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Structure and history of the Suretta nappe (Pennine zone, Central Alps) - a field study

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ABSTRACT

The Suretta nappe, a major tectonic unit in the Pennine zone of eastern Switzerland, is made up of four main lithological complexes: (a) Roffna gneiss (a deformed Hercynian granite-porphyry); (b) Timun complex (an older crystalline complex, the country rock of the Roffna intrusion); (c) «Trias» (quartzites and marbles, originally laid down as sediments unconformably on the Roffna-Timun basement); (d) Bündnerschiefer (calcareous schists and prasinites of Jurassic-Cretaceous age). Structural analysis of major and minor deformational features showed that four phases of Alpine (i.e. post mid-Cretaceous) deformation can be distinguished: 1. early thrusting/imbrication/brecciation *(Avers phase)*, causing slicing and piling up of basement and cover without major relative displacement; 2. early isoclinal folding *(Ferrera phase)*, resulting in numerous deep infolds of cover into basement and in the main foliation in the Roffna gneiss S_F; 3. late thrusting *(Schams phase)*, juxtaposing the far-travelled Schams nappes on top of the Suretta complex; 4. late isoclinal folding *(Niemet phase)*, producing a huge north-closing recumbent fold, with the Suretta nappe as its core, associated with widespread minor folds and a sporadic foliation S_N. Correlation of the structural with the available stratigraphic and radiometric data indicates two major periods of orogenic movement in this area: the first in the mid-Cretaceous (Avers and Ferrera phase), the second in the early Tertiary (Schams and Niemet phases), both showing initial brittle and subsequent, with increasing tectonic burial, ductile deformation. The movement direction during the early Tertiary was almost certainly to the north (i.e. along south-dipping thrust planes and ductile flow zones). In contrast, during the mid-Cretaceous a southward movement direction is indicated.

ZUSAMMENFASSUNG

Die in der Ostschweiz liegende mittelpenninische Suretta-Decke ist aus vier lithologischen Hauptelementen aufgebaut: (a) dem Roffna-Gneis (ein verformter herzynischer Granitporphyr); (b) dem Timun-Komplex (eine alte Kristallinmasse, vermutlich das Wirtgestein der Roffna-Intrusion); (c) der «Trias» (ursprünglich stratigraphisch auf (a) und (b) abgelagerte Quarzite und Marmore); (d) den Bündnerschiefern (Kalkschiefer und Prasinite jurassisch-kretazischen Alters). Die geometrische Analyse von Gross- und Kleinstrukturen ergab, dass die alpine Orogenese in diesem Gebiet in vier Deformationsphasen zerlegt werden kann. 1. *Avers-Phase:* Überschiebung, Verschuppung und Brekzienbildung (Zerschlitzung und Zusammenschub der lithologischen Elemente ohne grossen Relativtransport). 2. *Ferrera-Phase:* Isoklinalfaltung (Einfaltung der Sedimentbedeckung ins Kristallin und Bildung der Hauptschieferung S_F im Roffna-Gneis). 3. *Schams-Phase:* Überschiebung der ursprünglich weit entfernten Schamser Decken auf den schon verformten Suretta-Komplex. 4. *Niemet-Phase:* Isoklinalfaltung (Bildung einer riesigen, nach Norden schliessenden, liegenden Falte mit der Suretta-Decke als Kern, dazu verbreitet parasitäre Kleinstrukturen und sporadisch eine neue Schieferung S_N). Die Korrelation dieser Resultate mit vorhandenen stratigraphischen und radiometrischen Daten weist auf zwei orogenetische Hauptbewegungen hin. Eine erste fand in der mittleren Kreide (Avers- und Ferrera-Phasen), eine

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zweite im unteren Tertiär (Schams- und Niemet-Phasen) statt; beide mit anfänglich spröder, dann, mit zunehmender tektonischer Überlast, duktiler Verformung. Im unteren Tertiär war die Bewegungsrichtung mit grosser Wahrscheinlichkeit nordwärts, d.h. entlang nach Süden einfallenden Überschiebungsflächen bzw. duktilen Fliesszonen. Hingegen in der mittleren Kreide war sie möglicherweise südwärts gerichtet.

Introduction

The Suretta nappe, and the Schams nappe complex which is wrapped around its «frontal» (northern) edge, has been the subject of detailed geological investigations over many years (e.g. ZYNDEL 1912, STAUB 1926, WILHELM 1932, STREIFF 1939, JÄCKLI 1941, GRÜNENFELDER 1956, STREIFF et al. 1971/1976). From these descriptions, however, it is difficult to build up a clear picture of the structural history of the region. They provide only snapshots of such features as the huge fold hinge comprising the «front» of the nappe (e.g. STREIFF 1962; TRÜMPY et al. 1969, Fig. 14), or the spectacular «back folds» with which the upper part of the Suretta nappe is decorated in all cross-sections (e.g. WILHELM 1929; STAUB 1958, Fig. 39 and Plate II), without placing them within a deduced developmental framework. The present study started as part of a more general review of the structure of the Pennine zone in eastern Switzerland (cf. MILNES 1974), but, because of the unusually favourable

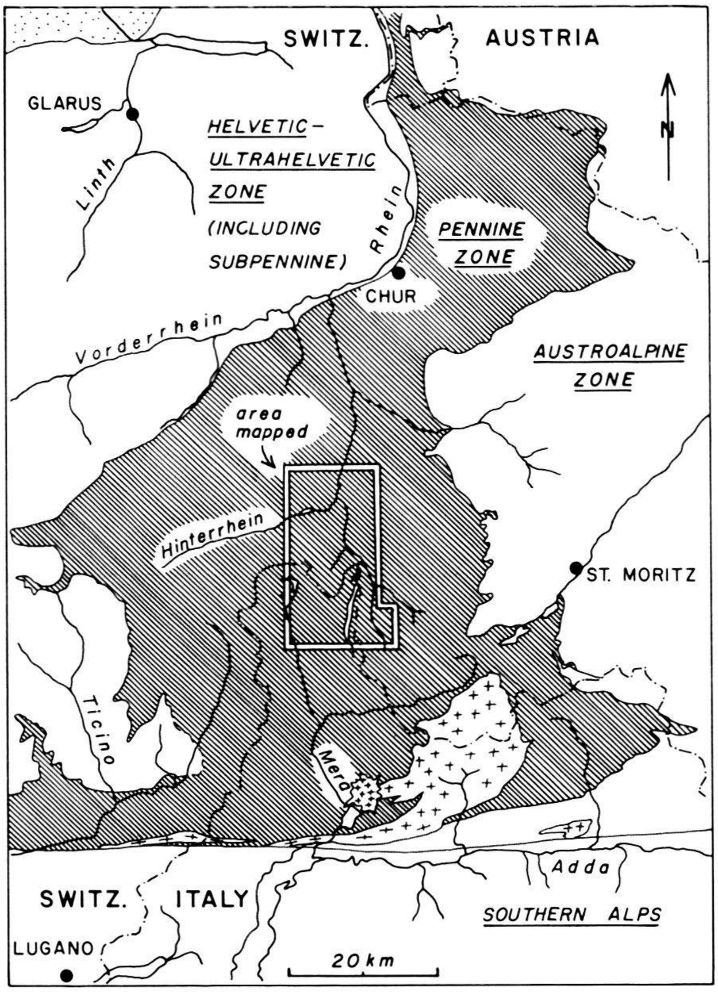


Fig. 1. Geographical and geological location of the area studied.

conditions presented in the area for the unambiguous deduction of the structural relations, it soon developed into an extensive field campaign. Work concentrated on the Suretta and Timun mountain groups, the area bounded by the valleys leading to the Splügen pass in the west, by the Hinterrhein valley in the north and by the Ferrera and Madrisch valleys in the east (Fig. 1). Field mapping was carried out between 1972 and 1975 at a scale of 1:25000, which by present-day Alpine standards is little more than reconnaisance, and the results presented here are based solely on the field data. No doubt the picture will be filled out and modified by more systematic and detailed studies of key localities, and by concomitant microstructural and petrofabric analysis, and we hope that the results of our field study will provide a reasonable framework for such future work.

Main lithological complexes

The Suretta nappe consists of a pre-Triassic basement core surrounded by a Mesozoic sedimentary cover. The «frontal» (northern) part of the core is made up of the *Roffna gneiss*, originally a rather homogeneous granite-porphyry intruded about 350 m.y. ago (HANSON et al. 1969) into an older crystalline complex of extremely heterogeneous make-up, here referred to as the *Timun complex* («Timunmasse» of WILHELM 1929, 1932; «Timun-Stellamasse» of ZURFLÜH 1961) and now lying to the south. Lying on and wrapped around this basement are the parautochthonous Mesozoic units, consisting of a quartzite-carbonate succession *(«Trias»)* overlain by the *Bündnerschiefer* of Avers, a mass of Schistes lustrés with mafic-ultramafic intercalations generally considered to be of Jurassic-Cretaceous age (cf. PANTIĆ & GANSSER 1977). The main features of the rocks involved in these subdivisions are briefly summarized below (see Plate).

a) Roffna gneiss

The petrography of the Roffna gneiss has been studied in quite considerable detail (GRÜNENFELDER 1956, SCHÄRER 1974). In the areas where it has remained undeformed, it is described as a granite-porphyry, with typical rounded quartz phenocrysts (2-5 mm in diameter) and variable amounts and sizes of alkali felspar phenocrysts (up to 5 cm long) in a finer grained matrix. The deformed equivalents of this, probably hypabyssal or subvolcanic, intrusive rock are generally gneisses, often with well developed foliations and lineations, but they may have been converted into sericitic to phengitic schists in places. Apart from the variation in the amount of phenocrystic alkali felspar, the whole mass is chemically very homogeneous (cf. HANSON et al. 1969), and the different rock types in the field are given by differing degrees and types of deformation. The granite-porphyry contains numerous xenoliths which are useful for studying the states of strain in the deformed equivalents. It also shows nebulous dark horizons or vague compositional layering in places, which may represent an original flow lamination. Along the lower contact of the Roffna gneiss body, the typical gneiss grades locally into a much finer grained, strongly banded facies which has been interpreted as tuffite or ignimbrite (cf. GRÜNENFELDER 1956, HANSON et al. 1969) but which may be a mylonitized equivalent of the gneiss.

b) Timun complex

Again, parts of this extremely heterogeneous rock complex have been described petrographically in great detail (ZURFLÜH 1961, BLANC 1965). It is thought to be the country rock into which the Roffna granite-porphyry was originally intruded (see ZURFLÜH 1961). The complex consists mainly of chlorite-sericite schists and schistose gneisses, with discontinuous augen gneiss and amphibolite intercalations, as well as grey gneiss horizons, very similar to Roffna gneiss, and some more exotic rock types (e.g. the «eclogite» of Val di Lei, STAUB 1926, SCHÄRER 1974). In parts of the area, for reasons given below, the contact between the Timun complex and the Roffna gneiss cannot be defined unambiguously. Although the Alpine metamorphism was low grade over the whole area, and most rocks are completely retrograded, remnants of the original, probably Caledonian, amphibolite facies metamorphism of this basement complex have been described recently (WENK 1974).

c) «Trias»

The basement/cover contact is marked over much of the area by a thin, flaggy quartzite horizon, sometimes with a basal conglomeratic layer, overlain by a thick sequence of partly dolomitic marble with local carneole masses. In places, small lenses of dark shale occur between the quartzites and the marbles. Although no fossils have been found, this sequence corresponds well with other Alpine (Permo-)Triassic stratigraphic columns (conglomerate = ? Permian, see STREIFF 1939, ZURFLÜH 1961; dark shale = lower Anisian, see TRÜMPY et al. 1969), and it will be referred to as «Trias» for short. The basal quartzites are everywhere autochthonous with respect to the adjacent basement, whereas the carbonates are obviously considerably disturbed (containing masses of Roffna gneiss and Bündnerschiefer slices at a number of localities). However, the impression is that they are not far removed from their original stratigraphic position, so they are considered to be parautochthonous with respect to the basement. In spite of the evidence for strong internal deformation, the marbles are still quite massive and often devoid of a macroscopically visible deformational fabric.

d) Bündnerschiefer

The Schistes lustrés of the Avers region have only recently been studied in any detail (CORFU 1974, OBERHÄNSLI 1977). They consist mainly of brownish-weathering calcareous schists, containing white mica, chlorite, and varying amounts of albite, quartz and graphite, in addition to calcite. Compositional variations are gradational and apparently unsystematic, lending the whole mass a rather monotonous aspect, but occasional layers of distinctive composition occur (marble, graphite schist). Within this matrix one finds layers and lenses of mafic to ultramafic composition («ophiolites»), now metamorphosed to prasinites, Na-amphibole schists and actinolite, chlorite, talc and serpentine rocks. The Schistes lustrés with these mafic-ultramafic intercalations will be referred to collectively as Bündnerschiefer (the Avers Bündnerschiefer of the literature). A similar complex in a neighbouring tectonic unit (the Adula Bündnerschiefer) has been provisionally dated as Jurassic-Cretaceous (PANTIĆ & GANSSER 1977).

Although the contact between the Avers Bündnerschiefer and the Suretta «Trias» is generally tectonic (SCHÄRER 1974, CORFU 1974, SCHAEREN 1974), there is some indication of a stratigraphic relation in places (cf. BALDERER 1969). Lacking any positive indications to the contrary, we feel, therefore, that the four lithological complexes described above most likely lay more or less adjacent to eachother as the Alpine orogeny started (i.e., that also the Bündnerschiefer is parautochthonous with respect to the Roffna-Timun basement). They are taken together as comprising the Suretta nappe, a single major tectonic unit, and it is the Alpine deformational history of this unit which is of interest here. The nappe is covered by, and in the north enveloped by, the Schams nappe complex, a system of cover nappes showing a Mesozoic stratigraphy and facies completely different from those of the Suretta (see TRÜMPY et al. 1969, STREIFF et al. 1971/1976). The Schams nappes are exotic with respect to the Suretta, having been tectonically juxtaposed from a distant part of the Pennine realm. The internal structure of the Schams nappes is incredibly complicated and was not included in the present work. The basal contact, however, is relatively simple in shape and will be referred to in the following as the Schams thrust.

Structural sequence from the large-scale configuration

At the start of the field work, attention concentrated on the Roffna gneiss as the complex likely to reveal the structural relations most clearly. At an early stage it became clear that the large-scale configuration of this body provided a reliable framework for describing the structural history. In Val Ferrera, in the upper part of the Suretta nappe, the «Trias» and Bündnerschiefer penetrate the Roffna gneiss in a series of zones which could be established as isoclinal infolds and which were collectively called the Ferrera fold system (the «Suretta backfolds» of earlier authors, cf. STAUB 1958). The tectonic «Trias»/Bündnerschiefer contact is clearly affected by the Ferrera folding, as is also a thrust zone identified within the basement complex (the contact between the Roffna-Timun and Hüreli units, see Plate) and the imbricated elements within the «Trias». In contrast, the Schams thrust is not folded along the upper contact of the nappe and must therefore represent a post-Ferrera event. Finally, most of these features - the Schams thrust, the Ferrera folds and the Roffna-Timun / Hüreli boundary - become vertical and then overturned as they pass downwards through the axial zone of the nappe. The Suretta nappe is in fact the core of a huge, north-closing recumbent fold, the Niemet fold. Hence, the following structural sequence was set up as a working hypothesis at an early stage in our investigation:

1. *Early thrusting* (later called the *Avers phase)* - juxtaposition the Avers Bündnerschiefer and the «Trias», imbrication within the «Trias» and movement along the Roffna-Timun / Hüreli boundary.
2. *Early folding* (later called the *Ferrera phase)* - development of a system of isoclinal folds.
3. *Late thrusting* (later called the *Schams phase)* - movement on the Schams thrust (superposition of the Schams nappes on the Suretta complex).
4. *Late folding* (later called the *Niemet phase)* - development of a large recumbent fold with the Suretta nappe as its core.

This hypothesis was then tested by detailed analysis of the minor structural relations in the critical localities. As it became better established with time, the minor structures were used to map out the axial traces of the major folds. Towards the end of the investigation, we felt that the developmental sequence was so firmly based that it in turn could be used to interpret the structural relations in problematic areas, particularly within the Timun complex and along its contact with the Roffna gneiss.

In the following, some details of the structures developed during the various phases will be given. The data is presented as a structural map (Plate), giving the mean orientation of the various minor structures and the traces of the major structural surfaces, as composite stereograms of the various fabric elements at different localities (Fig. 2), and as a synoptic horizontal section illustrating the variations of the structural relations in space (Fig. 3).

Structural analysis

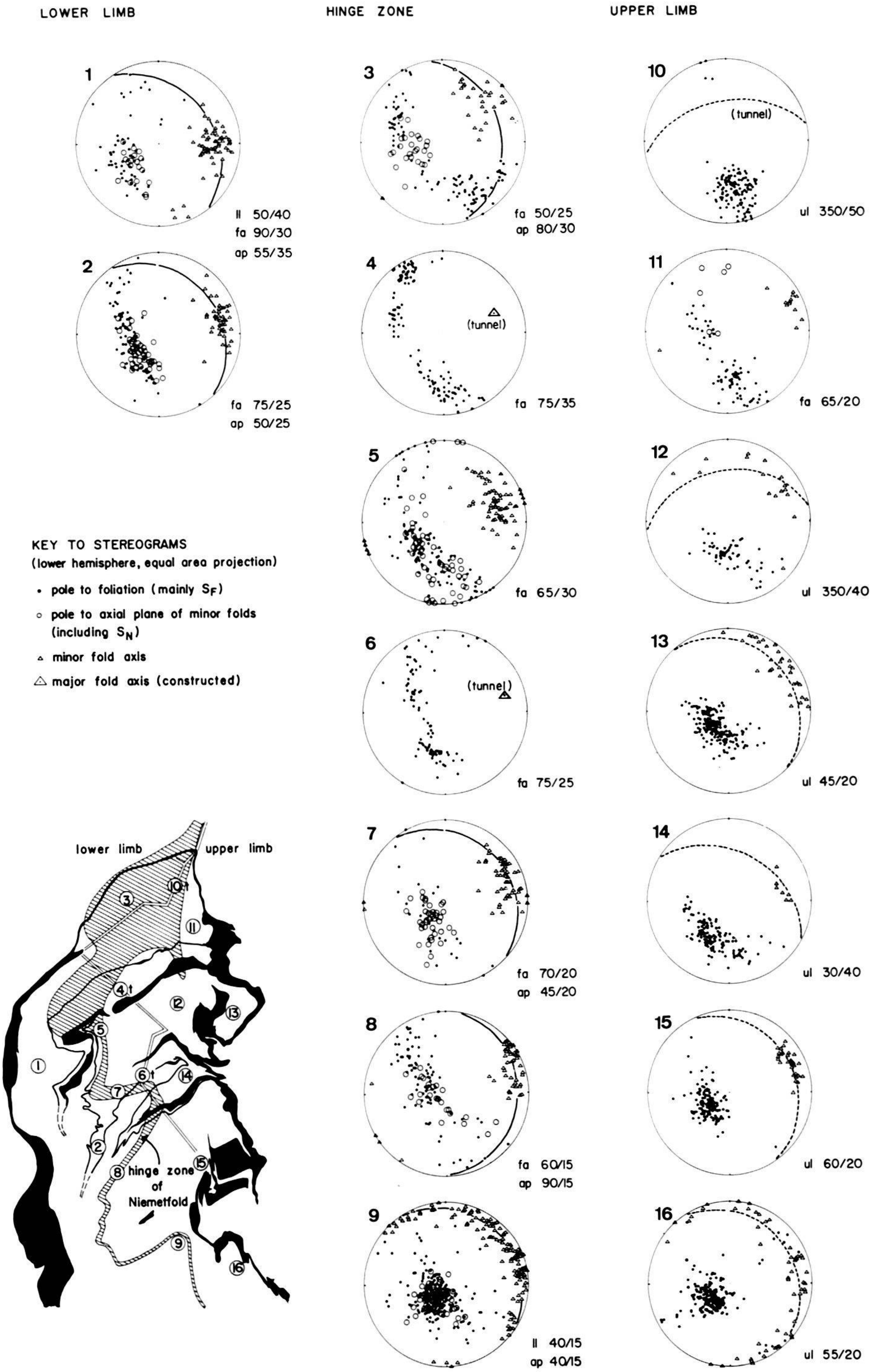
a) Niemet[3]*) phase structures*

In Val Niemet, between Piz Miez and Piz Muttala (Plate), the two Ferrera phase «Trias» synclines 6 and 8, and the intervening anticline 7 (see below), are affected by a major N-closing recumbent fold with an axial plane dipping NE at 15–25° subparallel to the ENE-plunging major fold axis (Fig. 2, e.g. stereograms 6, 7, 8). This major structure, the Niemet fold, is almost isoclinal on a large scale (compare upper limb stereograms 14 and 15 with lower limb stereograms 1 and 2, Fig. 2) and is accompanied by widespread parasitic minor structures. In Val Niemet, these fall into two style groups, associated with the two main lithologies found there. In the Roffna gneiss, the Niemet phase produced a fine crenulation cleavage which in many places is axial planar to mesoscopic folds of various amplitudes. In some places, the Niemet schistosity, S_N, appears as the only foliation in an otherwise homogeneous gneiss, although close inspection will often reveal a «herring-bone structure», indicative of a weak pre-Niemet foliation, and occasional earlier isoclinal folds in a vague compositional banding. In contrast, the schists of the Timun complex only show intense chevron-type minor folds with no new cleavage developed parallel to the axial planes. These relationships are summarized in Figure 3 (region *C–D–E* of the hinge zone trace).

[3]) In an earlier work (MILNES 1974), this was referred to as the «Suretta» phase and the Niemet fold called the «Suretta fold». This is avoided here, and should be in future, because Suretta is traditionally used to designate a nappe structure, which is conceptually quite different from a fold. The Suretta nappe has undergone a long deformational history, in which the development of this fold is just one of a sequence of events. Also, the fold affects not only the Suretta nappe, but also other tectonic units not bearing the name Suretta (e.g. the Schams nappes). It should also be noted that the postulated axial trace of the Niemet (= «Suretta») fold in the above work (Fig. 3) proved, in the course of subsequent work, to be incorrect in its southern part.

Fig. 2. Composite stereograms showing the degree of variability in orientation of the structural elements at various positions along the limbs and the hinge zone of the Niemet fold.

Abbreviations: *fa* = fold axis, *ap* = axial plane (full great circle on stereograms), *ll* = lower limb S_F, *ul* = upper limb S_F (dashed great circle on stereograms). *Numbers*, e.g. 70/30, give the mean dip or plunge direction/dip or plunge angle, in that order.


LOWER LIMB
HINGE ZONE
UPPER LIMB
1
ll 50/40
fa 90/30
ap 55/35
2
fa 75/25
ap 50/25
3
fa 50/25
ap 80/30
4
(tunnel)
fa 75/35
5
fa 65/30
6
(tunnel)
fa 75/25
7
fa 70/20
ap 45/20
8
fa 60/15
ap 90/15
9
ll 40/15
ap 40/15
10
(tunnel)
ul 350/50
11
fa 65/20
12
ul 350/40
13
ul 45/20
14
ul 30/40
15
ul 60/20
16
ul 55/20
KEY TO STEREOGRAMS
(lower hemisphere, equal area projection)
• pole to foliation (mainly S_F)
○ pole to axial plane of minor folds (including S_N)
▵ minor fold axis
△ major fold axis (constructed)
lower limb
upper limb
hinge zone of Niemetfold

The hinge zone of the major fold in Val Niemet can be followed both southwards and northwards from this type locality, but it changes character considerably in both directions. To the south, along the northwest flank of Piz Timun, it runs through Timun complex schists, becoming progressively tighter and associated with increasingly tight parasitic folds, still without the development of a new axial planar structure. Eventually, it runs into an augen gneiss zone, where it disappears as an identifiable fold hinge - the augen gneiss is homogeneous and contains a single penetrative foliation parallel to the zone margins (i.e. S_N parallel to the major axial plane, see region *F–G–H*, Fig. 3). North of Val Niemet, the axial trace lies mainly within the Roffna gneiss and is once more clearly defineable where it traverses a further zone of «Trias» in Val Suretta (region *C–B*, Fig. 3). Further north, although still locally accompanied by an associated axial planar foliation, the hinge zone becomes much broader and is made up of a massive Roffna gneiss showing a weakly developed rodding structure (*L*-tectonite, lineation parallel to the major fold axis). The occasional stretched xenoliths indicate that this lineation marks the finite strain elongation axis. A possible explanation would be the superimposition of two weak flattening strains perpendicular to eachother in the hinge zone, of which the later would be associated with the Niemet folding. The Roffna gneiss in this northern part of the Suretta nappe seems to have acted as a thick competent layer during the development of the Niemet fold, and the axial trace is no longer a mappable zone but a vague area where the pre-Niemet foliation is subvertical (cf. Plate). Even this is not a good rule, because the pre-Niemet relationships were themselves quite complicated, with at least two separate, superimposed foliations distinguishable in some areas (region *B–A*, Fig. 3, see later). This seems to have influenced the pre-Niemet shape of the Roffna gneiss / «Trias» contact in this area, since it does not show a geometrically simple folded shape. Unfortunately, the lack of exposure around Andeer makes a detailed reconstruction of the hinge there impossible. The northward continuation of the Niemet axial trace, through the Schams nappes and into the Prättigau Flysch by Nivaigl (Albula valley below Tiefencastel) can be deduced from the map and profiles in STREIFF (1962).

The upper and lower limbs of the Niemet fold in the Suretta nappe show a quite striking asymmetry. The lower limb, particularly where it starts turning into the hinge zone, is very intensely affected by parasitic folds on many different scales (size orders 1 cm–100 m). Since these are superimposed on complex structures of similar size orders from earlier phases, the geometrical relations are sometimes difficult to sort out, sometimes almost chaotic (e.g. around Piz Spadolazzo, see Plate). In contrast, the upper limb is almost completely devoid of small-scale Niemet phase structures. Since the earlier events resulted in similar structural relations on each limb, this asymmetry possibly reflects the fact that, in the case of such large-scale recumbent structures, the two limbs of a single fold may be deforming under

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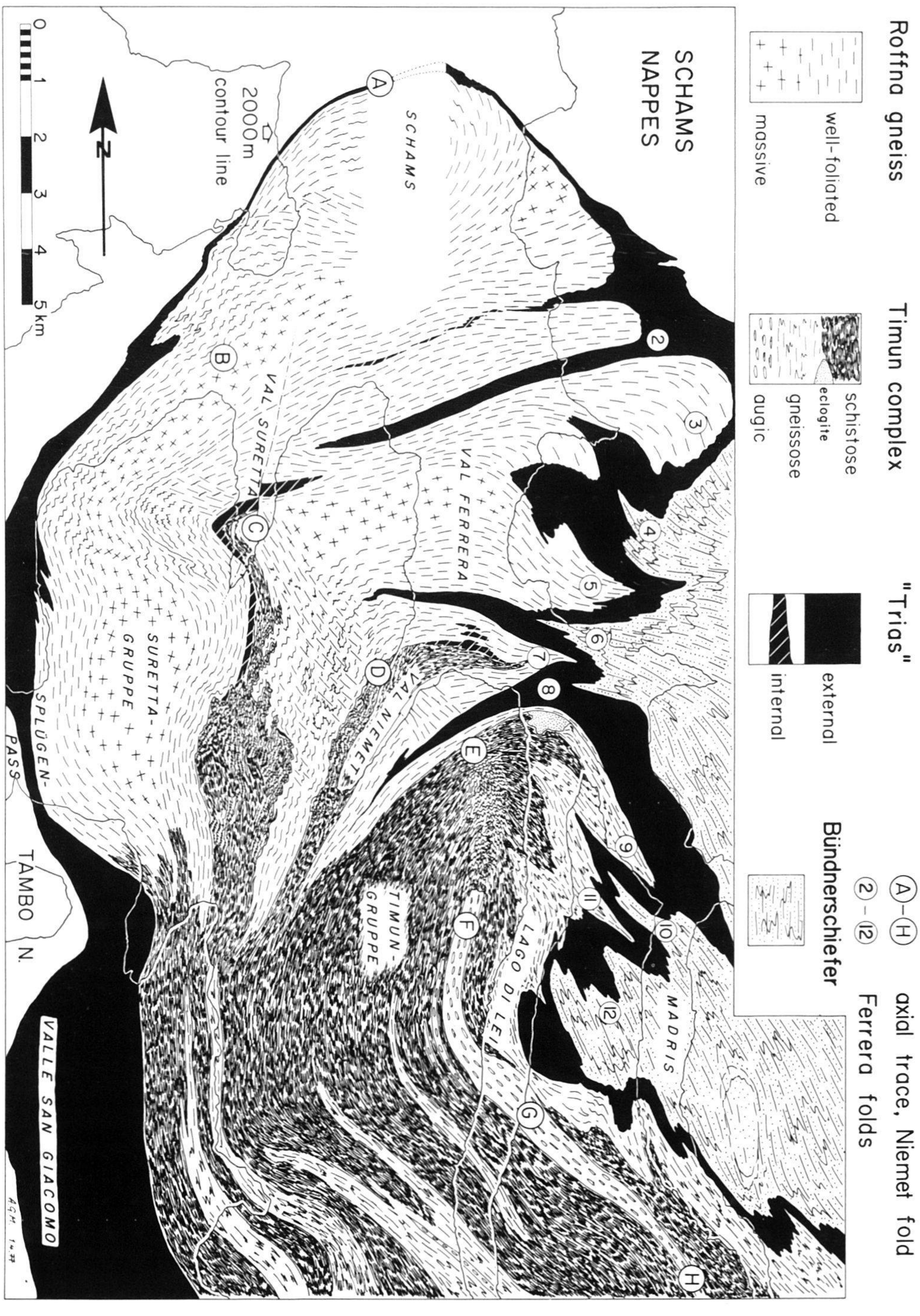
Fig. 3. Synoptic horizontal section at the 2000 m level through the Suretta group and adjacent areas, illustrating the variation in structural relations in space. Note that the major and minor fold axes over most of the area plunge constantly ENE, so the horizontal section becomes equivalent to a constructed (vertical) cross-section with a exagerated vertical scale when viewed with the west side of the diagram downwards.


Roffna gneiss
well-foliated
massive
Timun complex
schistose
eclogite
gneissose
augic
"Trias"
external
internal
Bündnerschiefer
A-H axial trace, Niemet fold
2-12 Ferrera folds
SCHAMS NAPPES
2000m contour line
N
0 1 2 3 4 5 km
SCHAMS
VAL FERRERA
VAL SURETTA
VAL NIEMET
SURETTA-GRUPPE
SPLÜGEN-PASS
TIMUN-GRUPPE
LAGO DI LEI
MADRIS
TAMBO N.
VALLE SAN GIACOMO

significantly different conditions (e.g. temperature differences of 100 °C and lithostatic pressure differences of 1 kb, corresponding to differences in level of 3-4 km).

The Niemet phase is the last of the sequence of major deformational events distinguishable in the Suretta nappe. However, some post-Niemet effects are locally important. Occasional small faults were mapped, but these have been omitted from the map (Plate) if no displacement, or displacements of only a few metres, could be proved. The only fault of significance runs N-S along Val Suretta and displaces the structures on either side of the valley by a few hundred metres (Fig. 3, Plate). More important for the regional picture are the obvious undulations in the Niemet fold axial surface (cf. Fig. 2 and 3). Some of these may be due to an accomodation of ductile flowing material to the several rigid pods of Roffna granite-porphyry which have survived undeformed through all the deformational events (Fig. 3). However, some are certainly due to slight post-Niemet warping about NE-plunging axes and subvertical axial planes, which also produced sporadic patches of similarly orientated minor folding. Extrapolating the axial traces of these open folds northeastwards brings one directly to the Ducan fold zone in central Graubünden, a zone of late, upright folds deforming the base of the Austroalpine nappes (cf. Trümpy 1973, Fig. 2, phase *D*).

b) Schams phase structures

The juxtaposition of the Suretta and the Schams nappes, certainly a pre-Niemet, post-Ferrera event, must have involved very considerable displacement (? size order 100 km) along their mutual contact, the Schams thrust (see above). However, these movements seem to have left no structural imprint on the Suretta rocks themselves, except possibly in the immediate vicinity of the thrust surface, where, however, exposure is particularly poor.

c) Ferrera phase structures

The major folds of the Ferrera phase are best developed along the flanks of Val Ferrera and its southward extension, Val Madrisch. For ease of reference, these have been numbered from north to south, synclines even and anticlines odd (Plate, Fig. 3). Of these, the three which run into Val Niemet (folds 6, 7 and 8, see above) are critical for an understanding of the history of the region, since their axial traces can be followed unambiguously across the hinge zone of the Niemet fold into the lower limb. The fold nature of these structures is best seen in synclines 2, 8, and 10, and in anticlines 5, 7, and 9, either because of well developed and exposed fold hinges or of a clear symmetry in the lithologies involved. Some «folds», however, show rather strange shapes which seem to stretch the term to its extreme limit («anticline» 1, «anticline-syncline pair» 3-4, see Fig. 3). The common feature of all these structures is the associated axial planar foliation, S_F, with or without associated tight folding, in the Roffna gneiss, and the parasitic isoclinal folding, with or without a related axial planar foliation, in the Timun schists. As a broad generalization, one can say that the main foliation in the Roffna gneiss belongs to this phase[4]), although both earlier and later (Niemet) foliations may be dominant in certain areas. However, the degree of development of this foliation varies quite unsystematically (with respect to the fold structures) and a number of rock volumes escaped penetrative deformation even under these highly ductile conditions. A further generalization is that the deformation was mainly of flattening type - elongation lineations are absent over most of the upper limb region of the Niemet fold (region where Niemet minor structures are absent, see above).

Interesting, though problematic, relations are discovered when the axes of the Ferrera folds are considered. In the northern part of the map area, they are coaxial with the Niemet phase folds - folded fold axes or lineations were not encountered north of a line between the Splügen pass and lower Val Madrisch. This northern area coincides with the region where the Niemet fold has a clearly defined hinge with a fold axis which can be constructed from the S_F foliation plots (see Fig. 2, stereograms 4 and 6). South of this line, the situation reverses itself - the major Niemet fold becomes completely isoclinal, without an identifiable hinge, and the minor fold axes (in this area, usually not assignable to one or the other of the fold phases) become extremely variable in trend (see Fig. 2, stereograms 9, 16). Also, in Val Madrisch, the hinges of the major Ferrera folds (e.g. folds 10, 11, 12) become strongly curved in the plane of the axial plane, leading to the change in closing direction obvious even on the early maps (STAUB 1926) and to the curious eye-shaped outcrop of the Na-amphibole schist above Zocca (CORFU 1974, see present Fig. 3).

Finally, it should be noted that the Splügen syncline, the zone of «Trias» separating the Roffna-Timun crystallines from the crystalline rocks of the Tambo nappe (see Plate) is probably a Ferrera phase structure, much larger than the ones described above. It shows a certain symmetry, with inverted series near the top (ZURFLÜH 1961) and the Schams thrust is not folded into its core (cf. STREIFF et al. 1971/1976), so at least it is to be interpreted as a pre-Schams fold structure (cf. Fig. 4).

d) Avers phase structures

Removing the effects of the above phases reveals abundant evidence of a more brittle deformation, including significant thrusting, at an even earlier stage, as well as evidence for very localized ductile flow (local, pre-Ferrera foliations). Although these effects may themselves represent a sequence of events, they are here lumped together as the results of the Avers phase. Typical of this phase was the development of tectonic breccias and imbricate zones, particularly in the cover near the basement contact (see also GRÜNENFELDER 1956). These include some large torn-apart rock masses of mappable size (cf. WILHELM 1929, STREIFF et al. 1971/1976). Whatever the scale, the components of these chaotic zones correspond exclusively to rocks of

[4]) Various authors (e.g. STREIFF 1939, GRÜNENFELDER 1956, ZURFLÜH 1961) mention the discordant relationship between the Roffna gneiss foliation and the bedding in the basal conglomerates of the «Trias» on Piz la Tschera, implying that, at least in some places, the foliation must be a pre-Alpine (pre-?Permian) effect. The observation that the basal «Trias» is also cut by a cleavage with the same orientation as the underlying gneiss foliation (with flattening of the pebbles in the cleavage planes) casts some doubt on this interpretation, and we prefer to interpret the foliation also here as mainly a Ferrera phase effect.

the lithological complexes within the nappe, with no sign of exotic types (for detailed descriptions, see CORFU 1974, p. 56–80; SCHÄRER 1974, p. 76–80; SCHAEREN 1974, p. 37–39). The mapping difficulties presented by this situation were overcome in the following, rather schematic, way (cf. Plate): the contact between Avers Bündnerschiefer and «Trias» was placed at the position where calcareous schist took over from marble as the dominant matrix of the breccia or imbricated fragments. This contact was then stylized as a thrust zone separating the Avers unit (mainly Bündnerschiefer) from the parautochthonous «Trias».

An important result of the detailed analysis of the major and minor structures associated with the ductile deformation phases was the discovery that certain «Trias» zones could not have been emplaced within the basement complex by infolding during the Ferrera phase. They – the «internal Trias» of Figure 3 and Plate – must have been in place before the folding took place, already sandwiched between crystalline rocks. As the mapping of the Ferrera folds was completed, it became clear that this internal «Trias» occupied a specific level in the nappe complex, coinciding with the contact Roffna gneiss / Timun schist in many places. Eventually it was possible to map out this level as a continuous contact (thrust surface) between two main tectonic units within the nappe, the Roffna-Timun and Hüreli units (Plate). The Hüreli unit consists only of Roffna gneiss, probably originally as a thin sheet, but now with a very complicated shape due to the superposition of major Ferrera and Niemet folds. The Roffna-Timun unit contains both Roffna gneiss and the whole of the Timun complex, with a contact between these two lithological subdivisions in the region of Piz Spadolazzo which ZURFLÜH (1961) describes as probably intrusive. Although there is no direct evidence, it seems probable that this internal thrust developed at the same time as the, also pre-Ferrera, imbrication and brecciation in the cover units.

Conclusions and discussion

The main result of the present field study has been to show that the Suretta nappe (Roffna gneiss + Timun complex + «Trias» + Avers Bündnerschiefer) has an internal structure and external shape which can be understood in terms of four main deformational phases acting on an originally coherent block of pre-Mesozoic continental basement and its Mesozoic cover. These were:

1. early thrusting/imbrication/brecciation (Avers phase)
2. early isoclinal folding (Ferrera phase)
3. late thrusting (Schams phase)
4. late isoclinal folding (Niemet phase)

There are few areas in the Alps where such a clear sequence of major Alpine events can be unambiguously established and there are few rock bodies which can equal the Roffna gneiss in preserving clear sequences of structural overprinting, so it is hoped that this field study will provide inspiration for more detailed, particularly microstructural, work. As far as the orogenic history of this part of the Pennine zone is concerned, two aspects are of particular interest – the absolute timing of the different phases, and the kinematic significance of the structural data. These are discussed below in turn.

The latest phase of ductile penetrative deformation in the Pennine zone (the Niemet phase in this area, ignoring the slight post-Niemet warping) has been dated as mid-Eocene to mid-Oligocene, mainly on circumstantial evidence (MILNES 1974, MILNES in press). Pressures and temperatures probably rose at this time, reaching lower greenschist facies conditions, and subsequently slowly declined. A recent radiometric study of the Roffna gneiss (HANSON et al. 1969) distinguished two metamorphic events - at 80-110 m.y. and at 14-32 m.y. ago. The latter could easily be related to the period of cooling and uplift subsequent to the Niemet phase, in agreement with the other evidence. However, HANSON et al. (op. cit.) place the main period of recrystallization of the Roffna gneiss, as indicated by the Rb/Sr whole-rock isochron, at about 110 m.y. ago (Albian-Aptian). The only pre-Niemet structural event capable of producing such complete transformation of the whole rock mass would be the Ferrera folding (main gneiss foliation), giving a tentative mid-Cretaceous date for this phase.

The thrusting phases are more difficult to date since they are unlikely to have left any isotopic finger-prints. However, compressional tectonics is generally considered to have started in mid-Cretaceous times, so it seems likely that the early thrusting (Avers phase) must have immediately preceeded the early folding (Ferrera), if the above correlation with the whole-rock age is correct. It is thus tempting to link the two as two stages in a major overthrusting episode, with the change from brittle to ductile conditions reflecting increasing tectonic burial. Similarly, since the Schams nappes contain rocks of supposed Eocene age as their youngest formation (STREIFF

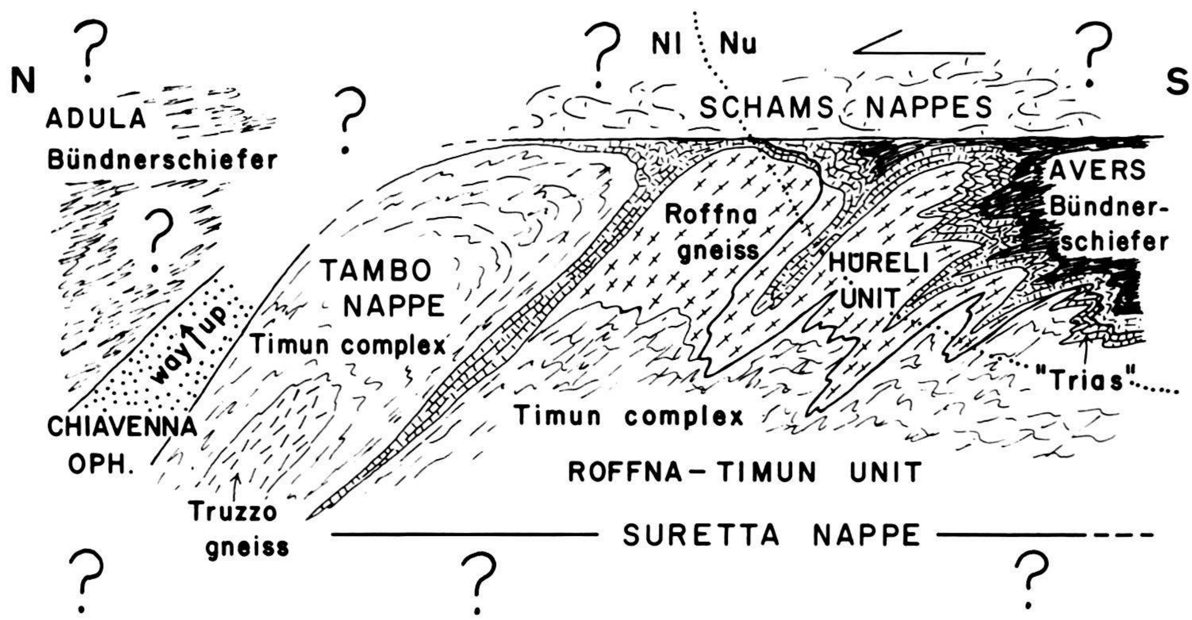


Fig. 4. Schematic section showing the approximate relative positions of the different units *after* the emplacement of the Schams nappes but *before* the development of the Niemet fold. *Nl* = lower limb, *Nu* = upper limb of the future Niemet fold.

1962), the late thrusting (Schams phase) is likely to have been an early Tertiary event and thus is to be considered as the immediate fore-runner of the late folding (Niemet). It looks as though the combined structural, radiometric and stratigraphic evidence indicates two quite separate episodes of major overthrusting and tectonic burial, in mid-Cretaceous and in late Eocene-early Oligocene times (equivalent to the Paleo-Alpine and Meso-Alpine orogenies of TRÜMPY 1973).

These conclusions lead on to the second question - that of the general kinematic picture during these movements, i.e. the overall «movement directions». In the case of thrust tectonics, the «movement direction» is theoretically definable as the overall displacement direction of the upper, relative to the lower, block (i.e. the direction of overthrusting). In ductile deformation, «movement direction» has little meaning, unless a plane strain field can be proved, but the term can be used as a vague indication of the displacement direction of a (perhaps hypothetical) block above a ductile flow zone relative to some point below it. Since strain on a small scale and displacement on a large scale are rarely directly related, such overall «movement directions» cannot be deduced from analysis of minor structures alone. They must be based on overall geological evidence, usually with an appreciable input of intuition. The Suretta nappe is a case in point. It is now fairly clear that the «movement direction» at the time of development of the Niemet fold was to the north (the Pennine zone was at that time a ductile flow zone beneath the northward overriding Austroalpine block, see DIETRICH 1976, MILNES in press). This means that the present upper limb of the fold is its normal limb, and that the present lower limb (including the Tambo nappe, and probably the Chiavenna ophiolite complex, which was earlier postulated as inverted on completely independent grounds, see SCHMUTZ 1976) must be inverted relative to its position before folding. Unfolding the Niemet fold thus shows relationships as in Figure 4. The Schams nappes lie above the subhorizontal Schams thrust on top of the Suretta and neighbouring Tambo units. Since we have seen that the Schams phase is temporally closely related to, and probably a fore-runner of, the Niemet phase, it most likely involved a related «movement direction», i.e. also to the north (emplaced from a more southerly location; «solution supra» of the Schams dilemma, see TRÜMPY et al. 1969). On the other hand, the reconstruction of pre-Niemet relations (Fig. 4) shows the large Tambo unit lying then to the north of the Suretta, with the now right-way-up Chiavenna ophiolites on its back, and the Ferrera folds with a southward vergence. This suggests the opposite sense of movement during the mid-Cretaceous episode, i.e. a «movement direction» to the south in a northward dipping ductile flow zone.

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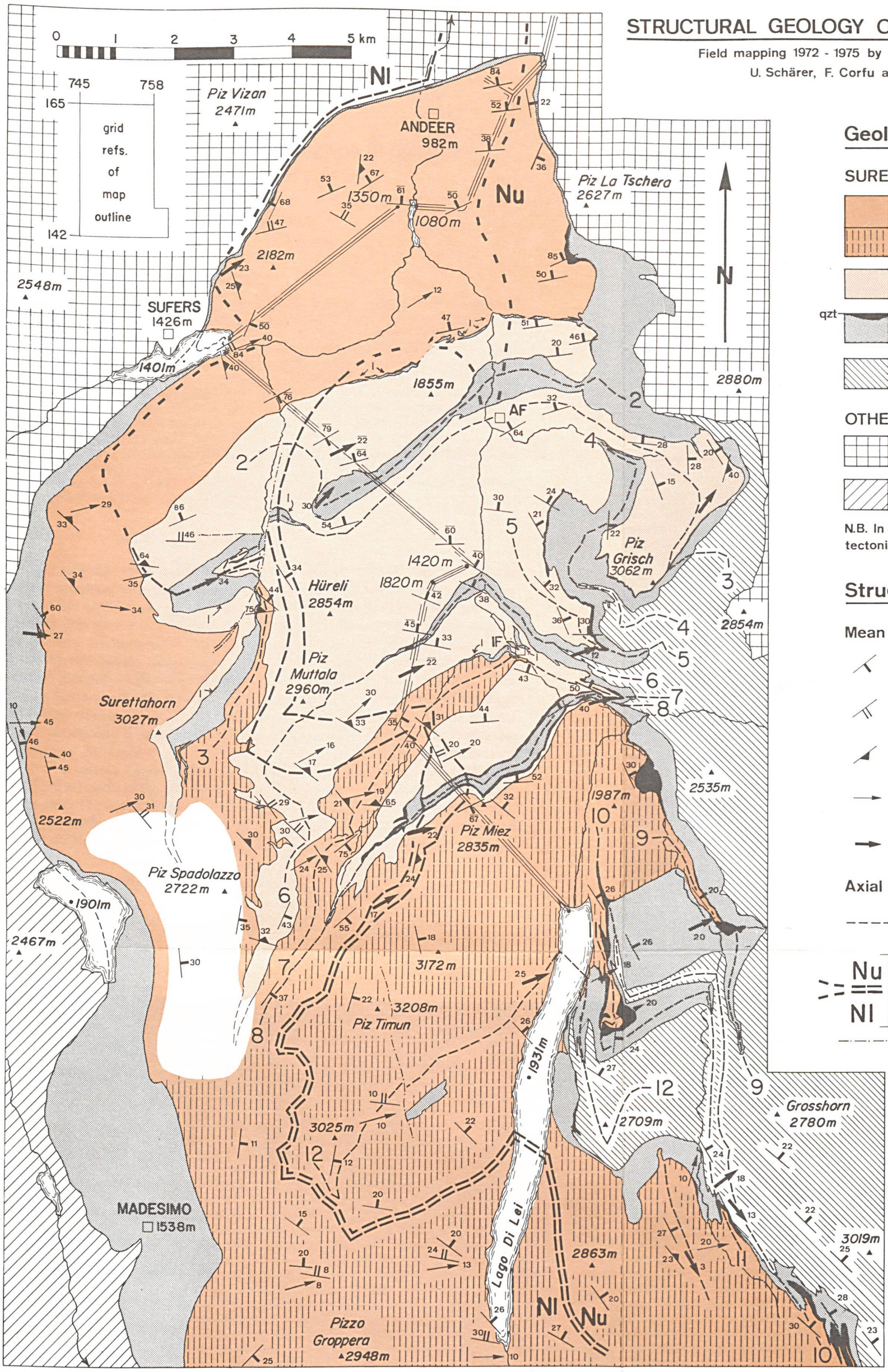
STRUCTURAL GEOLOGY OF THE SURETTA REGION

Field mapping 1972 - 1975 by A.G. Milnes, H.U. Schmutz, U. Schärer, F. Corfu and G. Schaeren.



Geologic - tectonic units

SURETTA NAPPE

- Roffna gneiss, Timun complex — ROFFNA - TIMUN
- Roffna gneiss — HÜRELI
- qzt — mainly "Trias" (I = INTERNAL)
- "Bündnerschiefer" — AVERS

OTHER UNITS

- SCHAMS
- TAMBO

N.B. In complex region around Piz Spadolazzo, tectonic correlations speculative

Structural symbols

Mean orientation of:

- foliation, often axial planar to minor isoclinal folds
- foliation axial planar to minor chevron or crenulation type folds
- axial plane of minor chevron or crenulation type folds, axial plane foliation absent
- lineations and minor fold axis
- major fold hinges (constructed axis)

Axial plane traces of major folds:

- Ferrera fold system 2-12
- Nu / NI — Niemet recumbent fold: Nu - upper limb, hinge zone, NI - lower limb
- main faults

Other information

- trace of hydropower tunnels with structural data underground
- 1420 m tunnel level at given points
- IF Innerferrera
- AF Ausserferrera