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Deformation in the Maggia and Antigorio nappes Lepontine Alps

By MARTIN HUBER, JOHN RAMSAY and CAROL SIMPSON[1])

ABSTRACT

The structural and metamorphic events recognized in the northern Lepontine region along the profile Basel-Chiasso are presented. The methods for investigating the tectonic structures are summarized. Three main phases of deformation have been recognized, the first related to production of the main fold nappes, the second related to pervasive refolding and crystallisation under amphibolite facies conditions, the third related to regional backfolding.

An accurately constructed cross section along the Geotraverse from Alpe Robiei to Il Rosso is presented. The Alpine structural effects seen in the basement rocks of the nappe cores are described: the basement shows conjugate sets of ductile shear zones. Strong deformations along these zones enable the basement mass as a whole to adopt new shapes in the nappe cores.

ZUSAMMENFASSUNG

Nach einer Zusammenfassung der Arbeitsmethoden, die im Felde zum Erkennen von Verformungsphasen und zu deren Korrelierung angewendet werden, werden eine Reihe von strukturellen und metamorphen Ereignissen im Gebiet des nördlichen Lepontin entlang dem Profil Basel-Chiasso diskutiert. Es werden drei Hauptphasen der alpinen Verformungsgeschichte unterschieden: Eine erste Phase ist verknüpft mit der Deckenbildung; eine zweite Phase hängt mit der durchdringenden Wiederverfaltung und einer Rekristallisation unter Amphibolitfazies-Bedingungen zusammen; während in einer dritten Phase eine Rückfaltung des Deckenstapels stattfand.

Ein Detailprofil auf der Spur der Geotraverse zwischen Alpe Robiei und Il Rosso wird vorgestellt. Auswirkungen der alpinen Verformung auf die Kristallingesteine werden beschrieben: Duktile Scherzonen bilden konjugierte Paare. Dank hohen Verformungsbeträgen in diesen Zonen können die Kristallinmassen ihre neue Form in den Deckenkernen annehmen.

Introduction

The upper Maggia valleys, Ticino, Switzerland, are situated in the northern part of the Lepontine area (Fig. 1), where schists, granites and banded granitic gneisses form the front of three basement nappes (from base to top: Antigorio, Lebendun and Maggia). They are separated from each other by calcareous cover (meta) sediments. The complicated tectonic picture (for a simplified distribution of the major tectonic units see Figure 1) results from an early thrusting and folding leading to a complex structure, which was subsequently subjected to further phases of deformation and to an amphibolite grade metamorphism.

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We have made a detailed study of the structure of this area, the results of which will be published elsewhere. The fact that the profile Basel–Chiasso of the Swiss Geotraverse runs between Alpe Robiei and Bignasco (see Fig. 1) through this area, gives the opportunity to present a short summary of some results. The aim of the present paper is therefore to present a profile on the trace of the Geotraverse, to integrate the field data in a more coherent picture of the tectonic evolution of this

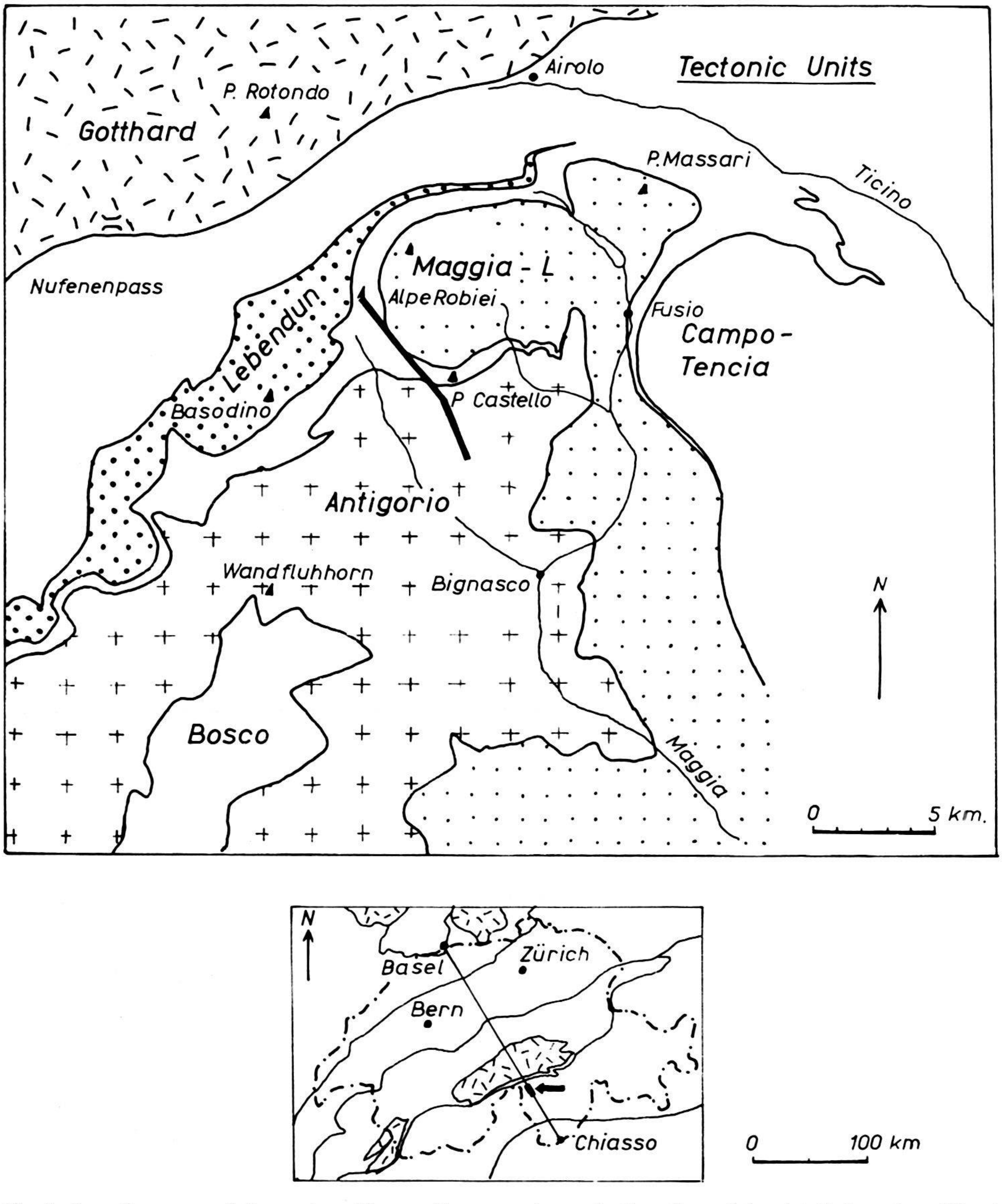


Fig. 1. Location map of the region. The smaller map shows the location of the detailed section (Plate) along the line of the Swiss Geotraverse.

area, and to discuss possible deformation mechanisms (connected with the emplacement of the basement nappes).

An excellent geological map of this area was established at the beginning of this century by PREISWERK (1918) and this detailed mapping and description has been the basis for many tectonic interpretations. The resulting overflow of tectonic hypotheses concerning the overall structure of the Penninic nappes and their connection to the equivalent nappes in the Grisons (compare e.g. NIGGLI et al. 1936, Tf. IV), perhaps led to a stagnation of ideas. Around 1940 detailed remapping of the terrain was begun on the initiative of Prof. E. Wenk and his students to establish a firmer basis for petrogenetic work. In this second phase a more detailed geometry of the nappes was established and a fine petrographic study ensued which forms the basis of our current understanding of the mineralogical and petrological features of the rocks. In a third phase of research from 1960 onwards the structural evolution of the nappes were studied: In a series of Ph.D. theses at the Imperial College, London, analyses of the structural geometry established the timing relations of the deformations and the relationships of deformational and metamorphic activity. This research established the concept of a "fold phase", a term which has subsequently come into widespread use in tectonic analyses in the Alps.

Practically all subsequent work has used the concept of deformation phases as a practical method by which the field geologist may, from observations of the geometrical features of the rocks, set up a framework of successive movement and deformation events which can be correlated from area to area. These geometric studies also enable the metamorphic fabrics of the rocks to be related to a sequence of deformation events and therefore ordered in a time sense relative to the deformation phases.

As this approach forms the basis of much current interpretation we begin by setting out the main concepts behind these techniques, and follow this by a direct application to unravelling the history of the region.

1. Criteria for the recognition of deformation phase

Deformation leads to extensions and contractions in different directions in a body and generally to shear displacements between layers. Most rocks are layered and the alternate layers have differing ductilities. Because of these relative ductility differences (termed competence differences), mechanical instabilities are set up which lead to characteristic structural forms in the different layers depending upon their orientations with respect to the principal strain axes. Competent layers embedded in a less competent matrix produce buckle folds in compression, or boudin structures in extension. A particular deformation event may therefore produce folds in one area and boudinage in another depending upon the orientation of the layering within the strain ellipsoid of that deformation. The folds produced in any particular lithology show characteristic geometric styles depending upon the competence contrast, likewise the structures at boudin necks are also a function of this competence contrast. The structural forms are related to the rock rheology under the specific stress and strain rate conditions of the deformation.

Where a second main phase of deformation is superimposed on a previously deformed rock, new structures will develop depending upon the orientations of the layering in the new strain field and on the rheological conditions in the new pressure–temperature–strain rate environment.

The practical criteria which enables the field geologist to recognize such successive deformation phases are as follows:

1. Because each deformation phase takes place at specific pressure–temperature–strain rate conditions *the structural forms show characteristic geometric styles* reflecting the rock rheology, and the structures formed in successive phases often show *differing geometric styles.*
2. Each phase of deformation has differently oriented principal stress and strain axes. The structures forming during any phase therefore show *characteristic orientations,* and structures of different phases are likely to have *differing orientations* (WEISS 1959, RAMSAY 1967, p. 538–553). Where the deformations are separable into distinct phases these *orientations should form distinct and discrete spatial groups* with few (if any) transitional orientations.
3. Successive deformation phases produce small scale structures which are superposed to give *characteristic geometric interference patterns.* Rocks stretched and boudinaged during one phase may be folded during a later phase and vice versa, and superposed folds of differing orientations give rise to highly characteristic interference geometry (RAMSAY 1967, p. 520–537). It is well-known that quite complex superposed fold sequences and extension-contraction structures can develop during a single deformation phase as a result of progressive change in the orientation of strain increments. What enables the field geologist to recognize separately phased events from such a continuous series of progressive shape changes in a one-phase event is the recognition of the geometric separable coherence of the sets of structures. Such a realization comes from *detailed field mapping over a wide area,* when successive phases are seen to be geometrically discrete. In our experience the study of a single cross section or traverse is not always sufficient to elaborate the full significance and regional geometric implications of the observed small scale structures. The interpretation of traverse data often fails to establish the true three-dimensional structural picture, the evaluation of the regional significance of a set of structures, and the appreciation of the regional intensity of deformation phases. Local deformation "hiccups" seen at one locality can be thought to have an importance out of all proportion to regional reality. The conclusions presented below establish fewer phase events in the region than have been established in surrounding terrains. However, we feel confident that the three main events we establish have true regional significance.

2. Regional deformation phases in the Lepontine Alps

We have pointed out that folds formed during different deformation phases often show differing geometric profile characteristics. In the Lepontine Alps such shape differences in the folded layers of any one rock type are very useful features for the separation of the deformation events. These differences in geometry can be very exactly specified in terms of tightness, changes of curvature of the boundaries of individual layers, fold amplitude and wavelength, and the relationships of crystal fabric to the whole structure. Perhaps it should be stressed that the eye of an experienced field worker can detect quite subtle differences in structural style without always having to rely on time consuming laboratory investigations carried out at a later date (although such a back-up should be carried out). There are certain dangers inherent in these techniques: arguments based only on fold shapes can turn out to be cyclic ones, and many workers are aware of the potential traps arising from the automatic assumption that folds of the same style were contemporaneous. However, when this method is used in conjunction with orientation data and interference relationships, it can be a very useful one.

As an example Figures 2, 3 and 4 illustrate folds which were formed in compositionally comparable rock types (layered quartz–feldspar–mica–hornblende gneisses) at different times during the Alpine orogeny.

The *first folds* which can be recognized (Fig. 2) have a tight to isoclinal profile and the layers show extreme thickening in the fold hinge relative to the limbs. The folded surfaces between layers of differing compositions are almost identically shaped: if lines joining points of equal dip are drawn through the surfaces (dip isogons – see ELLIOTT 1965, RAMSAY 1967, p. 363) they are practically parallel. Such folds are characteristic of environments subjected to differential shear and are termed "similar" folds. Generally, folds of this generation have little or no axial plane parallel alignment of the inequidimensional minerals, or they may be crosscut by such a planar fabric. In detail, the fold axes are often extremely irregular in

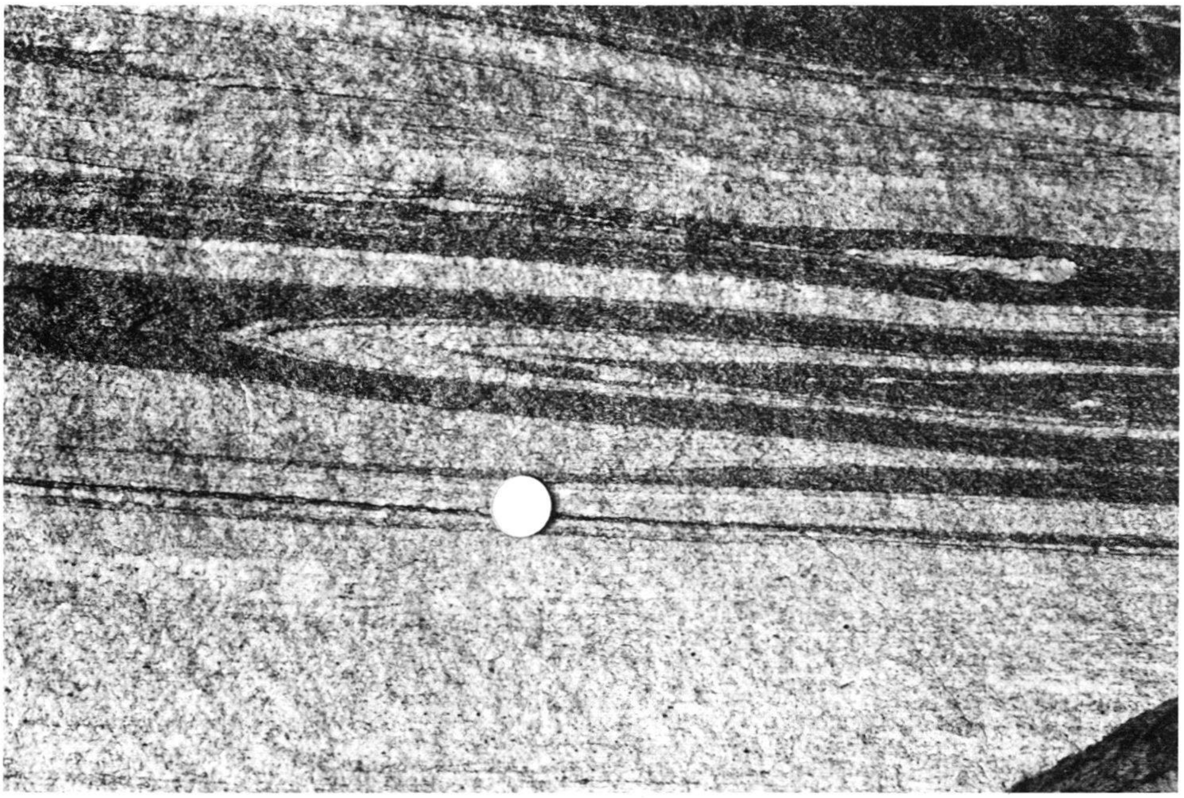


Fig. 2. Characteristic geometry of the first set of Alpine folds in banded basement gneisses.

Fig. 3. Characteristic geometry of the second set of Alpine folds.

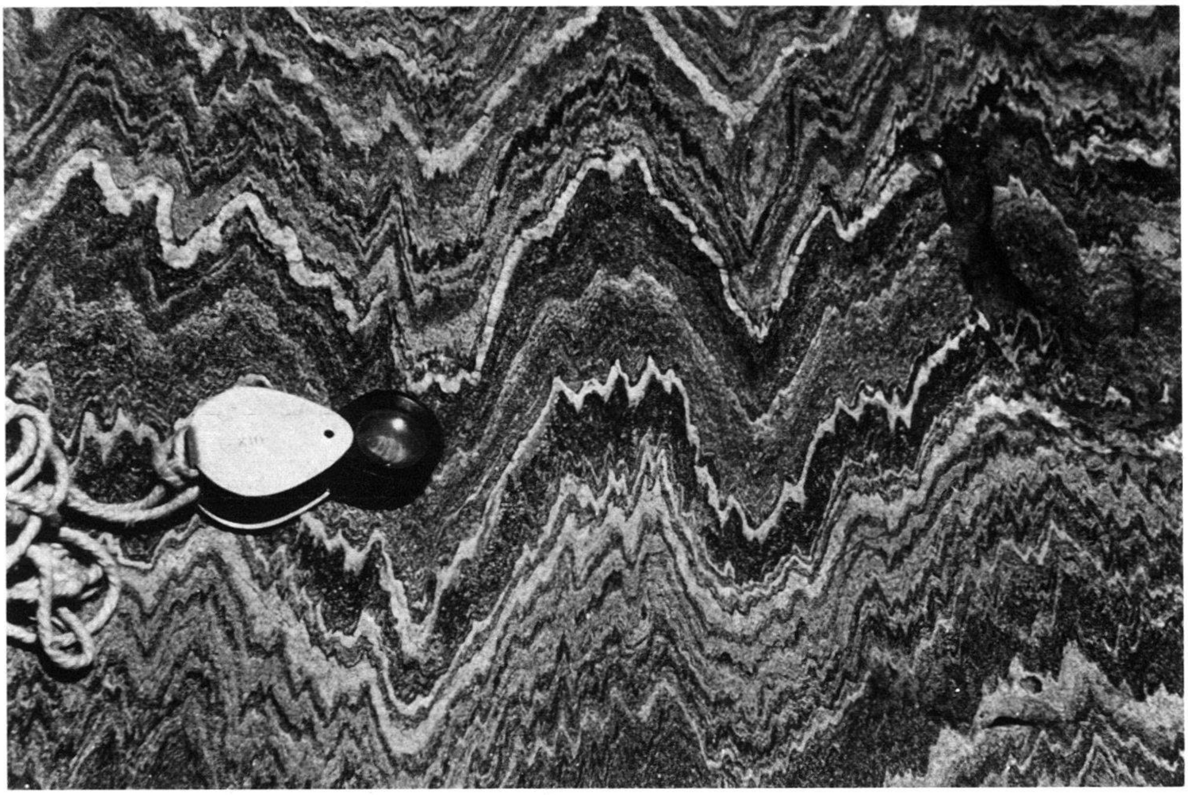


Fig. 4. Characteristic geometry of the third set of Alpine folds, showing crenulation cleavage.

orientation, although their average regional trend seems to be related to the axes of the major fold nappe hinges.

The *second folds* are generally tight, but not so tight as those of the first phase (Fig. 3). The layers show a relative thickening in the fold hinges, but again this is not so marked as is seen in the first phase folds. There are clearly marked differences of curvature of the surfaces on either side of every layer, and the dip isogons will show alternating convergent and divergent fans. In Figure 3 the outer arcs of the folded dark hornblende-rich layers have a smaller curvature than the inner arcs of the same layer. Features such as this indicate marked ductility or competence contrasts in the mechanical behaviour of the different rock types, and require buckling instabilities to produce the folds. These folds either have an axial plane alignment of platy minerals (micas and amphiboles), or show a rather irregular orientation of these minerals (Fig. 5). The implications of these observations is that the main metamorphic activity related to the overall thermal dome structure (WENK 1962, 1970; WENK & KELLER 1969, NIGGLI 1978) reached its peak partly with and partly after the second phase of deformation (AYRTON & RAMSAY 1974). The axes of the second folds are usually rather regularly oriented, and often accompanied by a parallel rodding or intersection lineation structure.

The *third folds* have more open profiles than folds of the two earlier generations (Fig. 4). They often show a characteristic chevron style with sharply angular hinge zones. There are slight differences in layer thickness from limbs to hinge, but these

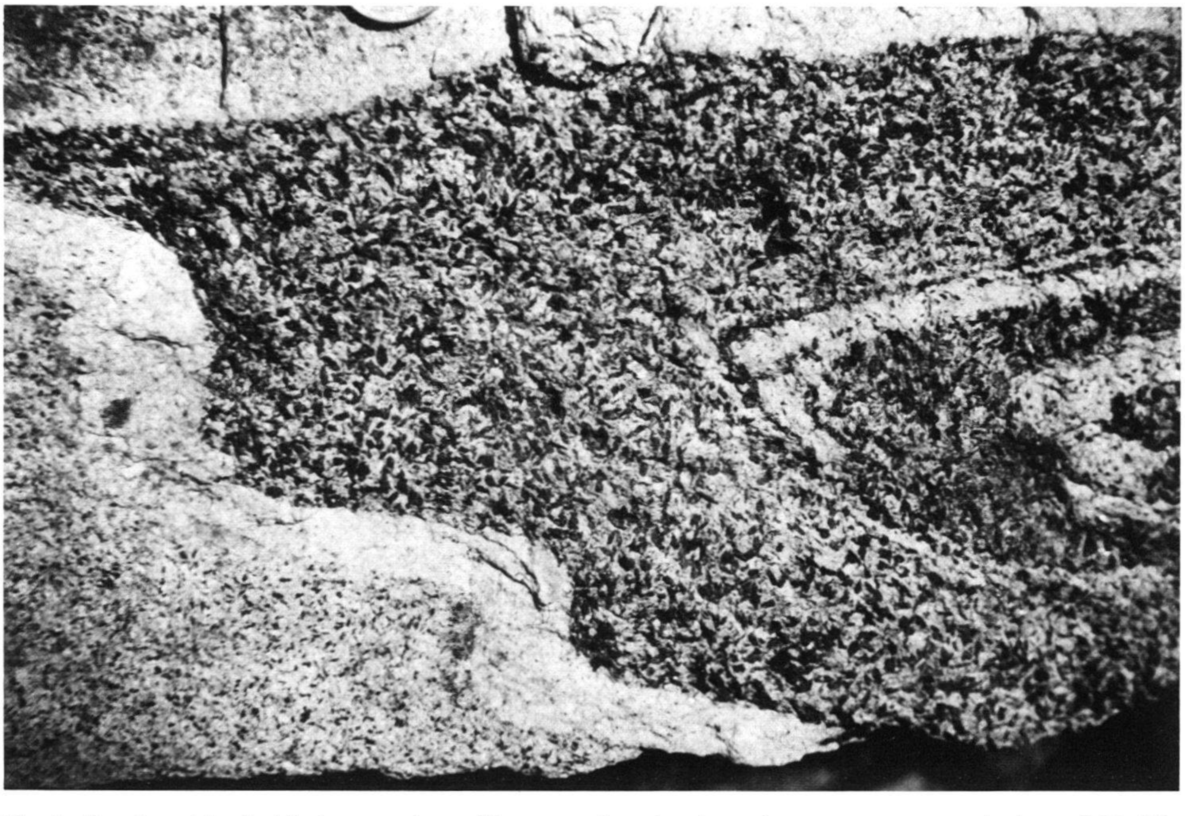


Fig. 5. Porphyroblastic biotite growing without preferred orientation across a second phase fold. The field of view is 22 × 15 cm.

are not as marked as those seen in folds of the earlier phases. Competence contrasts play a significant role in controlling the curvatures of the layer boundaries and usually indicate a stiffness contrast: hornblende-rich rocks > coarse quartz-feldspar rocks > fine grained quartz-feldspar rocks > mica-rich rocks. Usually these folds are associated with a crenulation of previously recrystallized minerals such as micas, amphiboles and kyanite, and they never have a true axial plane parallel schistosity. Although the fold axes are locally regular in orientation, this orientation depends upon the inclination of the surfaces on which they developed. Variation of axial direction is therefore inherited from the variability of layering and schistosity arising from previous fold events.

The timing relationships of the three main folding events have been established on interference geometry. The axial surfaces of the later sets of folds are usually fairly regularly oriented and crosscut the folded axial surface of earlier formed folds (Fig. 6). These geometric relationships imply that deformation on the earlier systems had become more or less dead: the earlier folds were acting as more or less passive markers in the newly activated strain system. Geometric analysis of the successive fold orientations and of the relationships of mineral growth to folding suggests that there were two relatively static periods of deformation between the three fold phases. It is of course possible that the rock mass as a whole was being displaced uniformly, for deformation only occurs where the displacement gradients are variable.

Figure 7 sets out in diagrammatic form the succession of structural events. The

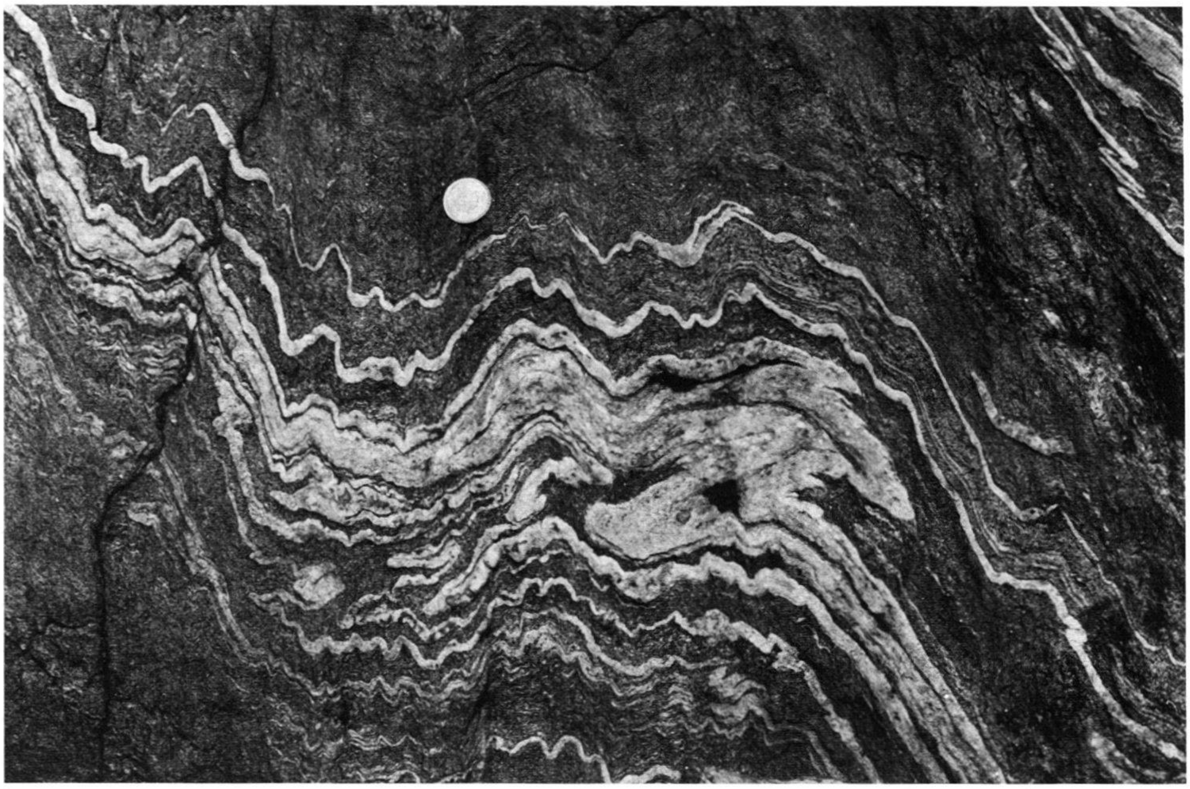
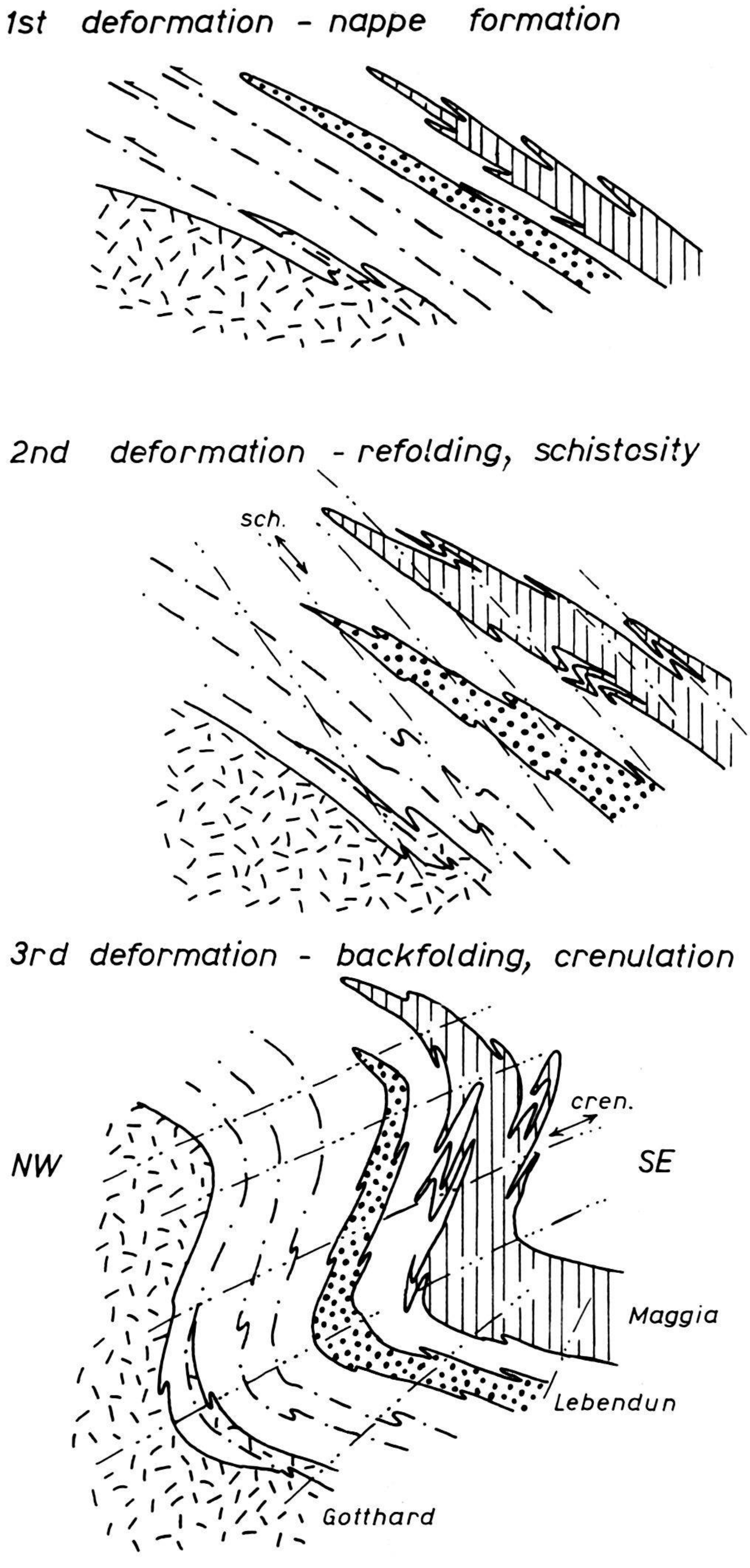


Fig. 6. Interference pattern between second phase and third phase folds. The axial surfaces of the second folds have been folded, whereas the axial surfaces of third phase folds are more regularly oriented.


1st deformation - nappe formation

2nd deformation - refolding, schistosity

3rd deformation - backfolding, crenulation

Fig. 7. Schematic summary of the structural development of the Maggia nappe, Lebendun nappe and Gotthard Massif. The dashed lines represent the orientations of fold axial planes and movement planes of the successive deformations.

first phase appears to be related to main fold-nappe development. The crystalline basement rocks form the cores of upward facing folds (antiforms are anticlines) on a variety of scales, while along the southern side of the Gotthard basement extensive large scale schuppen structures developed. The second event led to a strong refolding of these structures and the development of strong planar schistosity and linear fabrics associated with the increase in thermal activity. The second folds are sometimes upwards facing (antiforms are anticlines), sometimes downward facing (antiforms are synclines) depending upon whether they developed on normal or inverted limbs of first folds. The third phase gave rise to the large scale regional "backfolding" and associated crenulation of previously formed schistose and banded rocks.

In detail the geometry of the combined phases has an extremely complex three-dimensional form. It is not possible to construct a truely representative geometrically correct profile, because it is nowhere possible to find a locality where all three sets of fold phases have parallel axial directions. The resulting profile schema shown in Figure 8 is therefore not a geometrically perfect section: it has been constructed to bring out the main relationships of the fold phases. This constructional problem should be born in mind when comparing Figure 8 and the Plate. Figure 8 is schematic and tries to bring the three-dimensional geometry into a representative cross section, whereas the Plate is an accurately reconstructed vertical cross section drawn along the Geotraverse which is not everywhere a true profile of the various folds in the region.

3. Features of the Geotraverse profile

Examination of the cross section along the trace of the Geotraverse between Alpe Robiei and Il Rosso (Plate) reveals obvious differences in the structural style of the basement cover contact of the Maggia nappe from those seen along the contact of the Antigorio nappe. At the contact of the Maggia nappe the thin marble bands and calcareous sediments are at various levels deeply interleaved with gneisses of almost every composition and texture. In some outcrops along this extremely heterogeneous zone a clear sequence of fold phases as described above can be recognized. The interleaving and refolding in its most complex form is particularly well seen in the steep western face of Pizzo Castello.

In contrast the contact of cover and granodioritic gneisses of the frontal part of the Antigorio nappe is more clearly defined and structurally less complex. Here the "Verschuppung" of cover and basement is on a minor scale, and only results in wedges some decimeters thick of crystalline rock in the metasediments. At some localities such small-scale slicing has led to the formation of detached pebble-like masses which match very well with rocks described by PREISWERK (1918) as basal conglomerates. From the frontal part of the Antigorio nappe southwards the more or less homogeneous mass of granodioritic gneisses becomes increasingly heterogeneous. Large zones of dark biotite-rich banded gneisses and amphibolites cut through the light-coloured granitic gneisses. Some of these bands seem to be the products of metamorphic differentiation during deformation by ductile shearing rather than representing primary lithological features of the basement.

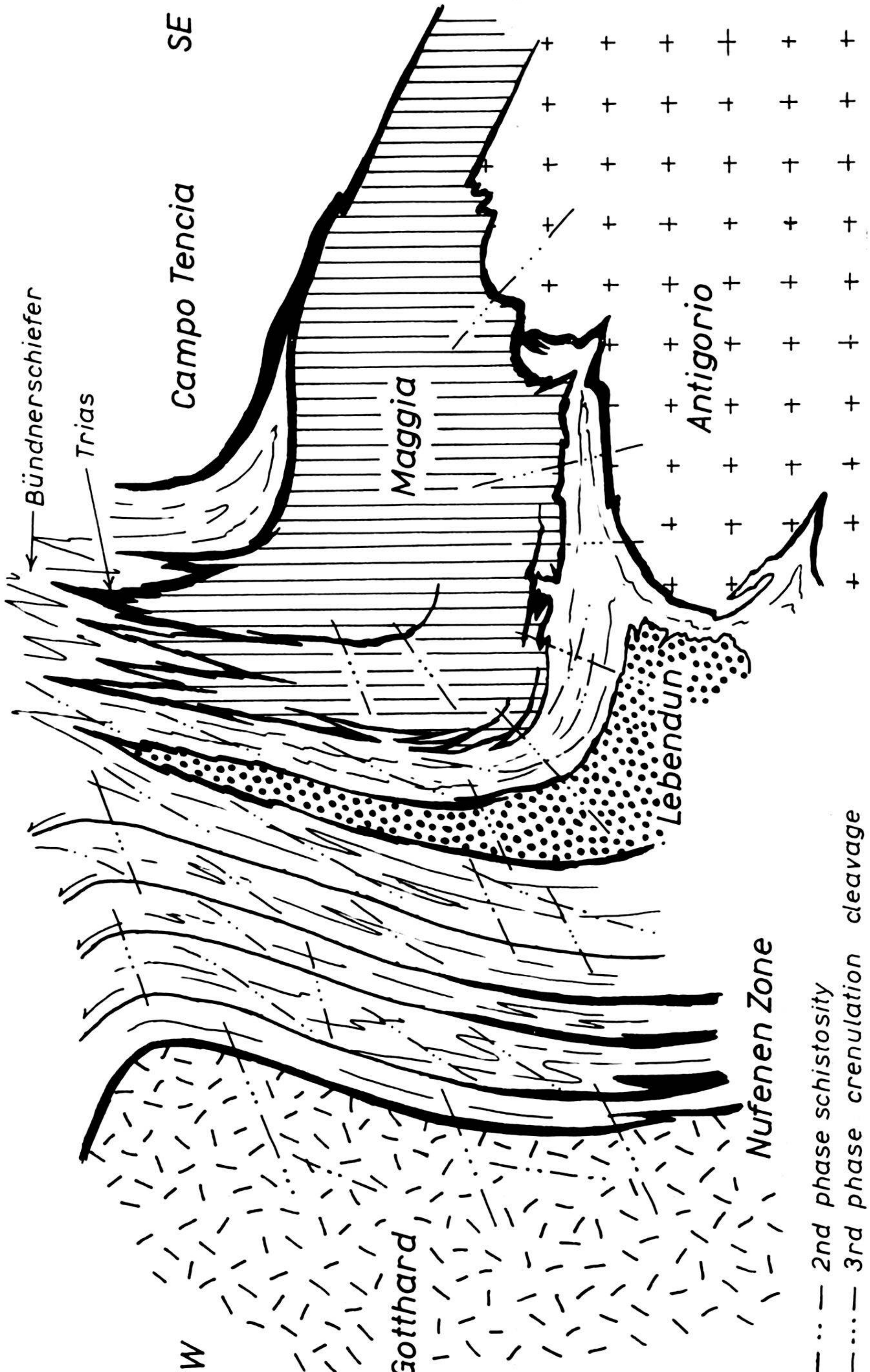


Fig. 8. Schematic profile from the Gotthard Massif southeastwards showing the principal geometric relationships of the Penninic nappes.

4. Tectonic features of alpinized basement rocks

It has always been of interest to structural and metamorphic geologists to try and understand the mechanisms whereby large crystalline masses of basement can be deformed to produce the cores of the large fold nappes that are seen in this area. In order to investigate the characteristic deformation modes of this alpinized basement we have carried out extensive detailed mapping at scales ranging from 1:10,000 to 1:50 of selected areas between Fusio, Poncione di Brage and Pizzo Massari (Fig. 1 for localities). Here the basement is of variable composition consisting of granites, diorites, augen gneisses, banded gneisses of various types and garnet-biotite schists (GÜNTHERT 1954, 1976). Although much is highly deformed and shows strong linear and planar fabrics of Alpine age, certain regions do contain some relatively unmodified basement and transitional structural states from little- to highly-alpinized rocks. Particularly useful in these studies has been the recognition of various aplite, pegmatite and lamprophyre dyke swarms that were originally cogenetic with the plutonic Hercynian rocks. These dykes and the xenoliths contained in the plutonic rocks provide excellent markers whereby we can investigate Alpine displacements and strains (Fig. 10).

The first signs of Alpine deformation of this basement is the production of anastamosing zones of ductile shearing (Fig. 9). These are conjugate, one set showing righthand displacement, the other set being lefthanded, and they intersect

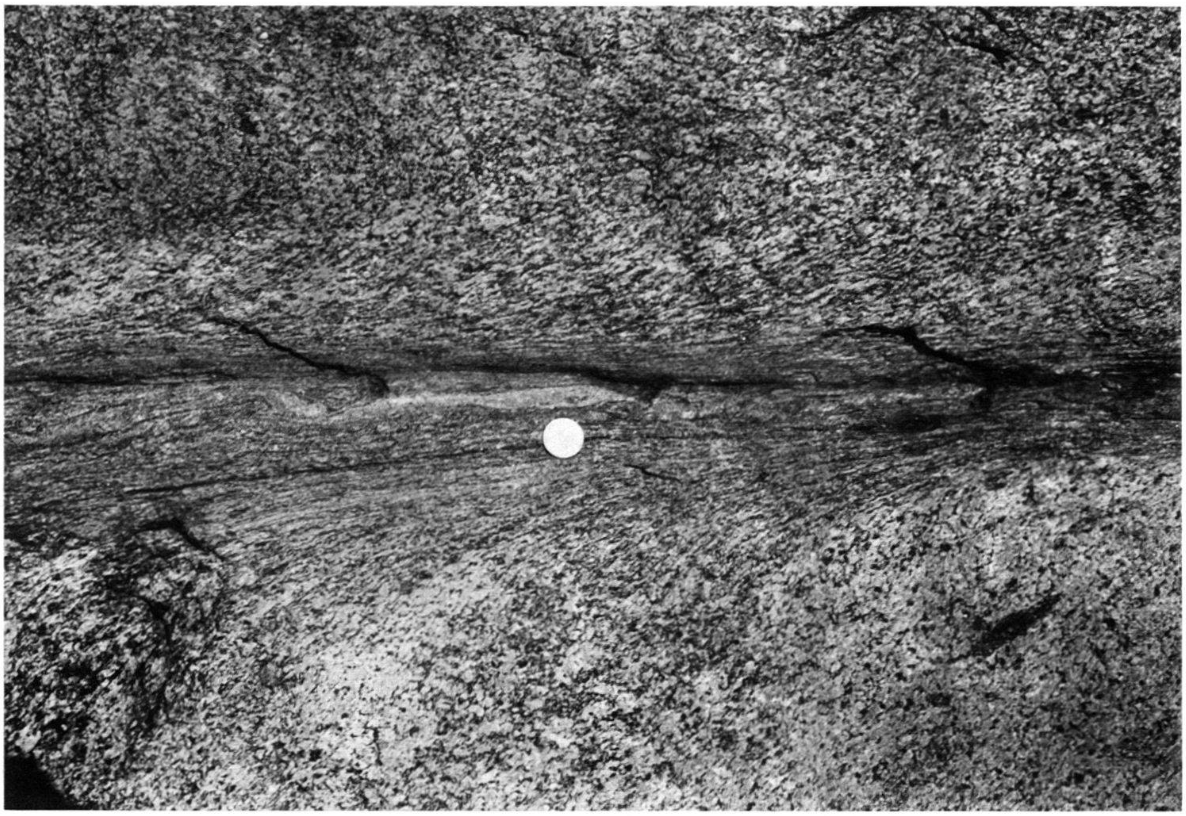


Fig. 9. Typical ductile shear zone of Alpine age passing through a xenolithic granite. A strong schistose fabric has been produced in the granite as a result of realignment of the mineral components, and the deformation has also led to the development of a banding from an initially unbanded parent.

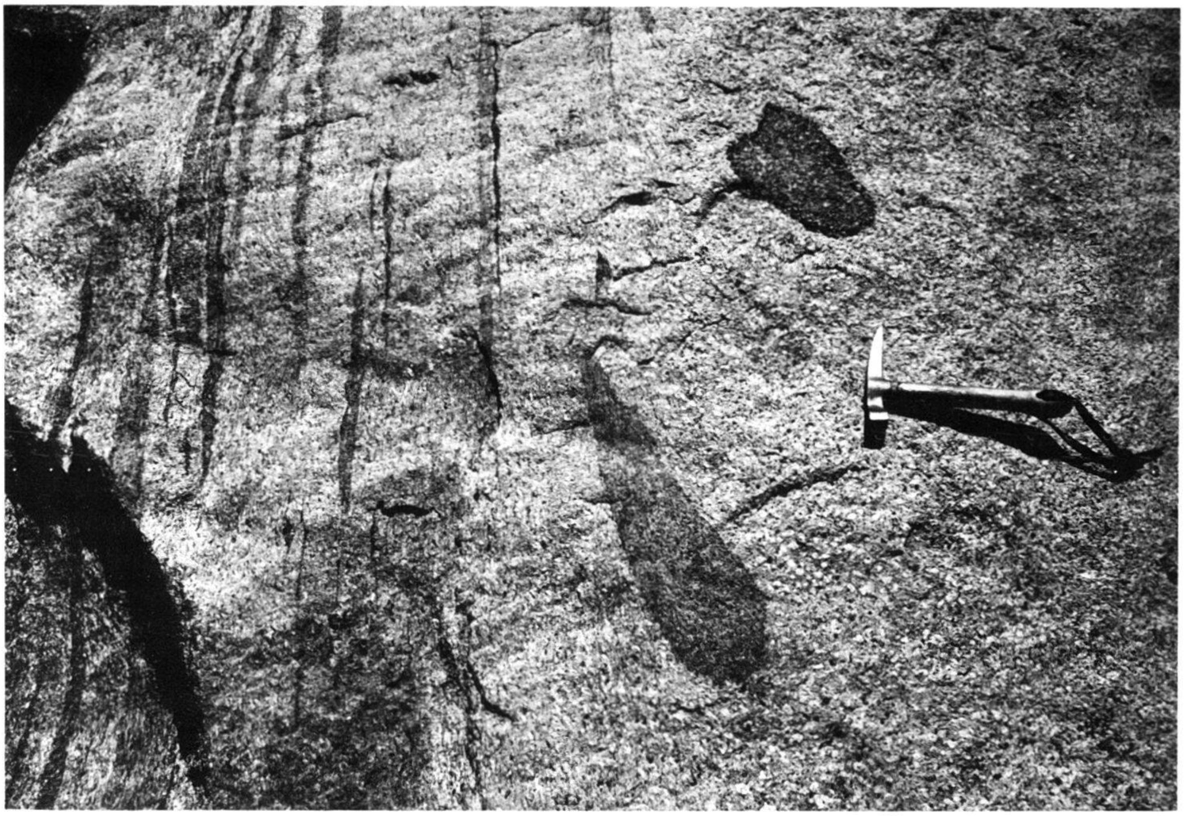


Fig. 10. Xenolithic granite of Hercynian age being deformed by an Alpine ductile shear zone. The original granite seen on the right side of the photograph has very little fabric, whereas in the shear zone on the left it has acquired an intense schistosity as a result of strain. From the xenolith shapes it is clear that this schistosity is perpendicular to the maximum finite shortening.

to give characteristic deformation patterns of lozenge-shaped pods of relatively undeformed basement surrounded by more or less planar zones with very strongly developed Alpine schistosity (Ramsay & Allison 1979). The relatively massive Hercynian plutonic rocks are progressively transformed into strongly deformed platy gneisses with strong Alpine schistosity. The initially fairly homogeneous granites often become banded as a result of the Alpine deformation. Although this feature clearly indicates that chemical redistribution was a major factor during the deformation, it is of interest that the banded rocks in the shear zones are effectively isochemical with their parent material and there is no evidence of large scale chemical transfer of material along the shear zone. Where the starting plutonic rock contained porphyritic feldspar, deformation leads to the production of banded augen gneisses. The amphibolite grade metamorphism outlasted the intense deformations seen in the shear zones: in biotite schists one finds randomly oriented crosscutting tourmaline, amphibole and kyanite, and in the shear zones the quartz and feldspar are almost completely strain free as a result of recrystallization.

Conclusions

1. Three major phases of deformation have been recognized throughout the Northern Lepontine Penninic nappes. Each phase produced folds, and these folds

show differing geometric styles and varying relations to the metamorphic crystal growth. The main thermal event (amphibolite facies) occurred late during the second phase and reached its peak in the period between second and third phases when deformational activity was very small.

2. A structurally schematic profile through the region is presented (Fig. 8), together with an accurately constructed vertical section from Alpe Robiei to Il Rosso (Plate) along the Geotraverse.

3. The gneisses and plutonic igneous rocks in the fold nappe cores are characterized by Alpine deformations along subplanar conjugate ductile shear zones.

Acknowledgments

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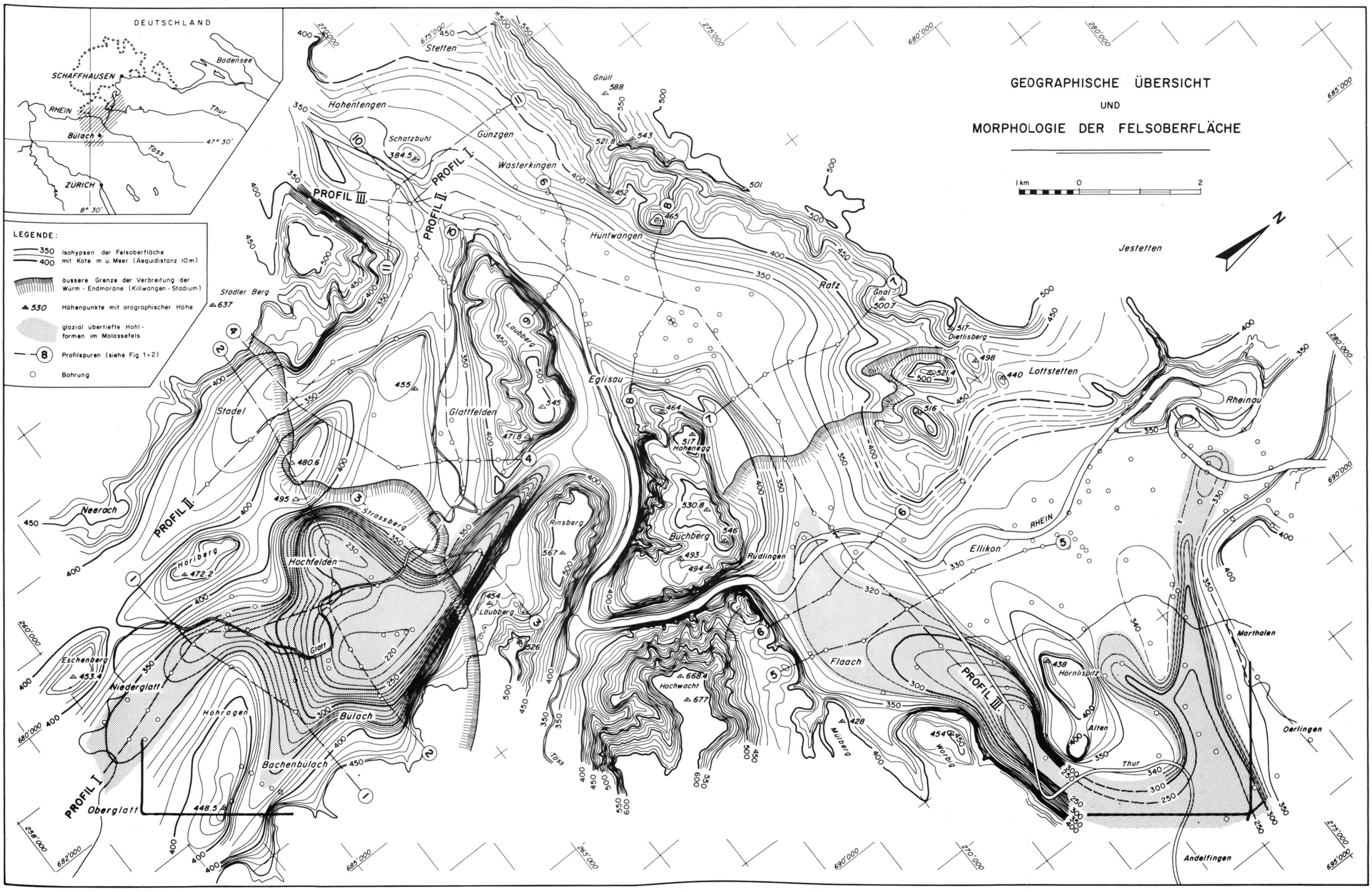
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