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Objekttyp: **Article**

Zeitschrift: **Eclogae Geologicae Helvetiae**

Band (Jahr): **73 (1980)**

Heft 2: **Symposium alpine geotraverses with special emphasis on the Basel-Chiasso profile : Lausanne, 4-5 October 1979**

PDF erstellt am: **17.05.2024**

Persistenter Link: https://doi.org/10.5169/seals-164980

Eclogae geol. Helv.	Vol. 73/2	Pages 619-633	2 figures in the text 1 table and 1 plate	Basle, July 1980

Tectonic evolution of the Central Alps in the cross section St. Gallen-Como

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ABSTRACT

The Swiss Geotraverse Basel-Chiasso is badly placed for investigating the tectonic evolution of the Central Alps since several important elements of Alpine structure are not exposed along it. For this reason, a new structural cross section to the east of the Geotraverse (St. Gallen-Como) is presented, along which the missing elements are well exposed and have recently been analyzed in detail. A series of structural zones can be recognized, characterized by complex deformational histories, each involving at least four phases which resulted in thrust sheets and/or major folds. Correlation from zone to zone and between structural, stratigraphic and radiometric age data is often uncertain, but a synthesis is attempted which reveals a complicated tectonic evolution, starting in the mid-Cretaceous and ending in the Pliocene. In a general way, this can be understood in terms of continental collision. However, some features suggest that gravity may have played a major role at some positions and at certain times. For instance, the shape in cross section and the high deformation at the toe of the Helvetic nappes are features thought to be characteristic of gravity gliding. Closer study, however, reveals criteria which exclude this process but which would allow for nappe emplacement partly being driven by gravity spreading. Further, the southern part of the section shows a number of features suggesting the action of strong buoyancy and diapirism (southern steep zone, Soé gneiss dome), but definitive structural evidence is lacking. These and other examples show how little we still understand large-scale tectonic processes.

ZUSAMMENFASSUNG

Die Schweizer Geotraverse Basel-Chiasso ist etwas ungünstig gelegen für das Studium der tektonischen Entwicklung der Zentralalpen, da mehrere wichtige Elemente des Alpenbaus entlang diesem Profil nicht aufgeschlossen sind. Längs der hier präsentierten Geotraverse (St. Gallen-Como) sind diese Elemente nicht nur vorhanden, sondern sie wurden in neuerer Zeit auch detailliert untersucht. Aufgrund dieser Untersuchungen liess sich diese Geotraverse in verschiedene Zonen gliedern, und für jede dieser Zonen ergab sich eine komplexe Deformationsgeschichte mit mindestens je vier Phasen von grossräumigen Überschiebungen und/oder Faltungen. Korrelationen zwischen diesen Zonen sowie zwischen strukturgeologischen Befunden, stratigraphischen Randbedingungen und absoluten Altersbestimmungen sind zwar oft unsicher, aber eine Synthese ergibt unweigerlich ein kompliziertes Bild einer tektonischen Entwicklung, die ihren Anfang mitte Kreide nimmt und im Pliozän beendet ist. Diese Entwicklung kann, generell gesehen, als Folge der Kollision zweier Kontinente betrachtet werden. Einige Phänomene hingegen scheinen darauf hinzudeuten, dass die Schwere an einigen Orten zu bestimmten Zeiten eine wichtige Rolle spielte. So könnten z. B. die Querschnittsgeometrie und die hohe Verformung der Front der Helvetischen Decken als Hinweise auf den Prozess der Schweregleitung aufgefasst werden. Bei näherer Betrachtung hingegen findet man Kriterien, die diesen Prozess ausschliessen und allenfalls

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auf ein Mitwirken der Schwere bei den Deckenbewegungen in Form der Schwereausbreitung hinweisen. Ferner vergewärtigt man im südlichen Teil dieser Geotraverse Phänomene, wie z.B. den Soé-Gneisdom und die «südliche steilstehende Zone», die auf die Wirkung eines starken Auftriebes und Diapirismus hinzudeuten scheinen; eindeutige strukturgeologische Beweise hierzu fehlen jedoch. Die Beispiele zeigen, wie wenig wir die grossräumigen tektonischen Prozesse noch verstehen.

1. Introduction

The official Swiss Geotraverse, Basel–Chiasso, gives only a fragmentary view of the tectonic evolution of the Central Alps. Because it runs along the Aar-Ticino culmination, several important elements of Alpine structure are lacking, including the southern parts of the Infrahelvetic and Helvetic, and practically the whole of the Pennine and Austroalpine zones (MILNES 1974, profile CD). For this reason, any synthesis of the orogenic history of the Alps along the Geotraverse must be largely based on data from traverses east and west of the actual line (op. cit. profiles AB and EF). Our main aim here is to present a new cross section from the eastern side of the culmination, along the line St. Gallen (eastern Switzerland) to Como (northern Italy), and to discuss some aspects of the structure of the Helvetic and Pennine zones which are well exposed there and which may be of some significance in understanding Geotraverse tectonics.

Our new profile (see Plate) represents a synthesis of numerous earlier works along various parts of the complete cross section. We refer particularly to TRÜMPY 1969, 1975, TRÜMPY et al. 1969, MILNES & PFIFFNER 1977, MILNES 1978, PFIFFNER 1977, 1978, 1980, which together give complete details of the extensive literature. Recent structural mapping supported by the "Schweizerischer Nationalfonds" has enabled us to determine the sequence of major thrust and fold structures in specific areas. Here we attempt to correlate these structures across the whole section and to fit this tectonic evolution into the stratigraphic/radiometric timescale of the area (see Table). The tectonic evolution has already been interpreted in terms of continental collision (MILNES 1978). Although we do not doubt this general conclusion (see also DIETRICH 1976, BICKLE & HAWKESWORTH 1978), there is a danger that giving it a name will leave the impression that all is now explained. To show that this is not the case, we shall consider the structural relations in two parts of the section in more detail. The question is: what, if at all, was the role of gravity at different positions within the collision zone and at different stages of the collision process and how can this role be defined on the basis of the structural sequence and style? The examples discussed include the Helvetic nappes in the northern part of the section and the Soé gneiss dome in the south.

2. Structural history – St. Gallen–Como cross section

The Alpine orogenic history of the Central Alps can be roughly bracketed between the mid-Cretaceous (earliest flysch-type sedimentation, radiometric dating) and the Pliocene (undisturbed sediments in the Jura mountains and the Southern Alps). Since then, differential uplift of the core zone of the Alps has continued due

Table: *Skeleton time scale for the Alpine orogeny in the St. Gallen–Como cross section, Central Alps.*

time scale		northern structural zone		central structural zone		southern structural zone	
m.y.	stratigraphic subdivisions	deformation phase	other data	deformation phase	other data	deformation phase	other data
1-2	PLIOCENE						
	start of post-tectonic differential uplift						
6	MIOCENE	RUCHI				(brittle faulting) TONALE (ductile faulting)	highest temp. attained, followed by rapid cooling
23			?acme of metamorphism		post-Niemet major folding in Lukmanier area		26 m.y. Novate intrusion
	OLIGOCENE	CALANDA, CAVISTRAU, PIZOL	youngest pre-Pizol sediments		35 m.y. acme of metamorphism	CRESSIM	30 m.y. Bergell intrusion; high temp. first attained
38	EOCENE			NIEMET, SCHAMS	youngest pre-Niemet (?pre-Schams) sediments	MISOX	
54	PALEOCENE						
65	UPPER CRETACEOUS						
100	LOWER CRETACEOUS			FERRERA, AVERS	110 m.y. main recryst. Roffna gneiss	?PAGLIA	
135		phase names after MILNES & PFIFFNER 1977		phase names after MILNES & SCHMUTZ 1978		phase names new this paper, see FUMASOLI 1974, HEITZMANN 1975, MILNES 1978	

to isostatic readjustment, apparently without appreciable tectonic effects, and this continues to the present day (GUBLER 1976).

In constructing our cross section, we have tried to remove these passive post-tectonic effects using an average longterm relative uplift and erosion rate of about 1 km/my for the central section. This was compensated by passive tilting in the northern section and by movement along late faults (following earlier fracture zones like the Tonale and Musso lines) in the south. This gives a more realistic picture of the structural relations at the end of orogenesis - particularly important when discussing gravity effects - than the present day situation.

For outlining the structural history, we subdivide the cross section into three parts - the northern, central and southern structural zones (see Plate). These correspond to the structural zones $A+B$, $C+D$, and F respectively defined by MILNES (1978) and should be clearly distinguished from the better-known tectono-stratigraphic units (Helvetic, Pennine, Austroalpine) which are defined mainly using pre-Alpine criteria (Mesozoic facies realms, basement petrography). Each of the structural zones is characterized by a sequence of at least four deformation phases producing major thrust and/or fold structures. Although the absolute timing of these events is often uncertain, it is clear that there is no one-to-one correlation of structural histories from zone to zone (see Table). For this reason we have avoided misleading numbering systems and have preferred to name the phases after localities in which structures of that phase are dominant or particularly well developed.

a) Northern structural zone

The main phase of ductile deformation in the Infrahelvetic complex and Helvetic nappes is the *Calanda* phase, which in most areas and rock types is marked by penetrative cleavages and stretching lineations (MILNES & PFIFFNER 1977, PFIFFNER 1977, 1978, 1980). On a large scale it developed systems of thrusts and folds with a constant northward vergence but quite variable fold axes, combined with transverse faults. Calanda phase structures are superimposed on two sets of earlier ones, thrusts of the *Pizol* phase (at the base of exotic strip sheets derived from south of the original Helvetic facies realm) and the remains of thrusts and folds of the following *Cavistrau* phase. Subsequent to the Calanda phase, the Helvetic nappe complex was transported northwards on the Glarus overthrust; this *Ruchi* phase produced extensive overprinting of Calanda phase structures (crenulation cleavage), particularly in the footwall of the overthrust in suitable rocks within the Infrahelvetic complex.

This structural sequence is completely post-lower Oligocene - sediments of that age are overridden by the exotic nappes of the Pizol phase - but otherwise the placement in the time scale is rather uncertain (see Table).

b) Central structural zone

The structural history of the central structural zone is best known in the Suretta nappe (MILNES & SCHMUTZ 1978). Here, the earliest phase, the *Avers* phase, caused thrusting, imbrication and brecciation, particularly along the contact between the Suretta complex and the Avers Bündnerschiefer. Both units were then subjected to a phase of ductile deformation (*Ferrera* phase) which produced the spectacular deep infolds of cover into basement along the Ferrera valley and the main foliation in the basement granites (Roffna gneiss). Later thrusting juxtaposed the far-travelled *Schams* nappes on top of the Suretta-Avers complex. And finally, in the *Niemet* phase, the whole system (Schams-Suretta-Avers) was isoclinally folded, producing a huge north-closing recumbent fold whose axial trace disappears into lower Eocene Flysch in the north and into basement rocks in the south, parallel to the main penetrative foliation in these areas. Circumstantial evidence suggests that the Niemet phase overprinted all units in the central zone (MILNES 1978) and that major features such as the Misox suture (see below), the Oberhalbstein flysch "syncline" and the intense imbrication and thrusting in the Austroalpine/Pennine boundary zone (TRÜMPY 1975) all originated at this time. It seems likely that the development of the basal Pennine thrust zone and the final ductile penetrative deformation of the Adula nappe also belong to this phase, in which case complicated major post-Niemet deformations are signalled in the north (KUPFERSCHMID 1977).

The orogeny in the central structural zone took place in two main episodes, the first at the end of the lower Cretaceous (Avers + Ferrera), the second in the Eocene and lower Oligocene (Schams + Niemet, see MILNES & SCHMUTZ 1978).

c) Southern structural zone

The dominant structure in the southern structural zone is the *Cressim* antiform which marks the northern limit of the southern steep belt (often referred to as the "root zone", see MILNES 1974). This fold post-dates the main foliation in the Adula basement nappe and the parallel strongly laminated zone of Mesozoic rocks and basement slices known as the Misox suture. This *Misox* phase deformation seems to be superimposed on even earlier major folds (FUMASOLI 1974, Pizzo Paglia antiform) and thrusts indicated by already present Mesozoic intercalations, indicating an earliest Alpine deformation, here called the *Paglia* phase. After this sequence of three ductile phases, the steep belt was affected by the ductile and brittle faulting which led to the formation of the Tonale line and which is here called the *Tonale* phase.

Some constraint on the ages of the structures in the southern structural zone is given by the radiometric data from the Novate and Bergell intrusions (GULSON 1973, KOEPPEL & GRÜNENFELDER 1975). The Cressim fold clearly pre-dates the Novate granite (intrusion age ca. 25 my) and either pre-dates or is partly coeval with the Bergell intrusion (age ca. 30 my), whilst the *Misox* deformation is definitely earlier than both.

d) Structural correlation between zones

A tentative correlation between the major structural events in the three zones is given in the Table (see also insets, Plate). It is important to note that a one-to-one correlation of the sequences in the different areas is certainly inapplicable. Correlation over such a wide area must be based on continuity from one zone to the other, combined with dating with respect to stratigraphic, geochronologic, metamorphic or intrusive markers, and on circumstantial evidence. The resulting temporal mosaic has earlier been interpreted in terms of continental collision (MILNES 1978). Our aim here is to put the different parts into a coherent picture (Plate) and then to take a closer look at some details of the collision process. It seemed to us that in spite of the main driving force being horizontal compression, some features indicate that gravity played a significant role at different places and at certain times. Is it possible to define this role more precisely once the large-scale structural development has been established? The following two examples are intended to illustrate the possibilities and limitations of making dynamic interpretations from structural and kinematic data.

3. Role of gravity in the northern structural zone

In discussing the role of gravity in the movement of thrust sheets, we start from the observations of the effects of deformation made in the field. In the literature there exists a whole catalogue of deformational features which have been linked to this tectonic process by kinematic or dynamic arguments, or just by intuition. In the following we first discuss briefly the models for thrust sheet movements currently used and list the deformational features thought of to be characteristic for each model; in the next section, critical structural arguments which can be assessed in the northern structural zone and the St. Gallen–Como cross section are presented and discussed.

a) Structural criteria for gravity effects

In the "longitudinal compressive surface force theory", referred to here as the "compression model", horizontal stresses are transmitted (e.g. from a collision zone) and act as driving force of deformation. Gravity as body force is the motor for the movement of thrust sheets in the "gravity gliding model", where thrust sheets travel down-slope losing gravitational energy, as well as in the "gravity spreading model", where a topographic surface slope provides the driving force and where the basal thrust may slope backward. In the latter two models, the rocks need not transmit stresses, except for the very front of the thrust sheet (the toe region).

The following criteria have been used in the literature for recognizing "gravity gliding" (e.g. DE SITTER 1954, MUDGE 1970, PRICE 1971, PIERCE 1973, LEMOINE 1973, MILICI 1975):

1. Development of far-travelled thrust sheets of wide extent relative to thickness.
2. Presence of structures indicating extensional flow, pull-apart fracturing or a "tectonic gap" at or behind the trailing edge of the thrust sheet.
3. Presence of structures indicating "pile up" and high deformation at the leading edge of the thrust sheet.
4. Succession of thrust development from foreland to hinterland ("front-to-back").
5. Tendency to chaotic relations, for instance, deviations from the rule "the higher the unit the more internal its origin".

6. Existence of a rigid fundament with a forward slope.
7. Existence of a lubricating layer at the base of the thrust sheet.

For the "gravity spreading model" the development of a piggyback stack of imbricate thrust sheets, i.e. a succession of thrust development from the hinterland to the foreland ("back-to-front"), has been used as a criterion (ELLIOTT 1976).

Criteria for recognizing the "compression model" are (MILICI 1975, CHAPPLE 1978):

1. succession of thrusting back-to-front;
2. high deformation within and in the interior part of the fold-and-thrust belt,

but could clearly also include criteria 5, 6 and 7 of the "gravity gliding model". In the "compression model" CHAPPLE (1978) concluded that a topographic high near the source of the "push" is not necessary for, but rather may be a consequence of, deformation, thus creating a situation similar to the one needed for the "gravity spreading model".

b) Critical structural relationships

The nappe-internal deformations in both the Helvetic nappes and the underlying Infrahelvetic complex are essentially due to the Calanda and, to a lesser extent the Cavistrau phase. In the Helvetic nappes this includes a decollement structure following lowermost Cretaceous marl which now separates the Upper from the Lower Glarus nappe complex (Säntis thrust in Figure 1; see also PFIFFNER 1980); in this cross section the decollement structure is restricted to the Helvetic nappes, i.e. the major structure later to separate these nappes from the Infrahelvetic complex, the Glarus overthrust, must have existed already in some form. During the following Ruchi phase, passive transport of these structures occurred along the Glarus overthrust. When discussing the role of gravity it is therefore necessary to strictly distinguish between Cavistrau and Calanda phase on the one hand and Ruchi phase on the other.

Considering the Helvetic nappes there are some arguments which seem to speak for the "gravity gliding" process:

1. The nappes are relatively long and thin, far travelled sheets. The Upper Glarus nappe complex (essentially the Säntis nappe, cf. PFIFFNER 1980), for example is 35 km long, 1.5 km thick and its toe moved roughly 50 km from the break off point. Both the shape and most of the displacement, which in part is due to internal deformation associated with decollement processes, are effects of the Calanda phase. The thrust surface of the Glarus overthrust, along which further displacement of the nappe pile occurred during the Ruchi phase, defines a broad antiform above the Aar massif and a broad synform to the north of it. The arch over the Aar massiv is an old, pre-Ruchi phase feature (SCHMID 1975; MILNES & PFIFFNER 1977; PFIFFNER 1977). Thus nappe transport during the Ruchi phase took place along a curving basal thrust most of which sloped backward, which excludes the process of "gravity gliding". The same argument holds also for the Calanda phase thrusts within the Infrahelvetic complex and the Helvetic nappes.

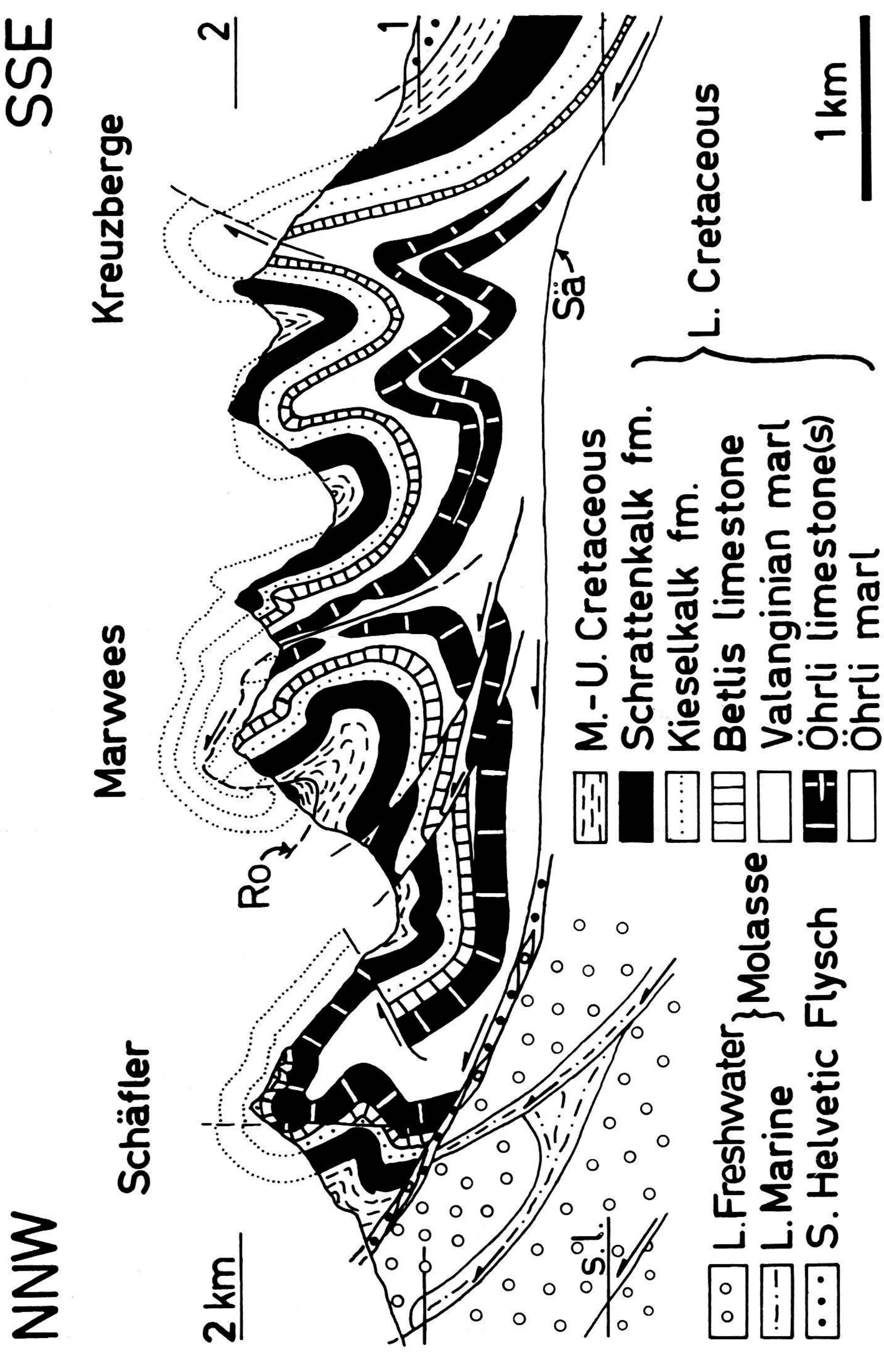


Fig. 1. Cross section through the Säntis nappe showing back thrusts (south of Schäfler and Kreuzberge) and back fold (antiform with steeply north-dipping axial surface south of Marwees). *Ro* = folded thrust of Rotsteinpass; *Sä* = Säntis thrust, which truncates thrust in underlying Subalpine Molasse.

2. As is evident from the cross section (Plate) the Helvetic nappes thin out towards their rear end and are now more or less separated from their original basement (Tavetsch massif). Closer inspection, however, reveals that rather than pull-apart structures, features suggesting shortening in the transport direction can be traced all the way back to the nappes' rear end. This Calanda phase shortening (cleavage) is oriented at high angle to the thrust surfaces, turning into parallelism with the latter only at their very vicinity. Thus the separation of the cover from the basement is interpreted more as a detachment and a large scale simple shear rather than as a pull-apart structure indicating "gravity gliding".
3. There is a possibility that the succession of Calanda phase folding and thrusting of the Upper Glarus nappe complex in the Säntis area was from the foreland (N) to the hinterland (S). This is indicated by the existence of longitudinal faults ("verstärkende Brüche" of ALB. HEIM 1921) and folds with a shear sense opposite to the one of the main movement direction (back thrusts and back folds; see Fig. 1). Such features are known to occur in situations where a rock mass is forced to move up a pre-existing ramp (see results of SERRA 1977, 1978; MORSE 1978, e.g. Fig. 26; WILTSCHKO 1979; JACOBEEN & KANES 1974). In the example of the Säntis area, the "ramp" would be represented by a more frontal fold.
   On the other hand one clearly recognizes a succession of folding and thrusting from the hinterland (S) to the foreland (N). An example of this is illustrated in Figure 1: above and north of Marwees the Rotstein thrust is folded by (and thus older than) the Marwees folds; if the synform is unfolded the sequence in the hanging wall is seen to be inverted and can only be derived from a fold located south (i.e. on the hinterland side) of Marwees. Structures pre-dating clear Calanda phase folds and resulting in overturned series are attributed to the precursor of the Calanda, the Cavistrau phase, and can also be found in the Infrahelvetic complex (see PFIFFNER 1977, Profil V; PFIFFNER 1978, Fig. 6*a*).
4. The toe of the Upper Glarus nappe complex is a zone of strong Calanda phase shortening (pile-up structure). But shortening does also exist at the rear end of this unit and the nature of deformation seems to indicate a more ductile behaviour of the rocks in the more interior parts (more folding with increasing thinning and thickening of individual layers, less thrusting). In the Lower Glarus nappe complex as well as in the Infrahelvetic complex Calanda phase deformation (namely shortening) increases towards the interior parts, and is accompanied by an increase in ductile behaviour, too.

The structural features displayed in the Helvetic nappes are superficially those expected in a "gravity gliding model". Closer inspection excludes this process for both the Calanda and Ruchi phases.

However, the molasse deposits in the north of the cross section indicate a northward dipping surface slope during the Miocene which could have driven "gravity spreading". Are there structural arguments which speak for this process?

1. The northern part of the Lower Glarus nappe complex in this cross section represents a stack of imbricates, but the structural relationships found so far do not allow to deduce whether or not these imbricates develop in a piggyback

fashion (i.e. from south to north; see e.g. ELLIOTT 1976); all one can say is that they are Calanda phase structures.

2. The progression of Cavistrau-Calanda phase deformation is at least in part back-to-front, but the structures developed are of folding character and do not resemble a "piggyback stack of imbricates" with its systematic order "the higher the unit the more interior its origin".
3. The Subalpine Molasse thrust sheets represent a stack of imbricates with the basal detachment following marls of the Lower Marine Molasse (cf. Fig. 1 and Plate). The basal thrust of the Upper Glarus nappe complex (Säntis thrust in Fig. 1) in the roof of the southernmost imbricate truncates the latter, maybe indicating that sedimentation stopped due to overriding by its own scource area, namely Austroalpine and Penninic nappes riding piggyback on the Helvetic nappes. The youngest sediments (cf. HABICHT 1945) within the southern thrust sheets are of middle Oligocene (Stampian), the ones in the northern of upper Oligocene (Aquitanian) and the ones in the folded Plateau Molasse still farther north of Miocene age. This succession is compatible with a development of this stack of imbricates in a piggyback fashion occurring later than the middle Oligocene and throughout the Miocene. Thus it would at least in part be contemporaneous with movements along the Glarus overthrust during the Ruchi phase (see Table). Since the latter was mainly sloping backward, it must have produced topographic relief and thus triggered "gravity spreading"; this tectonic uplift is in fact indicated by the Miocene Plateau Molasse containing pebbles from the Helvetic nappes (TANNER 1944).

From the structural data available, it is clear that the role of gravity is extremely difficult to define precisely for the different phases of deformation. We feel that they exclude the possibility of "gravity gliding" being an important process, except during the formation of the exotic strip sheets of the Pizol phase. These are, however, so strongly deformed and dismembered by later events that it is doubtful whether more than pure speculation on their mode of emplacement will ever be possible. For the succeeding Cavistrau, Calanda and Ruchi phases, the "compression model" seems more appropriate, aided to some extent by "gravity spreading" when tectonic uplift in the hinterland resulted in the necessary northward topographic slope. The data are insufficient, however, to define the importance of "gravity spreading" in the different phases.

4. Gravity-driven vertical movements, southern structural zone

Several features of the southern structural zone suggest that gravity in the form of buoyancy and/or diapirism played a part in the later stages of its development. On general grounds, the strong uplift of the Central Alps relative to the Southern Alps - which probably caused the development of the Cressim antiform, the formation of the southern steep belt and the faulting of the Tonale phase - is probably the isostatic response to the thickening of the continental crust during the preceding phases (MILNES 1978). This implies that the thickened overridden wedge had an unusually abrupt southern termination in order that the compensatory movements be so strictly localized. Again on general grounds, the unusually localized and intense uplift in the Bergell area at this time (WAGNER et al. 1979) suggests some diapirism due to thermal gradients and/or density inversions (cf. DEN TEX 1975). At the moment, however, the available structural data is insufficient or too indiscriminate to allow a reasoned assessment of these speculations. Only one structure on our section has been specifically interpreted as diapiric on structural evidence - the Soé gneiss dome in Val Bodengo (BLATTNER 1965, HÄNNY 1972) - and this provides an example of the type of arguments to be applied.

a) Structural criteria for basement diapirism

Structural relations taken to be indicative or characteristic of basement or granite diapirism mainly in the solid state can be summarized as follows (cf. WEGMANN 1930, ESKOLA 1948, RAMBERG 1967, TALBOT 1971, FLETCHER 1972, DEN TEX 1975, STEPHANSSON & JOHNSON 1976):

Regional features

1. Domal, bulbous or mushroom shape of granite or basement body, with continuous rim syncline and no large-scale discordant-intrusive relations.
2. Regular spacing of several such bodies and/or gravity anomalies thought to be associated with them.
3. Metamorphic isograds concordant with domal structure.

Structure of core

4. Preponderance of metamorphic/anatectic structures and microstructures, as opposed to purely magmatic ones.
5. Inner core *either* more isotropic/homogeneous than core margins *or* characterized by vertical fold axes, vertical sheath folds (eye folds in cross section), "Schlingen", subsidiary domes, etc. (general absence of related foliations and no constant axial plane orientation).
6. Vertical or radially arranged stretching lineations.

Core-country rock contact

7. Deformation related to dome formation concentrated at core-country rock contact, including development of concordance of pre-existing structures (even when evidence of original unconformity present), development of new foliation with strong flattening parallel to the contact, development of shear zone along contact.
8. Evidence of vertical flattening and stretching around the subvertical margins of dome (foliation, lineation) and/or radial stretching across roof of dome (boudinage, extensional faulting and fracturing, localized intrusion of core material forming net veins or intrusion breccias).
9. Rapid dying out of dome-related deformation outside rim syncline.

In all cases, a search must be made for criteria which rule out the possibility that the structural relations could be due to superimposed folding (STEPHANSSON & JOHNSON 1976).

b) The Soé gneiss dome

The structural relations in the relevant part of the southern structural zone are shown in Figure 2. The Soé granite gneiss lies in the core of the Cressim antiform (see Plate) at the position where the antiform axis culminates. Northwest of Soé the axis plunges progressively more steeply, reaching 30° northwest in Valle Mesolcina, whereas southeastwards its plunge changes to 50° in the opposite direction. It is part of an Hercynian intrusive body (BLATTNER 1965, HÄNNY et al. 1975) and is weakly foliated parallel to its domal contact with the surrounding, more heterogeneous and biotite-rich gneisses and migmatites. These are in turn foliated concordant to the contact and often show strong rodding or a marked stretching lineation, parallel to the Cressim fold axis in the hinge zone but constellated as a regional fan structure on the gently dipping northern limb. Parasitic folds related to the Cressim antiform typically have their axial planes marked by zones of partial melting, indicating very high temperatures during folding (HÄNNY 1972, HEITZMANN 1975). Features indicating that the Soé gneiss may be the extreme top of a larger gneiss dome which showed diapiric tendencies during or immediately following the Cressim folding are as follows:

1. The radial fanning of the main lineation, particularly north of the antiform (HÄNNY 1972).
2. The unusually strong curvature of the axis of the Cressim antiform - a change in plunge of 80° between Valle Mesolcina and Valle della Mera (HEITZMANN 1975).
3. The evidence indicating temperatures approaching the melting point accompanying and immediately succeeding the major fold formation (remobilization along parasitic fold axial planes, intrusion of Bergell and Novate granites, acme of metamorphism from radiometric data, see Table). This would favour high mobility even though there is no doubt that the Soé granite remained subsolidus throughout the process (Hercynian wholerock Rb/Sr ages).

Even so, there are a number of uncertainties involved and some opposing evidence which make a clear interpretation impossible. The main problem is the doubt about the age and significance of the radial stretching lineation fan. The lineation is certainly not a structure which post-dates the Cressim antiform and so cannot be related to a purely post-Cressim diapiric movement. In some areas, the stretching lineation is certainly *pre*-Cressim in age being folded across the hinges of Cressim phase minor folds (HEITZMANN 1975), whereas in other areas it is considered as being related to the Cressim phase deformation itself (HÄNNY 1972). The situation thus seems to be much more complicated than in some other examples of basement diapirism (e.g. Rum Jungle, STEPHANSSON & JOHNSON 1976) and clarification in the field is needed before the radiating lineation fan can be explained in terms of this process rather than in terms of superimposed ductile deformations. Features which would rather oppose the diapir interpretation include the lack of

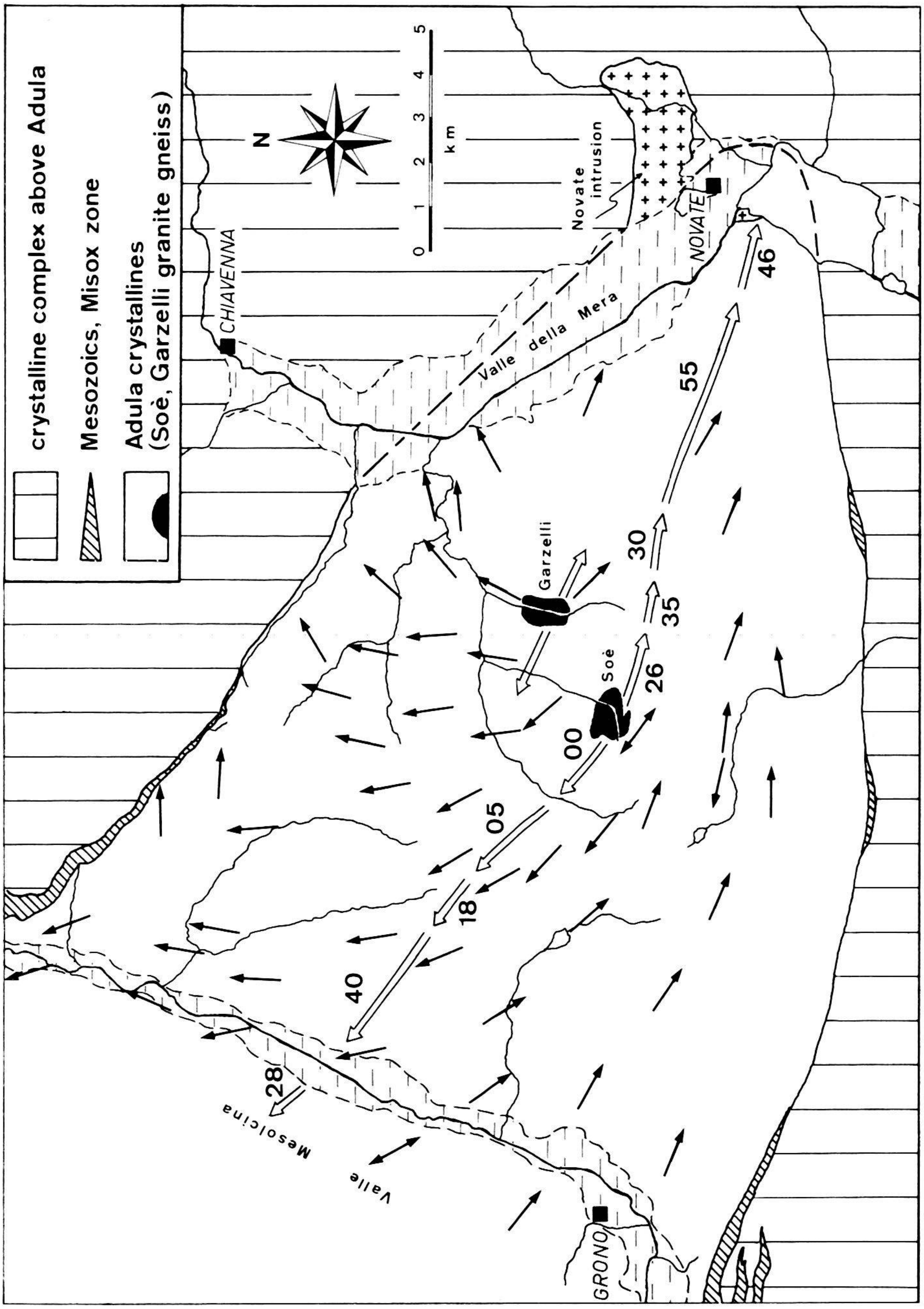


Fig. 2. Sketch map of the Soè gneiss dome showing the axial trace of the Cressim antiform and the lineation fan on its northern limb (after Hänny 1972, Heitzmann 1975).

evidence for the dying-out of the dome-related deformation away from the core, the lack of reported evidence of increased lamination or shearing at the contact between the Soé gneiss and its country rock, and the short time span in which near-melting conditions were available to provide increased mobility (see Table).

In conclusion, we feel that conditions were certainly favourable for buoyancy and diapirism to have played a significant role in the development of the southern structural zone during and immediately following the Cressim phase but the uncertainties and gaps in the structural data do not allow a clear assessment of the importance of these mechanisms.

Acknowledgments

The work reported here was carried out as part of projects 2.436.71, 2.532.71 and 2.859-0.77 of the "Schweizerischer Nationalfonds", whose support is gratefully acknowledged. Our thanks are also due to A. Uhr for drafting the Plate.

REFERENCES

BICKLE, M.J., & HAWKESWORTH, C.J. (1978): *Deformation phases and the tectonic history of the Eastern Alps.* Bull. geol. Soc. Amer. *89,* 293-306.

BLATTNER, P. (1965): *Ein anatektisches Gneissmassiv zwischen Valle Bodengo und Valle di Livo* - Schweiz. mineral. petrogr. Mitt. *45/2,* 973-1071.

CHAPPLE, W.M. (1978): *Mechanics of thin-skinned fold-and-thrust belts.* - Bull. geol. Soc. Amer. *89,* 1189-1198.

DEN TEX, E. (1975): *Thermally mantled gneiss domes: the case for convective heat flow in more or less solid orogenic basement.* In: BORRADAILE, G.J., RITSEMA, A.R., et al. (Ed.): *Progress in Geodynamics* (p. 63-79). - R. Netherl. Acad. Arts and Sci. (Amsterdam).

DE SITTER, L.U. (1954): *Gravitational gliding tectonics: an essay in comparative structural geology.* - Amer. J. Sci. *252,* 321-344.

DIETRICH, V.J. (1976): *Plattentektonik in den Ostalpen. Eine Arbeitshypothese.* - Geotekt. Forsch. *50,* 1-84.

ELLIOTT, D. (1976): *The motion of thrust sheets.* - J. geophys. Res. *81/5,* 949-963.

ESKOLA, P.E. (1948): *On the problem of mantled gneiss domes.* - Quart. J. geol. Soc. London *104,* 461-476.

FLETCHER, R.C. (1972): *Application of a mathematical model to the emplacement of mantled gneiss domes.* - Amer. J. Sci. *272,* 197-216.

FUMASOLI, M. (1974): *Geologie des Gebietes nördlich und südlich der Iorio-Tonale-Linie im Westen von Gravedona (Como, Italia).* - Mitt. geol. Inst. ETH u. Univ. Zürich [N.F.] *194.*

GUBLER, E. (1976): *Beitrag des Landesnivellements zur Bestimmung vertikaler Krustenbewegungen in der Gotthard-Region.* - Schweiz. mineral. petrogr. Mitt. *56,* 675-678.

GULSON, B.L. (1973): *Age relations in the Bergell region of the southeast Swiss Alps, with some geochemical comparisons.* - Eclogae geol. Helv. *66,* 293-314.

HABICHT, K. (1945): *Geologische Untersuchungen im südlichen sanktgallisch-appenzellischen Molassegebiet.* - Beitr. geol. Karte Schweiz [N.F.] *83.*

HÄNNY, R. (1972): *Das Migmatitgebiet von Valle Bodengo.* - Beitr. geol. Karte Schweiz [N.F.] *145.*

HÄNNY, R., GRAUERT, B., & SOPTRAJANOVA, G. (1975): *Paleozoic migmatites affected by high-grade Tertiary metamorphism in the Central Alps (Val Bodengo, Italy)* - Contr. Mineral. Petrol. *51,* 173-196.

HEIM, ALB. (1921): *Geologie der Schweiz* (Bd. II/1). - Tauchnitz, Leipzig.

HEITZMANN, P. (1975): *Zur Metamorphose und Tektonik im südöstlichen Teil der Lepontinischen Alpen (Prov. di Como, Italia).* - Schweiz. mineral. petrogr. Mitt. *55,* 467-522.

JACOBEEN, F., Jr., & KANES, W.H. (1974): *Structure of the Broadtop synclinorium and its implications for Appalachian structural style.* - Bull. amer. Assoc. Petroleum Geol. *58,* 362-375.

KOEPPEL, V., & GRÜNENFELDER, M. (1975): *Concordant U-Pb ages of monazite and xenotime from the Central Alps and the timing of the high-temperature Alpine metamorphism, a preliminary report.* - Schweiz. mineral. petrogr. Mitt. *55*, 129-132.

KUPFERSCHMID, C. (1977): *Geologie auf der Lugnezer Seite der Piz Aul-Gruppe.* - Eclogae geol. Helv. *70/1*, 1-58.

LEMOINE, M. (1973): *About gravity gliding tectonics in the Western Alps.* In: DE JONG, K.A., & SCHOLTEN, R. (Ed.): *Gravity and tectonics* (p. 201-216). - Wiley & Sons, New York.

MILICI, R.C. (1975): *Structural patterns in the southern Appalachians: evidence for a gravity slide mechanism for Alleghenian deformation.* - Bull. geol. Soc. Amer. *86*, 1316-1320.

MILNES, A.G. (1974): *Structure of the Pennine zone (Central Alps): a new working hypothesis.* - Bull. geol. Soc. Amer. *85*, 1727-1732.

— (1978): *Structural zones and continental collision, Central Alps.* - Tectonophysics *47*, 369-392.

MILNES, A.G., & PFIFFNER, O.A. (1977): *Structural development of the Infrahelvetic complex, eastern Switzerland.* - Eclogae geol. Helv. *70*, 83-95.

MILNES, A.G., & SCHMUTZ, H.-U. (1978): *Structure and history of the Suretta nappe (Pennine zone, Central Alps) - a field study.* - Eclogae geol. Helv. *71/1*, 19-33.

MORSE, J.D. (1978): *Deformation in ramp regions of thrust faults: experiments with rock models.* - MSc thesis, A. & M. University, Texas.

MUDGE, M.R. (1970): *Origin of the disturbed belt in Northeastern Montana.* - Bull. geol. Amer. *81*, 377-392.

PFIFFNER, O.A. (1977): *Tektonische Untersuchungen im Infrahelvetikum der Ostschweiz.* - Mitt. geol. Inst. ETH u. Univ. Zürich [N.F.] *217*.

— (1978): *Der Falten- und Kleindeckenbau im Infrahelvetikum der Ostschweiz.* - Eclogae geol. Helv. *71/1*, 61-84.

— (1980): *Fold-and-thrust tectonics in the Helvetic nappes (E Switzerland).* In: MCCLAY, K., & PRICE, N. (Ed.): *Thrust and Nappe Tectonics.* - Blackwells Scientific Publ., Oxford.

PIERCE, W.G. (1973): *Principal features of the Heart Mountain fault and the mechanism problem.* In: DE JONG, A.K., & SCHOLTEN, R. (Ed.): *Gravity and tectonics* (p. 457-471). - Wiley & Sons, New York.

PRICE, R.A. (1971): *Gravitational sliding and the foreland thrust and fold belt of the North American Cordillera: discussion.* - Bull. geol. Soc. Amer. *82*, 1133-1138.

RAMBERG, H. (1967): *Gravity, deformation and the Earth's crust as studied by centrifuged models.* - Academic Press, London, New York.

SCHMID, S.M. (1975): *The Glarus overthrust: field evidence and mechanical model.* - Eclogae geol. Helv. *68/2*, 247-280.

SERRA, S. (1977): *Styles of deformation in the ramp regions of overthrust faults* (p. 487-498). - Wyoming geol. Assoc. Guidebook, 29th annu. field Conf.

— (1978): *Styles of deformation in the ramp regions of overthrust faults.* - Ph.D. thesis, A. & M. University, Texas.

STEPHANSSON, O., & JOHNSON, K. (1976): *Granite diapirism in the Rum Jungle area, Northern Australia.* - Precambrian Res. *3*, 159-185.

TALBOT, C.J. (1971): *Thermal convection below the solidus in a mantled gneiss dome, Fungwi Reserve, Rhodesia.* - Quart. J. geol. Soc. London *127*, 377-410.

TANNER, H. (1944): *Beitrag zur Geologie der Molasse zwischen Ricken und Hörnli.* - Mitt. geol. Inst. ETH u. Univ. Zürich (C) *22*.

TRÜMPY, R. (1969): *Die helvetischen Decken der Ostschweiz. Versuch einer palinspastischen Korrelation und Ansätze zu einer kinematischen Analyse.* - Eclogae geol. Helv. *62/1*, 105-142.

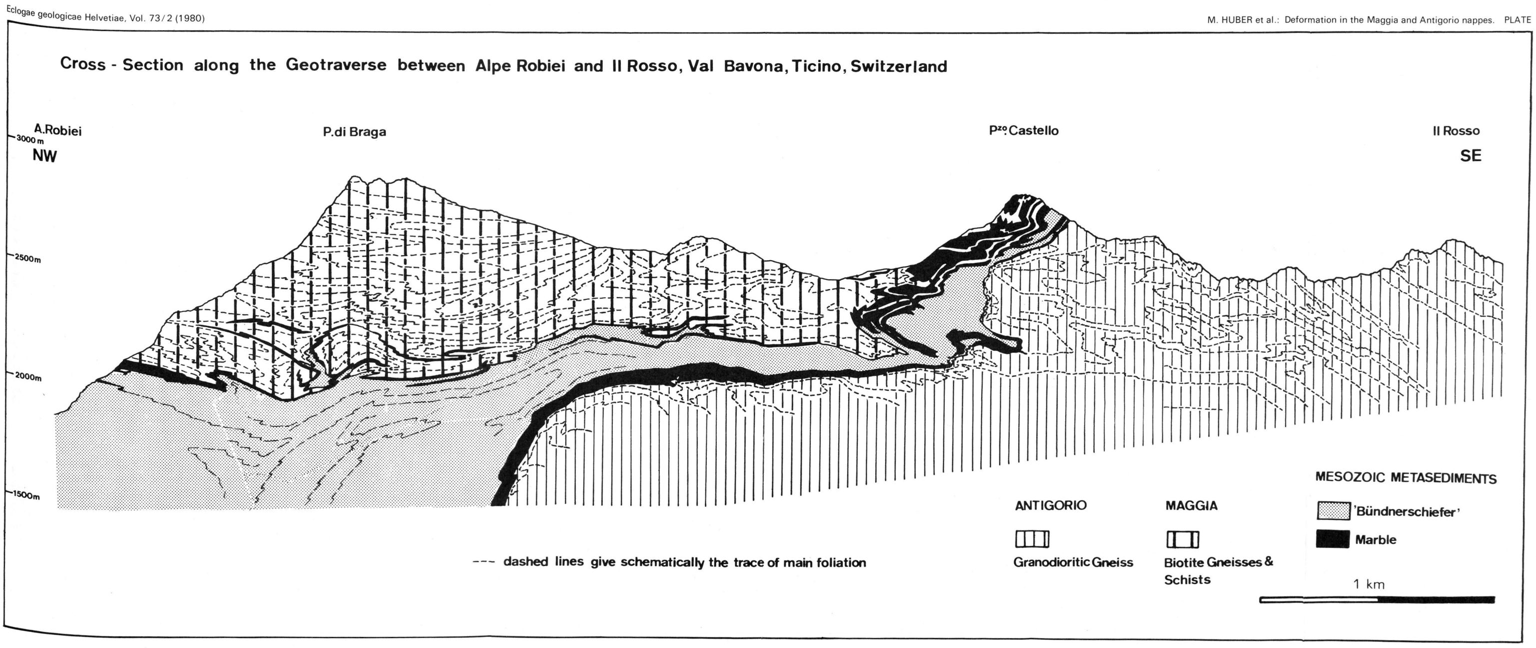
— (1975): *Penninic-Austroalpine boundary in the Swiss Alps: a presumed former continental margin and its problems.* - Amer. J. Sci. *275A*, 209-238.

TRÜMPY, R., FUMASOLI, M., HÄNNY, R., KLEMENZ, W., NEHER, J., & STREIFF, V. (1969): *Aperçu général sur la géologie des Grisons.* - C.R. Soc. géol. France *9*, 330-364, 391-394.

WAGNER, G.A., MILLER, D.S., & JÄGER, E. (1979): *Fission track ages on apatite of Bergell rocks from Central Alps and Bergell boulders in Oligocene sediments.* - Earth and planet. Sci. Lett. *45*, 355-360.

WEGMANN, C.E. (1930): *Über Diapirismus (besonders im Grundgebirge).* - Bull. Comm. géol. Finl. *92*, 58-76.

WILTSCHKO, D.V. (1979): *A mechanical model for thrust sheet deformation at a ramp.* - J. geophys. Res. *84*, 1091-1104.


Cross - Section along the Geotraverse between Alpe Robiei and Il Rosso, Val Bavona, Ticino, Switzerland
A.Robiei
3000 m
NW
P.di Braga
Pzo Castello
Il Rosso
SE
2500m
2000m
1500m
MESOZOIC METASEDIMENTS
ANTIGORIO
MAGGIA
'Bündnerschiefer'
Marble
Granodioritic Gneiss
Biotite Gneisses & Schists
--- dashed lines give schematically the trace of main foliation
1 km