. 2 and Pl. III). In the northernmost part of the root zone there is a system of steep fold axes and lineations (Pl. II) that point to vertical movements of two blocks along a N-S fault line, possibly caused by subduction of the tonalite beneath rocks of the root-zone. Prevalent rock types are sericitic gneisses and granites (Prato Tabiate), the latter resembling Bernina granites. All are strongly sheared and show effects of retrograde activity. Farther south, the Tonale schists extend over 500 m to the Insubric line. There is not much difference either in structure or rock types north and south of this major fault line. A more important boundary for the Bergell Alps is the contact between the tonalite and rocks of the root zone (i.e., between the Pennine zone and Austroalpine nappes), which separates two realms that have undergone a remarkably different deformation history. It is important to note the lack of roots for the Pennine nappes (except for Margna and possibly Suretta) in the root zone south of the tonalite.

Novate granite

The nonmegacrystic, homogeneous *Novate granite* ("granito di San Fedelino", PICCOLI 1957, 1961) is emplaced in the apex of the Adula antiform and the surrounding units such as Gruf complex and Zone of Bellinzona at least 1,500 m below the lowest outcrops of Bergell granite. It has no, or only very weak, foliation and often appears as a migmatite replacing country rock. The center of this granite, which penetrates the surrounding rocks as a *radiating dike system*, is on the eastern prolongation of the Adula antiform. The age is definitely Alpine and E. WENK (1956) and BLATTNER (1965) have related the granitic activity – more anatexis than magmatic intrustion – to the Lepontine regional metamorphism. In any case, there is no direct relation between the Novate granite and the megacrystic Bergell granodiorite, and the common color of the two rock types even on the most modern maps is misleading. Microgranitic, aplitic, and pegmatitic dikes which penetrate the Bergell granite in large swarms may be related to the Novate granite. These dikes vary in composition and texture. All are less deformed than the Bergell granite and crystallized at a late stage when the granite was already rigid. Crystallization from hydrothermal solutions is more likely than magmatic intrusion (WENK 1970), especially for the beryl bearing pegmatites which are often zoned, the coarsest phase being in the center. Relative age-relations indicate that Novate and micrugranitic dikes are usually the oldest and pegmatites generally younger than aplites. But occasionally this age-relation is reversed indicating a rather similar age for all these phases. These dikes are strongly oriented in a large area, striking EW and dipping gently N (Fig. 10b). The dike pattern is surprisingly independent of all other structures and also unrelated to the present joint system in the Bergell Alps (Fig. 10a). The poles of joint planes coincide mostly with the lineation (ac-joints) and fit well into the regional joint-pattern (WENK 1966). Pegmatite dikes, although particularly common in the Bergell Alps, occur in the whole southern zone of the Lepontine as far west as Domodossola.

Faults

Various types of faults are present in the Bergell Alps. The youngest are joints and shear zones, that generally run parallel to each other. They do not produce any

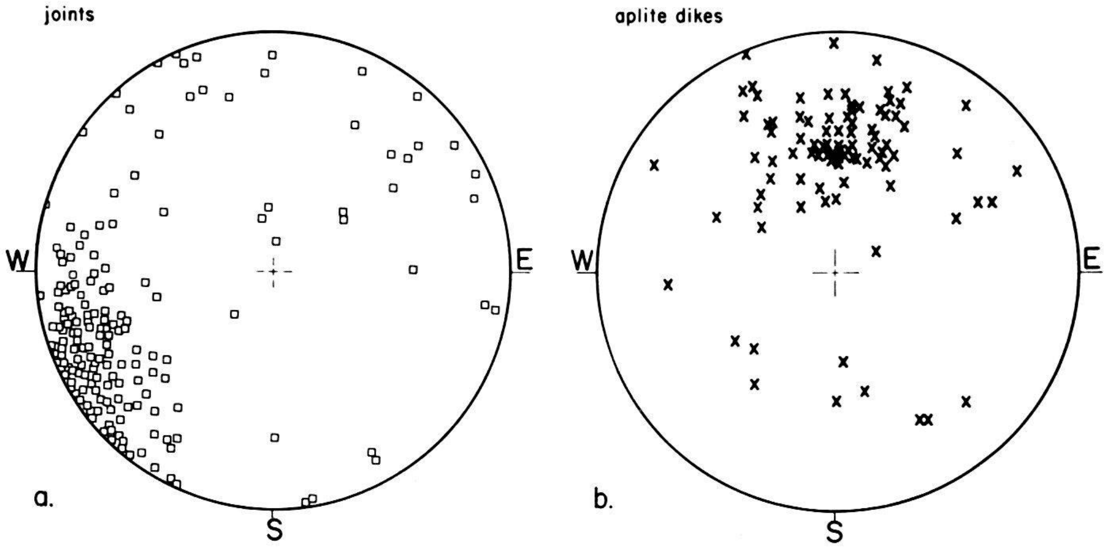

Fig. 10. Orientation of joints (a) and aplite dikes (b) in the central Bergell Alps. Poles are plotted in equal-area projection on upper hemisphere.

sizable displacement but have considerable impact on the morphology (e. g., the Val Piana Canyon in V. Codera). Of greater importance are the EW-normal faults, the most important one being the Insubric Line (Tonale Line) (see insert map in Pl. I and II), with a southern plate which is tectonically several kilometers higher than the northern one. The second major normal fault in the eastern Alps, the Engadine Line, can be traced as far as Casaccia but has no great significance in the Bergell. Other important faults are thrust planes separating the nappes, the most pronounced discontinuity being between the Pennine and Austroalpine nappes. Many of these thrust planes are composed of mechanically weak Triassic sediments ("Deckenscheider"). Of special importance and unique to the Central Alps is an extensive zone of extremely deformed mylonites along the fault planes between the Gruf complex and Tambo nappe, between the Gruf complex and Bergell granite and also in narrow zones inside the Gruf migmatites.

Microtextures

Despite the strong preferred orientation of parallel elements depicted in the structural maps, hand specimens of Bergell granite do not cleave parallel to the foliation and therefore, by definition, the Bergell granite should not be termed a gneiss. Yet, preferred orientation of megacrysts, mica, and dark inclusions was not, or was only rarely attained before complete crystallization of the rock as a flow texture in a molten magma. Nor has preferred orientation been formed during crystallization in a stress-field, like the Lepontine gneisses; nor is it the result of granitization of gneisses. The orientation is definitely the product of intense deformation in a predominantly solid state. The evidence for this – apart from macroscopic structures – can be seen most readily in thin sections. In Figure 11 various specimens of Bergell granite are compared with a typical igneous granitic rock, a quartz monzonite from the Cathedral peak pluton (Sierra Nevada, Calif.). In the latter, large quartz grains crystallized between more or less euhedral feldspars (Fig. 1 a). One never finds a large undisturbed quartz crystal in the Bergell granite. In the northeast corner where deformation is least

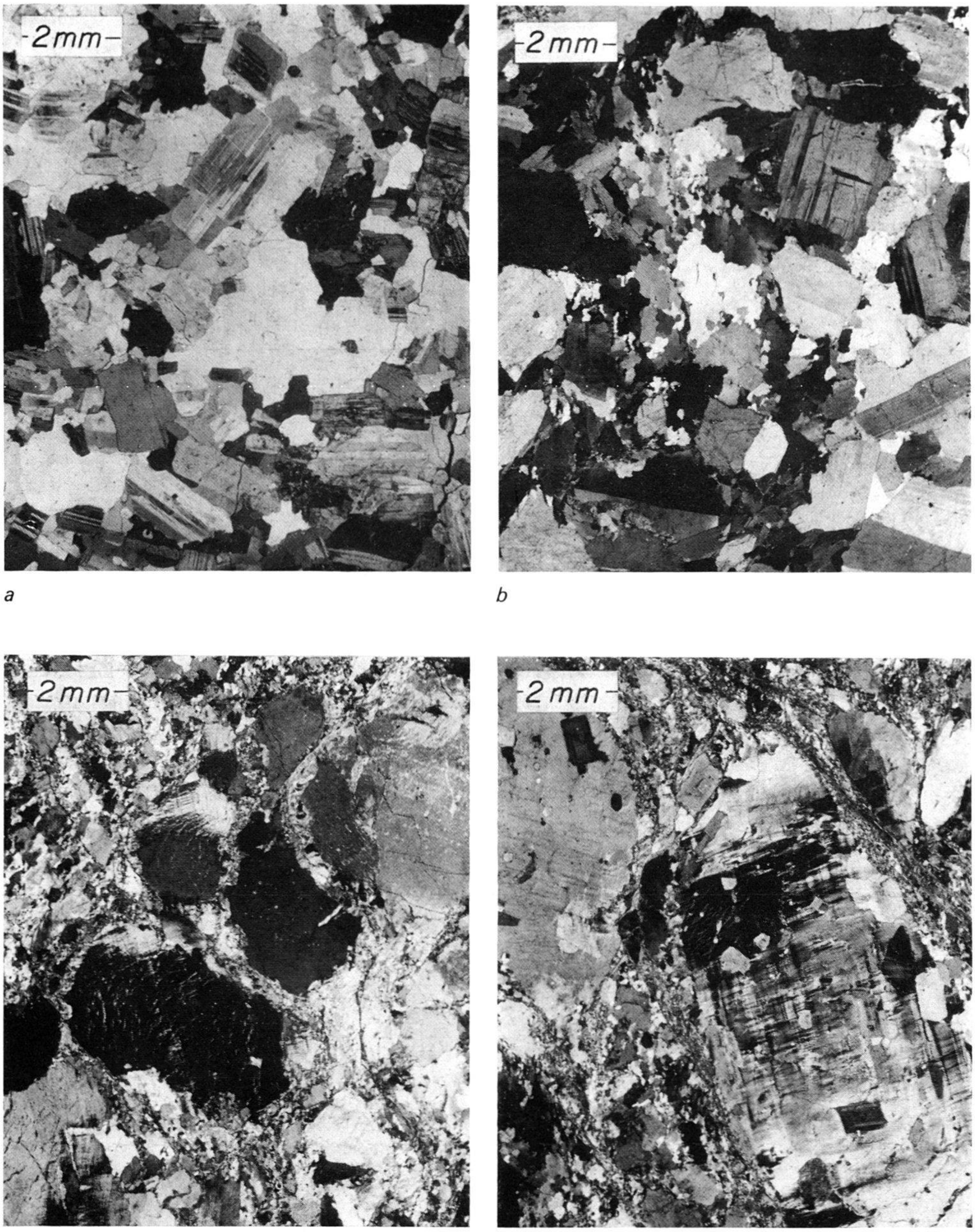

Fig. 11. Photomicrographs of granitic rocks. Crossed polarizers. a) WW2 Cathedral peak quartz monzonite. Sierra Nevada, California (for comparison). b) Sci 393b. Central Bergell granite. NW Sciora di dentro. a) Sci 492. Deformed Bergell granite. V. Albigna, contact. d) Sci 309. Mylonitic Bergell granite. Cant la Foja, N P. Cengalo.

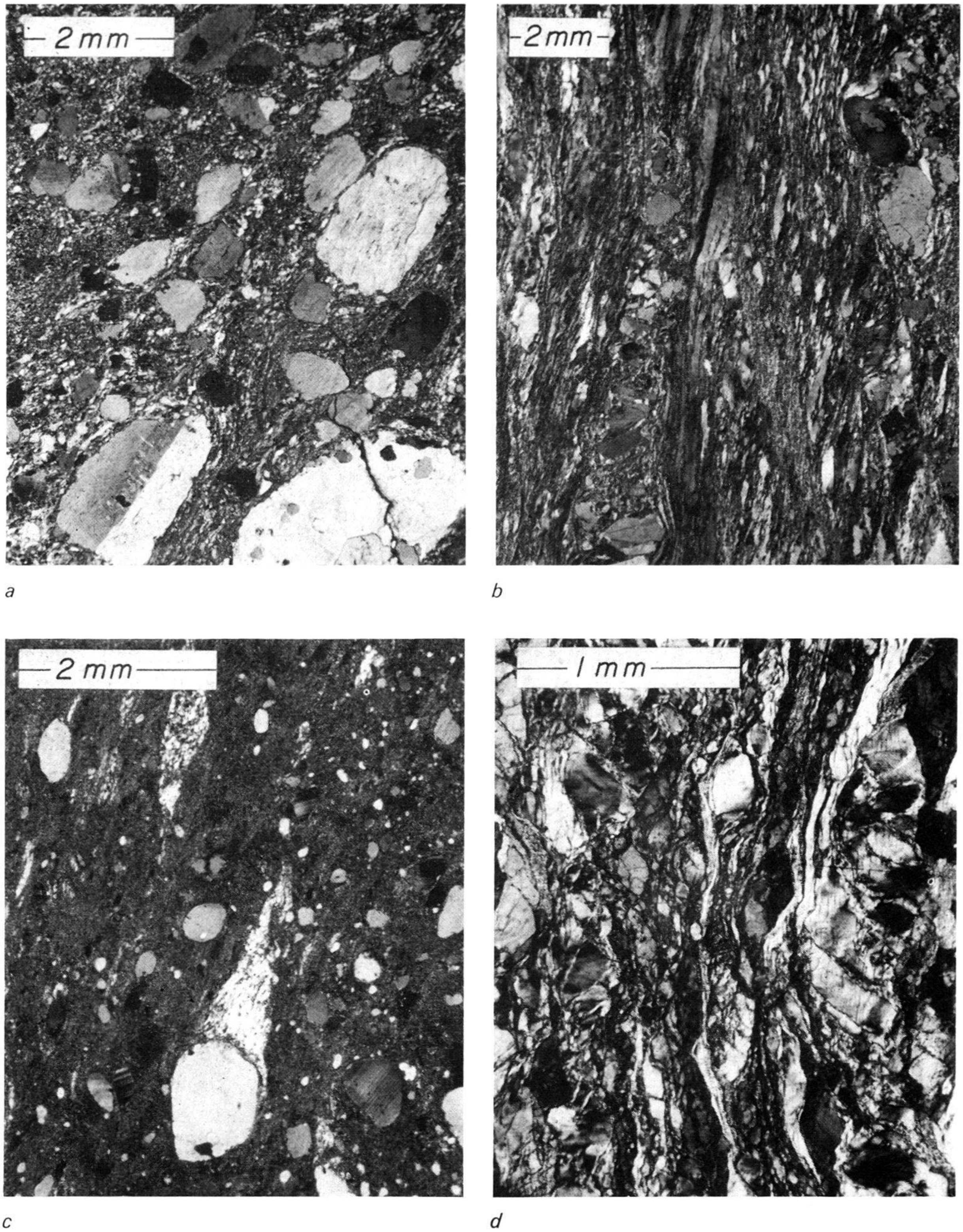

Fig. 12. Photomicrographs of mylonitic rocks close to the granite contact (1 km). a) Sci 308. Bergell granite N P. Cengalo. b) Sci 535. Tambo gneiss, V. Torta, 1,070 m, S. Vicosoprano. c) Sci 216. Gruf migmatite, Btta. Tegiola. d) VW 35. Experimentally deformed Cathedral peak quartz monzonite (compare Fig. 11a). Conditions: 900 °C, 15kb confining pressure, 10^{-6} sec^{-1} strain-rate, 60% shortening.

distinct, quartz shows undulatory extinction (Fig. 11b), but more commonly large quartz grains are broken into a fine agglomeration (Fig. 11c). Close to the contact, fairly euhedral feldspars (K feldspar megacrysts and plagioclase) float in a fine matrix of crushed quartz and micaceous material (Fig. 11d).

In addition to this cataclastic reduction of grain-size much of the quartz reveals plastic deformation and mylonitic recrystallization with highly flattened grains exhibiting intense preferred orientation (Fig. 12a). Feldspars are generally resistant to deformation although some are bent and rounded. The euhedral contours of feldspars even in strongly strained granites explain why mylonitization in granite is easily overlooked in hand specimens. Mylonitic textures are not restricted to the Bergell granite. They are found in the Tambo gneisses (Fig. 12b) close to the thrust plane. The most beautiful ultramylonites occur in the Gruf migmatites (Fig. 12c), in which plagioclase is slightly rounded but otherwise undeformed, and mica and quartz, which are separated into bands, are extremely fine-grained with strong preferred orientation. Quartz has recrystallized, first along grain-boundaries of large relict grains. The new grains are small and flattened, indicating plastic deformation.

These same textures which are found in the mylonites of the Bergell Alps can be reproduced in the laboratory. Deformation of Sierra Nevada granitic rocks (Fig. 11a) in a constant strain-rate piston-cylinder apparatus with talc as the confining pressure medium, at high temperatures (850–900°) and pressures (15 Kb) and large strains yielded textures resembling those of the Bergell granite (Fig. 12d). Feldspars are rounded and slightly bent, often with a tail of very fine-grained recrystallized quartz showing strong preferred orientation. Mica is fine-grained and concentrated in bands. Of course, there is no direct quantitative correlation between the conditions in these experiments and natural conditions during formation of mylonitic textures. High temperatures (> 850°) were needed to dehydrate the talc jacket in order to obtain free water diffusing into the specimen and causing hydrolytic weakening in quartz (GRIGGS and BLACIC 1965, GRIGGS 1967). If water is available, then weakening may occur at much lower temperatures (380°C at 0.13% water content, GRIGGS and BLACIC 1965). High pressures were required in the experiment to prevent melting at these high temperatures. Thus, both temperature and pressure were much higher in the experiments than those which existed in the natural environment in the Bergell Alps. Strainrates of 10^{-6} and 10^{-5} sec^{-1} were orders of magnitude faster than found in nature. At temperatures below those of dehydration of talc, deformation was brittle.

In the high temperature-experiments, the effects of hydrolytic weakening were always much stronger for quartz than for feldspars so that quartz showed plastic flow around rigid feldspars, as it does in natural specimens. Dry quartz is stronger than dry plagioclase (BORG and HEARD 1970); thus, hydrolytic weakening must have an important role in the formation of these characteristic mylonitic textures in granite.

The textures of quartz resemble strongly those produced in experimental deformation of flint and quartzites (GREEN et al. 1970, TULLIS 1971), and this suggests that the mode of deformation was recrystallization and plastic flow at elevated temperatures. The average strain in the Bergell granite may be 20–50%, but, in local areas, especially near contacts, it reaches many hundred percent, producing the above described mylonites and ultramylonites. This post-crystallization deformation makes it likely that most of the parallel structures (foliations and lineations) in the granite

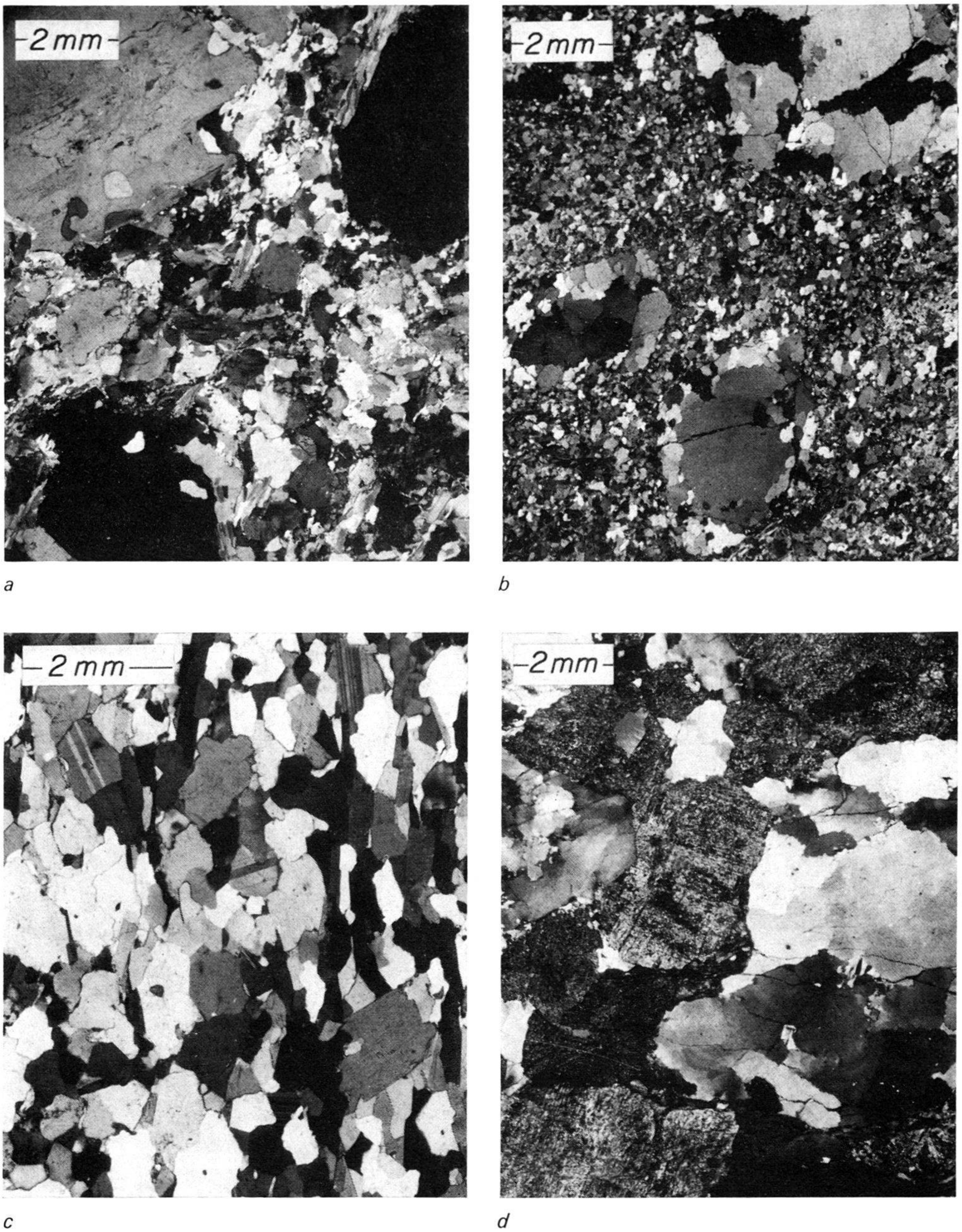

Fig. 13. Photomicrographs of granitic rocks of the Central Alps (for comparison). a) Sci 128. Novate granite ("granito di San Fedelino"). Quarries near Novate. b) Sci 591. Chiavenna granite (Tambo nappe). Liro-outcrop S San Giacomo. Notice the coarse quartz agglomerations. c) Os 40. Lepontine gneiss (Leventina). Quarries near Osogna, Ticino. Polygonal texture. d) GP 105. Julier granite (Austroalpine). Notice sericitic feldspars and deformation lamellae in quartz.

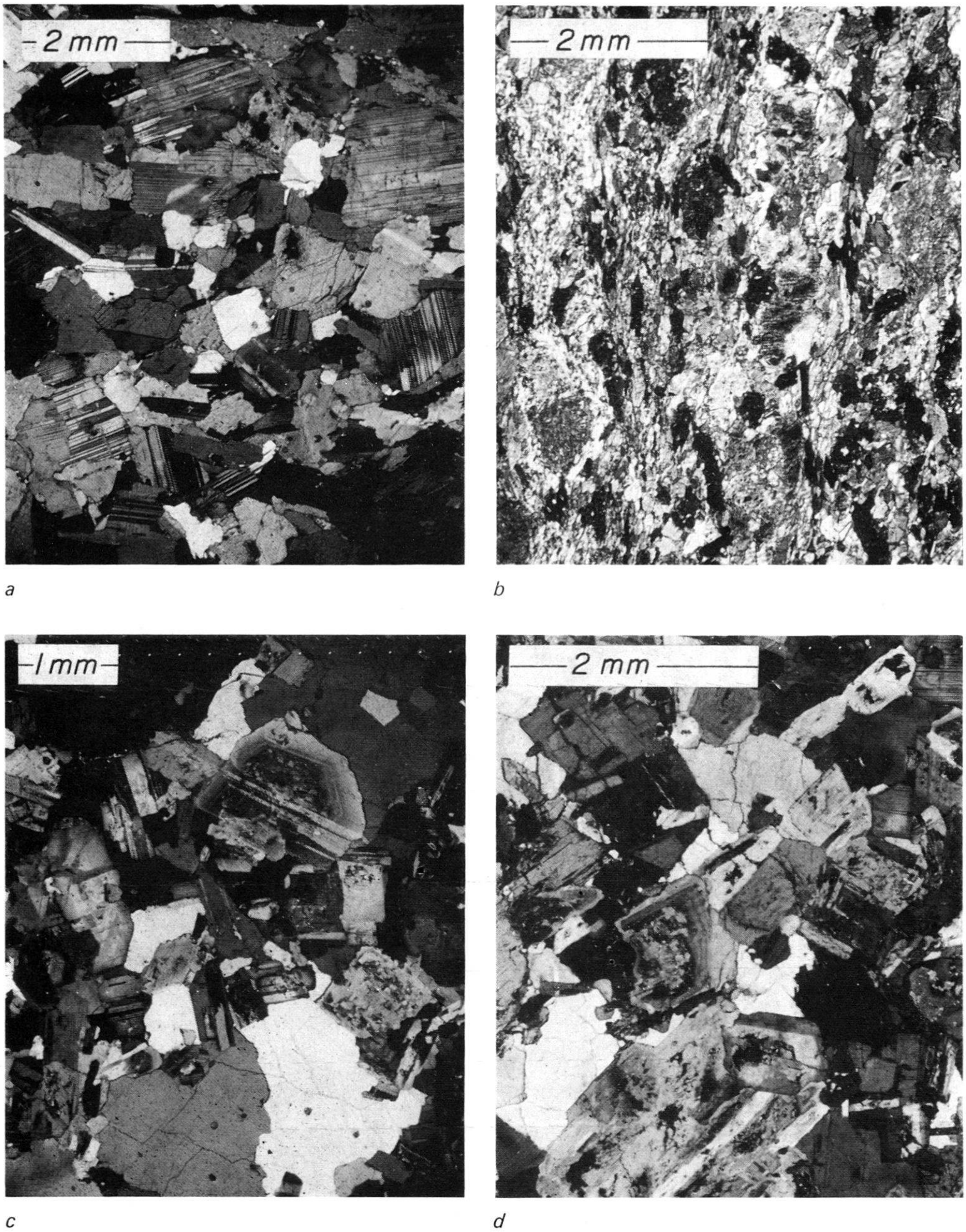

Fig. 14. Photomicrographs of tonalitic rocks of the Bergell Alps and the Adamello massif. a) Sci 714. Tonalite ("Serizzo"). Quarry between Bagni Masino and San Martino. b) Sci 866. Deformed tonalite, near contact with root zone. Cataeggio, V. Masino. c) Sci Ad 18. Tonalite. Lago Bissina, V. di Fumo, Adamello massif. d) Sci 698. Quartz diorite of Sondrio. Triangia, NW Sondrio.

are product of this deformation and not of magmatic flow or metasomatic granitization of gneisses. In the higher NE part of the granite, deformation is more brittle and heterogeneous, with shear zones separating blocks of undeformed material (Plan Canin), presumably because the temperature was much lower. Green biotite is frequently altered to chlorite. Deformation in the east is cataclastic in contrast to the mylonitic deformation in the west.

On the basis of these characteristic deformation features, the Bergell granite is easily distinguished from other granitic rocks in the Central Alps. Similar textures are found only in the *augengneisses of the Tambo nappe* directly adjacent to the Bergell granite (Fig. 12b) and in the *Novate granite* (Fig. 13a), suggesting the arther astonishing fact that even this young granite has undergone considerable post-magmatic deformation.

Augengneisses and granites in the Tambo nappe further west (*Chiavenna, Truzzo*) show a fabric of clusters of coarse mosaic quartz in a matrix of fine-grained quartz and feldspars (Fig. 13b), unlike textures seen in all other granitic rocks inthe region.

Another area which has undergone Alpine recrystallization is the Lepontine. Quartz in the Lepontine gneisses in the Ticino has recrystallized during or after the main deformation (WENK 1965) and shows a perfectly polygonal mosaic fabric with large, only slightly undulatory quartz grains (Fig. 13c). This is different from the Bergell granite which has often been compared with the Lepontine gneisses and interpreted as the result of the same geological event. The time relation between crystallization and deformation in these two regions was different. Granites of the *Gotthard massif* (GRÜNENFELDER and HAFNER 1962) are less deformed than the Bergell granite and the old granites of the Austroalpine nappes (*Julier, Bernina*) have been deformed at lower temperatures. Most of the feldspars in these latter rocks are altered to sericite, and large relic quartz grains are full of deformation lamellae (Fig. 13d). The Tertiary *Adamello igneous rocks* (BIANCHI et al. 1970) are on the whole undeformed with large quartz grains filling spaces between euhedral feldspar crystals. Plagioclase is strongly zoned (Fig. 14c), in clear contrast to granitic rocks of the Bergell. Tonalites of the Adamello massif have the characteristics of a rock crystallized from a magma whereas tonalite in the Bergell (Fig. 14a) has the mosaic texture of a recrystallized metamorphic rock and often is deformed like the Bergell granite (Fig. 14b). Resembling the granitic rocks of the Adamello is the *quartzdiorite of Sondrio* (CORNELIUS and FURLANI 1930). Figure 14d shows a typical example. All these rocks are very different in texture from rocks found in the Bergell and can be distinguished from the latter unmistakably. Based on this petrographic evidence and the fact that the characteristic K-feldspar megacrysts are missing in the Adamello, and a completely different tectonic position it is difficult to envisage any direct connection between the igneous rocks of the Adamello (and Sondrio) and the granitic rocks of the Bergell despite their similar age.

Strain in the deformed Bergell granite is depicted less by preferred orientation of mica, as in the Tessin gneisses, as by subdivision and mylonitic recrystallization of quartz. Thus, in conclusion it can be said that the appearance of quartz in thin sections helps to identify these granitic rocks, and a *regional survey shows that penetrative mylonitic recrystallization of quartz is confined to the Bergell Alps.*

Preferred orientation

A quantitative study of preferred orientation of quartz, mica and calcite in various rock units of the Bergell Alps is part of a separate study (Bunge and Wenk 1973). Here we show only a few important pole-figures to illustrate variation in preferred orientation of quartz (Fig. 15). These pole-figures have been determined with a pole-figure goniometer either from an overlap of a reflection and a transmission scan or from an overlap of reflection scans taken on three slabs (Baker et al. 1969). Since the pole-figure for 0003 is difficult to measure (weak reflection, close to the strong diffraction peak $11\bar{2}2$), $10\bar{1}4 + 01\bar{1}4$ which is close to *c* is given as a substitute.

A fine-grained quartz-mylonite from Btta. Tegiola (Gruf complex, near granite contact) shows extremely strong preferred orientation of crystallographic *c*-axes parallel to the hand-specimen coordinate a (in the foliation plane s, normal to the lineation l, Fig. 15a, b). Not only is the *c*-axis oriented, *a*-axes also are fixed parallel to l (lineation, Fig. 15a). This fabric compares well with the classical high temperature quartz mylonites of the Moine-thrust in Scotland (Christie 1963, Baker and Wenk 1972). Notice the minor but significant deviation of fabric symmetry axes from the mesoscopic fabric coordinates. A completely different pattern of preferred orientation exists in the low grade metamorphic presumably Triassic quartzite layers of the higher nappes. A muscovite quartzite from the Suretta nappe near Vicosoprano with polygonal mosaic texture shows preferred orientation of *c*-axes normal to the foliation with random distribution of *a*-axes in the plane of foliation (Fig. 5c, d). Suretta quartzites further north in Avers have slightly flattened grains also with *c*-axes normal to the foliation (Fig. 15e, f). Basal slip (Christie et al. 1964) may have been the mechanism that produced this fabric. An important feature of these last two rocks is the consistent deviation of fabric symmetry axes from mesoscopic coordinates and in these excellently foliated and lineated quartzites, there is no uncertainty in choosing fabric coordinates. The foliation may represent an old sedimentary bedding plane and the symmetry of the strain-field during deformation was different so that quartz crystals were reoriented accordingly.

In the quantitative analysis of the above mentioned fabrics (Bunge and Wenk 1973), which will include derivation of the orientation-distribution function from pole-figure data, special attention will be given to the difference in orientation for positive and negative rhombs in order to evaluate the significance of Dauphiné-twining which was shown to be an important mechanism in experimentally deformed quartzites (Tullis 1970).

Crystallographic evidence

Polymorphism of wollastonite can be used as an indicator for the deformation-history of metamorphic rocks (Wenk 1969). Disorder along a^* presumably caused by (100) stacking faults and visible as streaking of reciprocal lattice points parallel to a^* has been produced in the laboratory in syntectonic deformation experiments of 1 T wollastonite. Consecutive annealing may produce the 2 M and 4 T polymorphs which are typical for wollastonites in deformed calcsilicate rocks. Figure 16 displays the distribution of the various wollastonite polymorphs in the Bergell Alps. Wollastonite is found quite frequently in calcsilicate bands and lenses in amphibolites and less often in tonalites surrounding the Bergell granite. It also occurs scattered from east

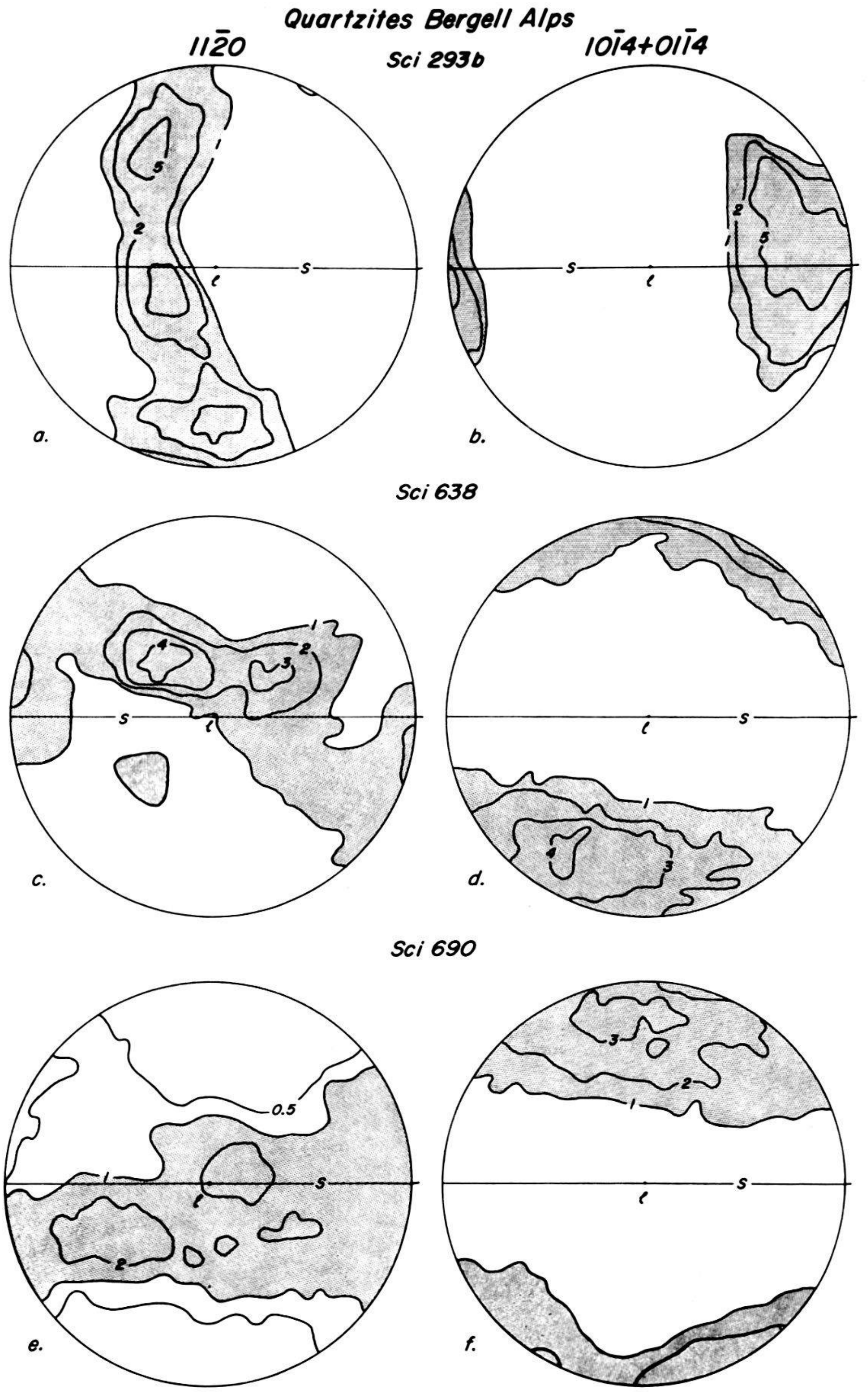

Fig. 15. Pole-figures measured on a X-ray pole-figure goniometer. Equal-area projection on upper hemisphere, contoured in multiples of a uniform distribution. Foliation (s) and lineation (l) are indicated. a) Sci 293. Quartzite mylonite in Gruf migmatites underneath the Bergell granite, Btta. Tegiola (1-slab reflection-transmission overlap). Quartz $11\bar{2}0$. b) Idem. Quartz $10\bar{1}4+01\bar{1}4$. c) Sci 638. Triassic quartzite, Suretta nappe, S P. dal Cam. (3-slab reflection overlap) Quartz $11\bar{2}0$. d) Idem. Quartz $10\bar{1}4+01\bar{1}4$. e) Sci 690. Triassic quartzite, Suretta nappe, Avers (3-slab reflection overlap). Quartz $11\bar{2}0$. f) Idem. Quartz $10\bar{1}4+01\bar{1}4$.

to west in the Gruf migmatites, generally associated with zones of mafic and ultramafic inclusions. In the western part of the Bergell Alps it forms a constituent of the calc-silicate layer separating the Gruf masse and the Adula nappe. The eastern occurrences are clearly associated with the Bergell granite. There is no simple pattern in the distribution of polymorphs. This is not surprising if stress and strain are causative factors. It has been amply shown in the description of macro- and microscopic structures that strain is very heterogeneous. From Figure 16 it appears that 1 T-structures are confined

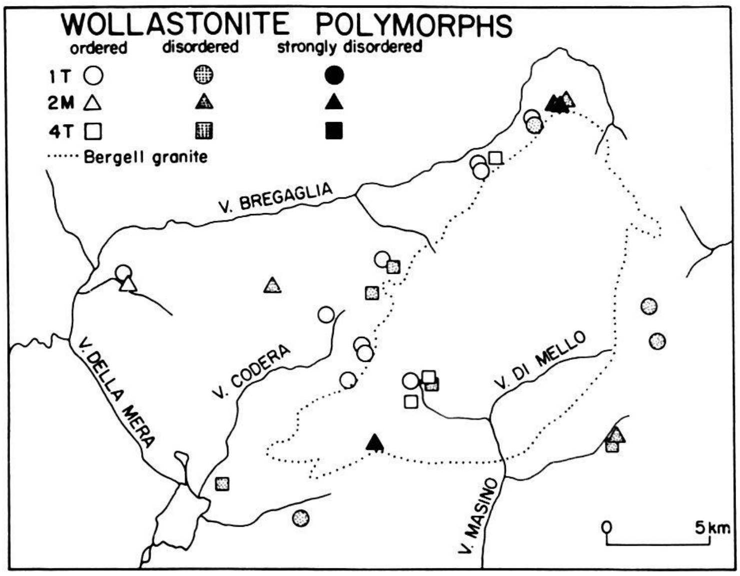

Fig. 16. Distribution of wollastonite polymorphs in the Bergell Alps. Determined on hk0 und h1l X-ray precession photographs.

to the central Bergell Alps. A possible explanation for this distribution of polymorphs is that 1 T-wollastonite has been produced as a contact mineral in the carbonate rocks during intrusion of the granite. Subsequent deformation produced at low temperatures (in the east) stacking-faults with 1 T-d polymorphs, and at intermediate temperatures with annealing (in the center and the west) partially disordered 2 M and 4 T polymorphs. West of Valle della Mera, wollastonite may be a product of the postkinematic Lepontine regional metamorphism, and the crystal structure does not show effects of deformation.

Formation of clinoenstatite from orthoenstatite is another similar transformation favored by nonhydrostatic stress (TURNER et al. 1960, TROMMSDORFF and WENK 1968). Thus, it is likely that clinoenstatite will be found in kinks or small lamellae, possibly on a submicroscopic scale, in the frequently occurring orthopyroxenes. So far it has not been reported.

Discussion and conclusions

Evidence presented so far is based on observations in the field, detailed analysis of geological structures, microscopic textures, especially of quartz, and on crystallographic studies of polymorphs in chain silicates. From these considerations it is concluded that the Bergell granite has been strongly deformed in a strain field which is closely related to deformation of the nappes. It has been demonstrated by geological mapping and structural analysis that the Bergell granite does not cut discordantly across already emplaced nappes in presently exposed outcrops. Thus, this prime argument for its post-Alpine age is no longer valid and the age of the Bergell granite can no longer be used to date the end of thrust movements. This requires a reevaluation of the geological history of this area, and this in turn may have an impact on the chronology of a larger part of the Alps. The new evidence may cause considerable revision of old concepts in stratigraphy, structure and petrology of the Central Alps. It adds new constraints to geological models and eliminates many hypotheses discussed in the literature. However, it leaves other possible solutions than the model discussed in the following paragraphs. First the geological background on which the model is based is summarized.

The *structure*, derived mainly from mapping petrographic units in three dimensional exposures (Sciora quadrangle; WENK 1973) is best seen in the profiles in Plate III.

The granite is a deformed plate resembling a nappe in the west and a steeply S-dipping synclinorium-type structure to the south. To the east, the E-dipping granite disappears beneath the Margna nappe. There are indications (structures in Pl. I and II and window of Albigna) but no proof that the granite may possess a similar sheet structure in the central part and does not extend into great depth. A zone of hornblende rich rocks surrounds the granite. These mafic rocks compose a thin, highly strained band of amphibolite to the north and west (20–50 m), a thicker sequence to the east (200–400 m) and an extensive unit of massive hornblende-biotite-labradorite gneiss ("tonalite") to the south (1–2 km). The amphibolites grade into tonalites and must be regarded as part of the same general unit. These mafic rocks, which are accompanied by lenses and layers of micaschists, ultramafics, marbles and calcsilicate rocks, form the "*contact-unit*". They probably partially represent sedimentary and volcanic fill of the Alpine geosyncline.

Metamorphism is best exhibited in these mesocratic and melanocratic rocks. Although the metamorphism in the Bergell Alps is a topic of a separate study (WENK et al. 1974), some preliminary observations are anticipated.

The contact rocks show high metamorphic grade with assemblages such as calcite–anorthite–wollastonite, hornblende–labradorite, and garnet–biotite–cordierite–alumosilicates–plagioclase. These parageneses are normal for an igneous contact, but the rocks are not typical hornfelses since they are strongly foliated and their fabric is polygonal as in regional metamorphic rocks. Gradation in metamorphic grade is not common in the Bergell Alps and often obliterated by late tectonic events.

Biotite schists contain Mg-rich cordierite, sillimanite, and occasionally sapphirine at the base of the granite (V. Codera) and Fe-rich cordierite and andalusite at the eastern front (M. Forno). Triple points with all three aluminosilicates – not necessarily coexisting in equilibrium – are at Albigna–Motta Ciürela and Cataeggio (Masino). This difference in mineral assemblages is most likely related to the gradient in pressure between the bottom and roof of the granite body during crystallization.

A temperature gradient is found in mica schists of the intermediate zone between Gruf complex and Tambo nappe. Close to the core of the Gruf anticlinorium, sillimanite is common; farther north we find a zone of kyanite/staurolite, and in garnet phyllites of the Suretta nappe (P. Gallegione) chloritoid has been found (WENK 1974).

Another metamorphic zonation has been described by TROMMSDORFF and EVANS (1972) in olivine assemblages in the Disgrazia ultramafic rocks with talc-tremolite close to the tonalite-contact, antigorite-tremolite at 500–1,000 m from the contact and antigorite-diopside farther away. It has been interpreted as a direct local effect of the tonalite intrusion. Because of the thrust character of the contact, strong deformation of the ultramafic body and retrograde metamorphism in the accompanying clinozoisite-micaschists, the time-relation between this narrow metamorphic gradation and the Bergell rocks is not clear. On geometric grounds their concept that "the Pennine nappes are crosscut by the young Alpine Bergell intrusives" and that the Alpine regional metamorphism (Lepontine) preceeded the Bergell intrusion becomes doubtful.

If the distribution of index minerals is contoured, then the "isograds" of the Bergell seem to continue west into the isograds of the Lepontine (E. WENK 1962). Yet, it is undecided by how many metamorphic events and at which times these metamorphic assemblages were formed. The present apparently continuous extension of the isograds certainly gives a distorted image, because large-scale deformation has altered the geometry of the Bergell Alps after the original intrusion of the granite and formation of contact aureole. Clear tectonic offsets are found between the Forno-Rossi-Murtaira contact series and the Margna and Suretta nappes and between the tonalite to the south and the low-grade metamorphic rocks of the root-zone.

Twenty years ago, when the Lepontine metamorphism was discovered (E. WENK 1952), an old tectonic concept in the Central Alps was destroyed. The next decades were devoted to detailed study of these metamorphic events. Emphasis has been on mineral assemblages and chemical equilibria, and this generated considerable progress in understanding metamorphic reactions. But it has often been overlooked that simultaneous with the metamorphic recrystallization, tectonic movements continued which displaced the metamorphic assemblages spatially and therefore the drawing of isogrades in the Bergell Alps is of limited value. New structural evidence requires revision and refinement of the metamorphic argument.

Isotope distributions impose constraints on geological models. Age[5]) determinations on zircons by GRÜNENFELDER and STERN (1960) showed that the granite is of Tertiary age. But their study also made it clear that a more detailed investigation of ages was necessary to resolve many ambiguities. We therefore collected specimens for isotope analyses and are thankful to the Bern Institute for studying the isotope distribution in these rocks and for following our suggestion to conduct a survey of granitic rock types (GULSON 1971; GULSON and KROGH 1972; GULSON 1973[6]). From their data various episodes can be distinguished: Rb/Sr total rock ages of Gruf

[5]) "Age" in this paragraph is used as a number derived from isotope ratios. It may or may not coincide with a geological event.

[6]) After completion of the manuscript, I received a preprint of GULSON's (1973) isotope study which is printed in the same issue. The *excellent data* are of great importance for the Bergell geologist and they agree with structural data. But since Gulson bases his *interpretation* of age heavily on unspecified "field observations" that I do not agree with, and which are the subject of this paper, I would like to reply briefly to some of the conflicting conclusions in his summary taking in account constraints imposed by the structural reality.

1. Truzzo granite grades into Tambo gneisses both forming a single large unit of granitic rocks. It is difficult to envisage a rhyolite body of such dimensions. Thus, Truzzo granite (showing only granitic textures) may not be a volcanic rock as proposed by Gulson because of its similarity in age to Roffna porphyry.

migmatites are generally prehercynic (GULSON 1971) but there are exceptions (JÄGER and HUNZIKER 1969). Tambogneisses have a high Rb/Sr ratio and their Rb/Sr total rock ages lie very closely on a 280–300 million years isochron. They are significantly older than the Sr-rich Bergell granite. Thus the suggestion that the Bergell granite is merely recrystallized Tambogneiss – a hypothesis which would be possible on tectonic grounds – can be rejected. U/Pb data (GULSON and KROGH 1972) are more difficult to interpret. Monazite in Bergell granite from V. Albigna gave a concordant age of 30.3 million years. Zircons in Bergell granite, "tonalite" and Novate granite gave nonconcordant older ages lying on a chord from 30 million years towards 70–700 million years thus indicating that old material was remobilized about 30 million years ago. The fact that the tonalite has a 2–3 times higher zircon content than the Bergell granite clearly points to a different origin of these two rock types. Thus for geological reasons mentioned earlier and from these isotope arguments I disagree with the *interpretation* of JÄGER and HUNZIKER (1969) who visualize Bergell granite, Novate granite and tonalite as a product of magmatic differentiation 30 million years ago.

Pebbles of megacrystic granite appear in great abundance in the Oligocene South-Alpine molasse of Como and Chiasso (CITA 1957). GULSON and KROGH (1972) determined their age and obtained the same figures as for presently exposed granite in the Bergell, thus proving convincingly that these pebbles are indeed Bergell granite. The Bergell granite must therefore have extended at one time over a much larger area than it does today and was already being eroded in late Oligocene time, shortly after its formation.

All these ages are *older* than Rb/Sr ages in biotites, muscovites and total rock (JÄGER and HUNZIKER 1969) and U/Pb ages in monazite (GRÜNENFELDER 1972) of rocks in the central Tessin. Therefore for isotopic reasons, as well as on structural grounds, there can be little doubt that *crystallization of the synkinematic Bergell granite is older than the postkinematic Lepontine gneisses of the Tessin.*

Based on this preliminary information, a new hypothetical model for the geological history of the Bergell Alps is proposed, which is a slightly revised version of an earlier concept (WENK 1970).

Stratigraphers (TRÜMPY 1970; AZZAROLI and CITA 1967) described in detail the submerging Alpine geosyncline being filled by large amounts of sediments in Mesozoic time (Figure 17a). This material was deposited on a probably thin continental crust consisting of Hercynic granites (Tambo-, Suretta-augengneisses) and Prehercynic

2. Augengneisses of the Tambo nappe as well as most metamorphic rocks of the Bergell Alps including Mesozoic sedimentary rocks, have undergone at least partial Alpine recrystallization as is amply evidenced by textures and mineral assemblages.

3. For similar reasons I have to disagree with Gulson's statement that there is "no evidence of any connection of the Gruf migmatites with the Alpine metamorphism".

4. From my experience it does *not* "agree with field observations that the contact metamorphism of the Bergell intursion is superposed on the young Alpine regional metamorphism". It may be that errors in the isotope data are slightly larger than estimated (the Rb/Sr age of muscovite at Promontogno agrees within less than 2 standard deviations with the U/Pb ages of zircons and monazite in the Bergell Granite), or that the 30 million years age of monazite represents the age of metamorphism (Lepontine?) and rejuvenation while zircon ages, lying on a chord towards 70–100 million years, point to the true age of intrusion.

basement rocks (Gruf migmatites). A fair abundance of amphibolites indicates intensive volcanic activity (possibly metamorphosed relics of oceanic crust). Ultramafic bodies (Disgrazia–Malenco and Chiavenna) may be altered ophiolites but the larger olivinite masses are more likely peridotite massifs. During early Alpine crustal movements, some units were buried while others were overthrust, thus producing a thick sequence of overlying nappes. Deep in the geosynclinal trough, old granitic basement, geosynclinal deposits and possibly underlying basaltic oceanic crust became metamorphosed under conditions of the granulite facies and some of it was remobilized probably during subduction of the Lower Pennines, including parts of the geosynclinal deposits beneath the Southalpine plate.

Because of complete recrystallization of the original material through diffusional exchange and formation of Alpine igneous rocks, only vague speculations about the pre-igneous source of these rocks can be attempted. On structural grounds, there is reason to believe that the Bergell granite is related to Tambo elements (and may actually represent the root of the Tambo nappe), the "tonalite" is related to amphibolites and the Novate granite to rocks of the Adula nappe. Emplacement of the Bergell granite and some tonalitic material began with the intrusion of these rocks into geosynclinal deposits around 30 million years ago, differences in gravity being a major driving force (RAMBERG 1967 and Fig. 17b). Intrusion produced contact metamorphism in limestones, pelitic sediments and volcanic rocks and additional remobilization of amphibolites. Especially in the mafic rocks metasomatic activity obliterated their original composition. The crustal shortening during Alpine folding produced deformation of the crystallizing granitic rocks. *The deformation and thus the nappe movements outlasted recrystallization.* The granite was very ductile at an early stage and deformation produced preferred orientation of megacrysts and elongation of xenoliths. Later, at the time of a probably hydrothermal formation of dikes, the body was already stiff and deformation was mainly expressed in a shear cleavage conspicuously parallel to the foliation (and not at all related to the present joint system). Most of the permanent penetrative strain was produced during the early history of the granite. At a later stage a completely crystallized granite, with large parts of the contact rocks attached to it, was thrust into a new position, somehow like a "large boudin" (Fig. 17c). The granite was more rigid than the surrounding rocks and produced anticlinal structures and intense deformation in the Upper Pennine nappes (Margna, Suretta) and basement (Gruf). During these thrust movements, ultramafic and mafic rocks at the base of the granite were brecciated (Trubinasca, V. Codera) and the basement was isoclinally folded, constrained from all sides.

Emplacement ended with formation of shear zones and simple anticlinal structures in the northeast (Muretto–Forno) in a rigid, brittle environment. It is difficult to divide the deformational history into separate episodes. Most likely, thrust movements started before intrusion of the granite and lasted *continuously* until after its complete recrystallization, thus extending over a considerable period of time.

The geosynclinal trough into which the Bergell granite was intruded was an area of crustal weaknesses that acted later as a major thrust zone separating the Pennine and Austroalpine realm, possibly representing two distinct plates. This zone, characterized by formation of extensive mylonites and granulite facies metamorphic rocks in Miocene, remained weak after emplacement of the nappes. Parallel to the thrust

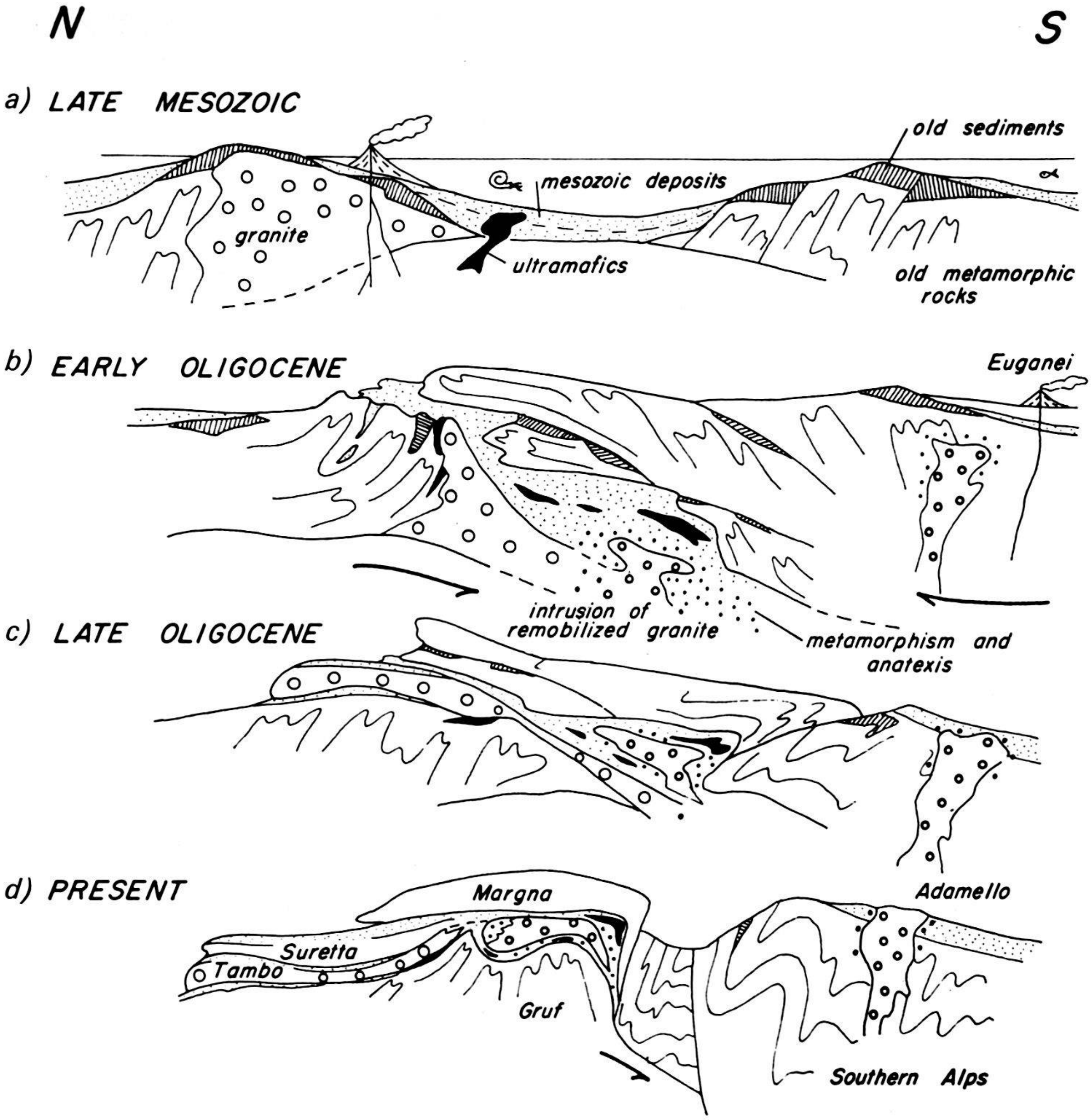

Fig. 17. Very hypothetical N-S cross sections through the Bergell Alps at various stages of the Alpine orogeny.

fault slightly farther to the south, a normal fault was active in Pliocene time – the Insubric (or Tonale) Line – which caused uplift of the Northern Alps of several kilometers. But these considerations of plate-tectonics are no more than fashionable speculations displayed in the imaginative drawings of Figure 17.

In conclusion it seems appropriate to mention some possible weaknesses of the suggested model. Although penetrative deformation of the Bergell granite is an unquestionable fact (Fig. 6a, b) some obvious objections may be mentioned:

– *Deformation of the Bergell Alps may be a very late event, related to young shear zones which are certainly post-Alpine.* Shear zones are common indeed, more in the country rock than in the granite itself. They are not confined to the Bergell Alps. As described already, these shear zones do not show any sizable displacements.

Locally they contain cataclasites, not plastically deformed mylonites. The total strain is negligible and furthermore the orientation of these late shear zones coincides with post-Alpine joint systems and is different from the orientation of foliation and lineation in the Bergell granite. Also the symmetry of the pattern of preferred orientation of quartz (Fig. 15a, b) in mylonites is related to the plane of foliation and not the shear plane thus proving convincingly that mylonitization and formation of shearzones are unrelated events.

– *Deformation of the Bergell granite may merely be the result of local uplift due to gravity forces and be unrelated to the big thrust movement of the nappes.* It is certainly reasonable to assume that gravity was an important factor in the uplift. Gravitational forces also operated in other granites such as Aar, Gotthard, Baveno, Julier, Bernina, and Adamello, just to mention a few examples from the Alps. None of these show similar strain features except at the very contacts. Deformation of the Bergell granite required high temperatures and very large strains. This raises the question as to when Alpine thrust movements ended. In my view, we should place it after the formation of anticlines with amplitudes of more than a kilometer, after isoclinal folding which most likely was produced by crustal shortening of more than 10 kilometers and after thrust movements of rigid units (Bergell granite) of 10 to 20 kilometers came to an end, even if the Bergell episode produced much smaller lateral displacements than, for instance, the Austroalpine thrusts.

Many questions remain open; the structure of the tonalite in the south is not at all clear; there are only suggestions for the geometry of the central granite, and no study of minor structures has yet been conducted to derive local age relations which would be particularly rewarding in the Muretto-Maloja area. The time-relations of the various metamorphic episodes are still unresolved.

This paper has discussed the major structures in the Bergell Alps in order to establish a frame for specialized research. It appears now to be of most pressing importance to study in detail metamorphic textures, reactions, and their relative succession. More isotope data will contribute much to a better understanding of age-relations, and chemical analyses of various rock-types may give indications concerning the source of granite and tonalite. Gravity measurements and seismic experiments may provide the key to the geometry of the central granite. It also is pertinent to mention here the very interesting measurments of the anisotropy of magnetic susceptibility which are in progress (B. Henry, Paris). This sensitive parameter confirms that Bergell granite, grosscutting dikes and Novate granite have been deformed after emplacement.

Acknowledgments

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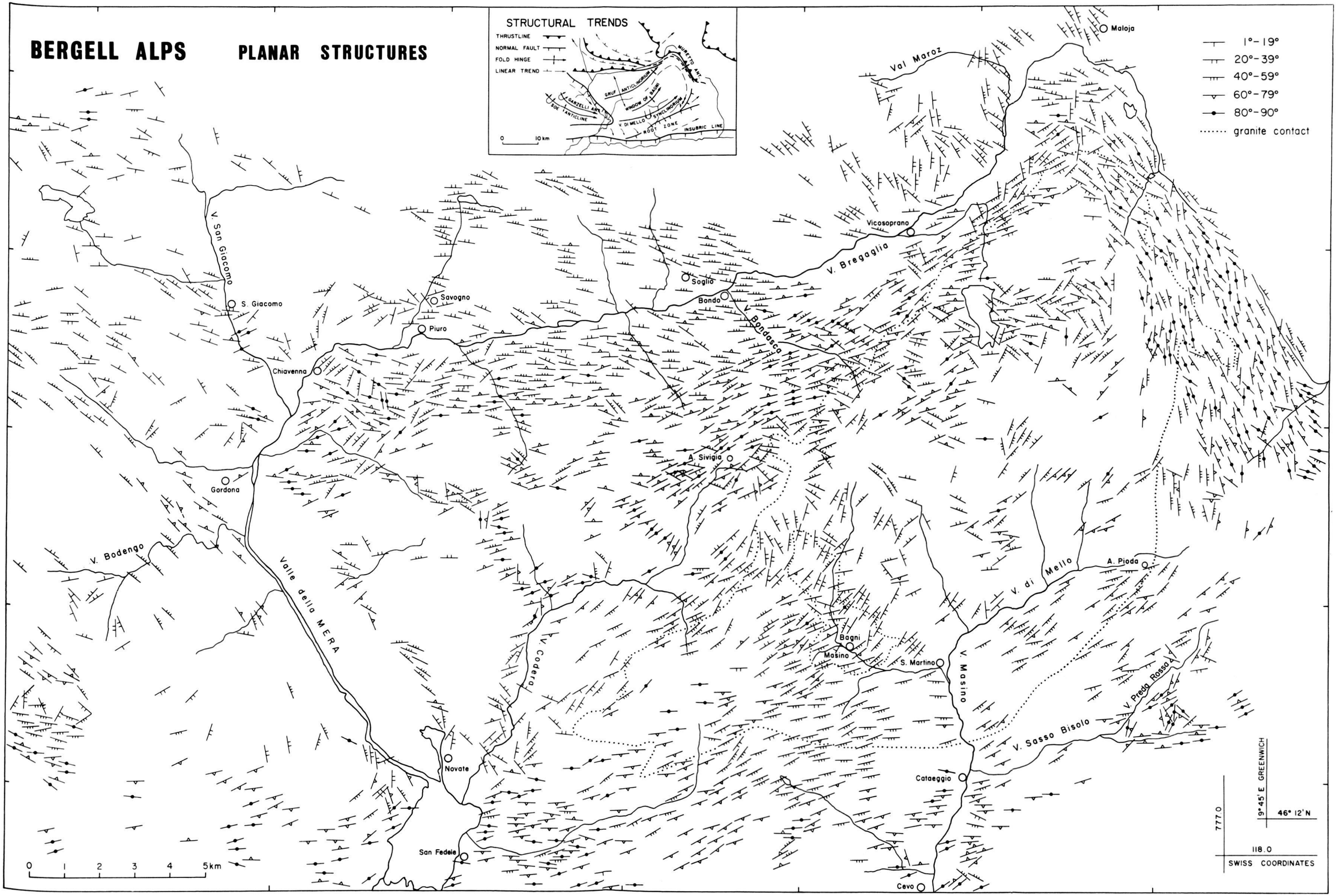
GEOLOGICAL MAPS OF THE BERGELL ALPS

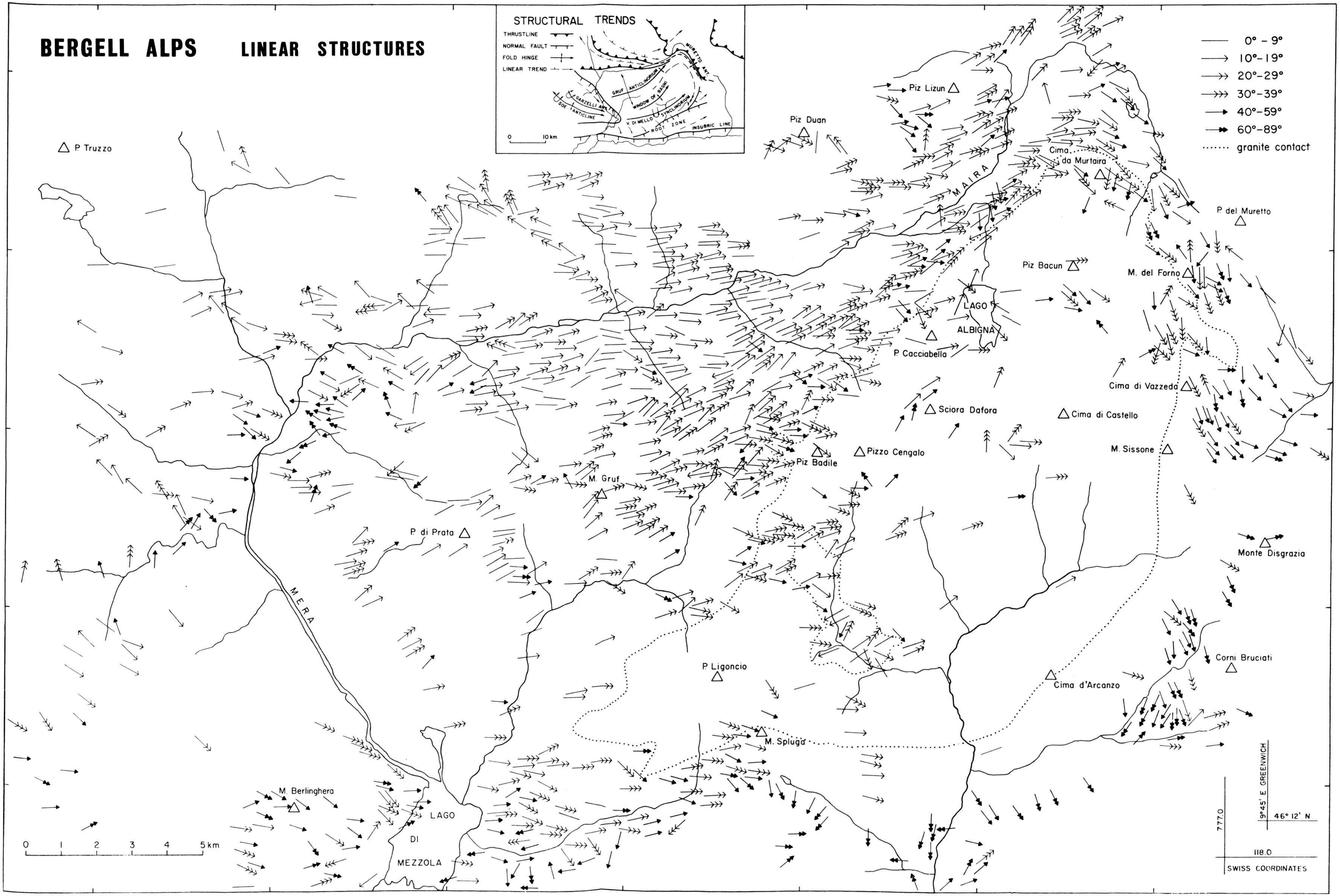
1:200,000: Geologische Generalkarte der Schweiz, Blatt 8, Engadin (Ed. A. Spicher 1964). Notice unfortunate errors, such as omission of the window of Bagni.

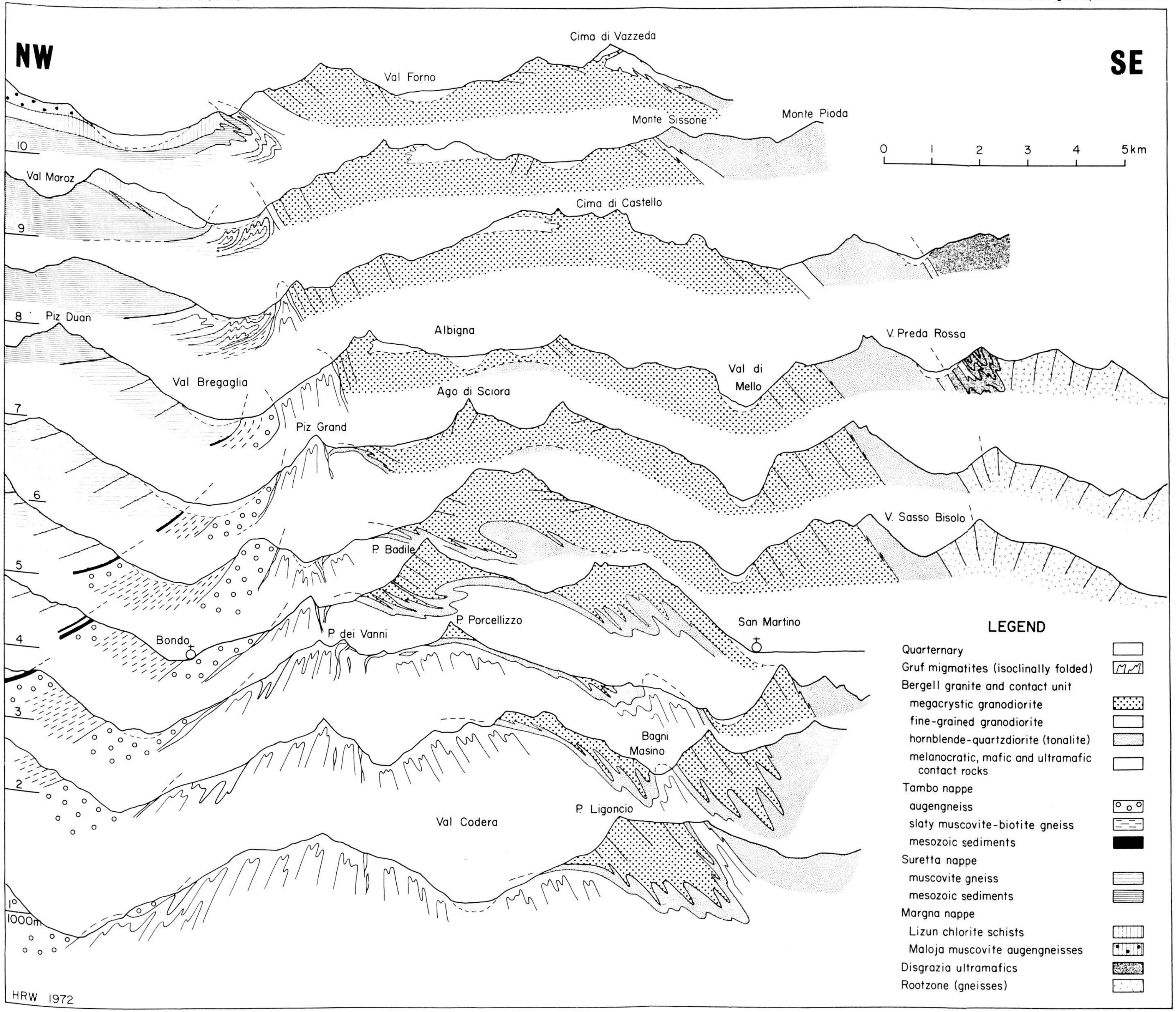
1:100,000: Carta geologica d'Italia, Foglio 7–17, Chiavenna (1941); Foglio 7–18, Pizzo Bernina–Sondrio (Ed. Schiavinato 1970).

1:50,000: Geologische Spezialkarten der Schweiz, Blatt 90, Geologische Karte des Val Bregaglia (Bergell), R. STAUB (1921); Blatt 118, Geologische Karte der Bernina-Gruppe, R. STAUB (1946).
1:25,000: Geologischer Atlas der Schweiz, Foglio 1296, Sciora, H.R. WENK (1973, in press).

For local maps, see also the papers of CORNELIUS (1972), CRESPI and SCHIAVINATO (1966), GYR (1967), and MOTICSKA (1970).


BERGELL ALPS PLANAR STRUCTURES
STRUCTURAL TRENDS
THRUSTLINE
NORMAL FAULT
FOLD HINGE
LINEAR TREND
GRUF ANTICLINORIUM
WINDOW OF BAGNI
V. DI MELLO SYNCLINORIUM
ROOT ZONE
INSUBRIC LINE
MURETTO ANT.
GARZELLI ANT.
SOE ANTICLINE
0 10 km
1°-19°
20°-39°
40°-59°
60°-79°
80°-90°
granite contact
Maloja
Val Maroz
Vicosoprano
V. Bregaglia
Soglio
Bondo
V. Bondasca
V. San Giacomo
S. Giacomo
Savogno
Piuro
Chiavenna
Gordona
A. Sivigia
V. Bodengo
Valle della MERA
V. Codera
Bagni
Masino
S. Martino
V. Masino
V. di Mello
A. Pioda
V. Preda Rossa
V. Sasso Bisolo
Novate
Cataeggio
San Fedele
Cevo
0 1 2 3 4 5 km
9° 45' E GREENWICH
46° 12' N
777.0
118.0
SWISS COORDINATES


BERGELL ALPS LINEAR STRUCTURES
STRUCTURAL TRENDS
THRUSTLINE
NORMAL FAULT
FOLD HINGE
LINEAR TREND
GRUF ANTICLINORIUM
WINDOW OF BAGNI
MURETTO ANT.
GARZELLI ANT.
SOE ANTICLINE
V. DI MELLO SYNCLINORIUM
ROOT ZONE
INSUBRIC LINE
0 10 km
0° - 9°
10°-19°
20°-29°
30°-39°
40°-59°
60°-89°
granite contact
P. Truzzo
Piz Duan
Piz Lizun
Cima da Murtaira
MAIRA
P. del Muretto
Piz Bacun
M. del Forno
LAGO ALBIGNA
P. Cacciabella
Cima di Vazzeda
Sciora Dafora
Cima di Castello
Piz Badile
Pizzo Cengalo
M. Sissone
M. Gruf
P. di Prata
Monte Disgrazia
MERA
P. Ligoncio
Corni Bruciati
Cima d'Arcanzo
M. Spluga
M. Berlinghera
LAGO DI MEZZOLA
0 1 2 3 4 5 km
9°45' E GREENWICH
46° 12' N
777.0
118.0
SWISS COORDINATES



Cross sections through the Bergell Alps 1 : 100 000

Traces of the profiles are indicated in Figure 3