Structure and deformational history of the Infrahelvetic flysch units, Glarus Alps, eastern Switzerland

Autor(en): **Lihou, Joanne C.**

Objekttyp: **Article**

Zeitschrift: **Eclogae Geologicae Helvetiae**

Band (Jahr): **89 (1996)**

Heft 1

PDF erstellt am: **20.09.2024**

Persistenter Link: https://doi.org/10.5169/seals-167909

Nutzungsbedingungen

Die ETH-Bibliothek ist Anbieterin der digitalisierten Zeitschriften. Sie besitzt keine Urheberrechte an den Inhalten der Zeitschriften. Die Rechte liegen in der Regel bei den Herausgebern.
Die auf der Plattform e-periodica veröffentlichten Dokumente stehen für nicht-kommerzielle Zwecke in Lehre und Forschung sowie für die private Nutzung frei zur Verfügung. Einzelne Dateien oder Ausdrucke aus diesem Angebot können zusammen mit diesen Nutzungsbedingungen und den korrekten Herkunftsbezeichnungen weitergegeben werden.
Das Veröffentlichen von Bildern in Print- und Online-Publikationen ist nur mit vorheriger Genehmigung der Rechteinhaber erlaubt. Die systematische Speicherung von Teilen des elektronischen Angebots auf anderen Servern bedarf ebenfalls des schriftlichen Einverständnisses der Rechteinhaber.

Haftungsausschluss

Alle Angaben erfolgen ohne Gewähr für Vollständigkeit oder Richtigkeit. Es wird keine Haftung übernommen für Schäden durch die Verwendung von Informationen aus diesem Online-Angebot oder durch das Fehlen von Informationen. Dies gilt auch für Inhalte Dritter, die über dieses Angebot zugänglich sind.

Ein Dienst der *ETH-Bibliothek*
ETH Zürich, Rämistrasse 101, 8092 Zürich, Schweiz, www.library.ethz.ch

http://www.e-periodica.ch

Eclogae geol. Helv. 89/1: 439–460 (1996)

0012-9402/96/010439-22 $1.50 + 0.20/0
Birkhäuser Verlag, Basel

Structure and deformational history of the Infrahelvetic flysch units, Glarus Alps, eastern Switzerland

JOANNE C. LIHOU

Keywords: Structural geology, Infrahelvetic, Sardona, Blattengrat, flysch, foreland basin

ABSTRACT

Structural mapping of the Infrahelvetic flysch units has revealed a coherency within the Sardona and Blattengrat units. An important late thrust, the Orglen thrust, has been traced into the Sardona unit. Two fold phases have been recognised: 'similar', asymmetrical, N-NNW-vergent folds with wavelengths of 500 to 1500 m, which plunge gently to the E/ENE or W/WSW and are associated with an axial planar cleavage, plus a second, overprinting N-S series of open folds. Kinematic data reveal that penetrative compressive deformation associated with N- to NNW-directed movement on the Glarus Overthrust was followed by E-W striking dextral faulting apparently only affecting the Infrahelvetic units.

Overprinting by later deformational phases has largely obscured penetrative structures associated with the earliest phase of deformation, in which the embryonic North Alpine Foreland Basin was telescoped onto the European (Helvetic) foreland. However, the structural contacts between the Sardona, Blattengrat and North Helvetic Flysch units can be restored to southward-dipping thrusts, suggesting that these early structures formed under horizontal compression. A thrust wedge of Penninic and Austroalpine nappes migrating towards the foreland might have provided the necessary horizontal force to detach these units and translate them northwards. The Infrahelvetic flysch units were subsequently buried to depths of 8-12 km within the nappe pile.

ZUSAMMENFASSUNG

Für die infrahelvetischen Flysche (Sardona-, Blattengrat- und Nordhelvetischer Flysch) wurde aus bereits vorhandenem Kartenmaterial und neuen Feldbefunden eine Strukturkarte zusammengestellt, in der besonders Sardona- und Blattengratflysch durch eine Reihe neuer Daten abgedeckt sind. Mit Hilfe dieser regionalen Gesamtdarstellung wurden drei vertikale Profile konstruiert, in denen die strukturelle Kohärenz zwischen Sardona- und Blattengratflysch ersichtlich wird. Innerhalb des Sardonaflysches wird die Verlängerung einen markanten späten Störung, die Orglen-Überschiebung, sichtbar. Zwei Faltungsphasen werden aus den Strukturen abgelesen: eine erste Phase besteht aus asymmetrischen, N- bis NNE-gerichteten Falten mit einer Wellenlänge von 500–1500 Metern und einer achsenparallelen Schieferung. Die Faltenachsen dieser Phase sind leicht gegen E-ENE oder W-WSW geneigt. Eine zweite Faltungsphase überprägt die erste mit N-S gerichteten, offenen Falten. In der Kinematik wechselte eine penetrative, kompressive Deformation, die mit der N-NNW gerichteten Bewegung entlang der Glarner Hauptüberschiebung im Zusammenhang steht, in eine E-W streichende Bruchtektonik mit dextraler Komponente, deren Spuren jedoch nur im Infrahelvetikum anzutreffen sind.

Von der frühesten Deformationsphase, während der die Sedimente des sich ausbildenden nordalpinen Vorlandtroges auf das europäische (helvetische) Vorland geschoben wurden, sind aufgrund der Überprägung durch spätere Deformationsphasen bisher keine penetrativen Strukturen erkannt worden. Die strukturellen Kontakte zwischen den drei Flyscheinheiten können jedoch als südwarts geneigte Überschiebungen rekonstruiert werden und lassen eine Entstehung der frühen Strukturen unter horizontal gerichteter Kompression vermuten. Der horizontale Schub, der benötigt wurde, um die infrahelvetischen Einheiten aus ihrem Kontext

---

Department of Earth Sciences, University of Oxford, Parks Road, Oxford OX1 3PR, UK
Present address: Koninlijke/Shell Exploratie en Produktie Laboratorium, Volmerlaan 6, PO BOX 60, NL–2280 AB Rijswijk

zu lösen und nach Norden zu verfrachten, dürfte durch eine grössere Schubmasse aus penninischen und ostalpinen Einheiten übertragen worden sein. Mit Fortschreiten des Zusammenschubes wurden die infrahelvetischen Flysche mit einem Gesteinpaket von 8 bis 12 km Mächtigkeit überdeckt.

1. Introduction

The Helvetic nappes of eastern Switzerland (Fig. 1) have been described as a classic area of décollement tectonics, the Helvetic sedimentary cover being separated from its crystalline basement and translated northwards onto the European foreland (Pfiffner 1985, 1993). The Infrahelvetic Complex comprises the tectonic units that structurally underlie the Helvetic nappes and are separated from them by the Glarus Overthrust (Fig. 2). The Helvetic nappes in the study area between Sernftal and the Rhine Valley (Fig. 1) are mainly represented by Permian Verrucano metasediments of the lowermost Glarus nappe (Schmid 1975), but the Verrucano wedges out towards the east so that the Lower Jurassic is exposed directly above the overthrust. Schmid (1975) described the present topography of the Glarus Overthrust as a WSW-ENE-trending culmination, with a southern flank that slopes 15–20° and a northern flank sloping 10-15°. The axis of the culmination coincides with inliers of the Aar massif basement, such as the one exposed at Vättis (Fig. 1) and plunges gently eastwards from Vättis to the Rhine Valley (Trümpy & Trommsdorff 1980).

The general geology of the Infrahelvetic Complex, in ascending structural order is:

(i) autochthonous and parautochthonous, Mesozoic and Tertiary cover of the Aar massif from the Helvetic paleogeographic realm, including the North Helvetic Flysch (NHF) unit;

(ii) the Blattengrat and Sardona units, known as 'exotic strip' or 'slip' sheets because they are thought to have been superimposed on the underlying units after being stripped off cover rocks far to the south (Schmid 1975; Milnes & Pfiffner 1978; Pfiffner 1986); and

(iii) allochthonous Mesozoic cover of the southern Aar massif with Mid to North Helvetic affinities (Trümpy 1969).

The detailed structure of the parautochthonous and autochthonous cover exposed to the south of the Sardona unit is presented in Bürgisser & Felder (1974), Schmid (1975) and Pfiffner (1977, 1978). Siegenthaler (1974) and Sinclair (1989) investigated the structure of the North Helvetic Flysch (NHF) unit in Sernftal. Schmid (1975) commented on the structure of the Infrahelvetic flysch units, including the Sardona and Blattengrat units, based upon limited field work in Sernftal. None of these authors attempted to decipher the internal structure of the Sardona and Blattengrat units. However, this had already been attempted by Bisig (1957), Rüefli (1959) and Wegmann (1961) in the course of their research: their theses include a number of complex cross-sections, but the accompanying maps show no structural information, or indeed measurements of any kind, only lithological variations. Therefore, I have compiled a structural map for the Infrahelvetic flysch units (Pl. 1), using all the available map resources plus personal field mapping. On the basis of this regional information, I have constructed a series of three cross-sections across these units (Pl. 2), incorporating illustrations from Bürgisser and Felder (1974) and Pfiffner (1977), which helped to extrapolate downwards into the parautochthonous Helvetic

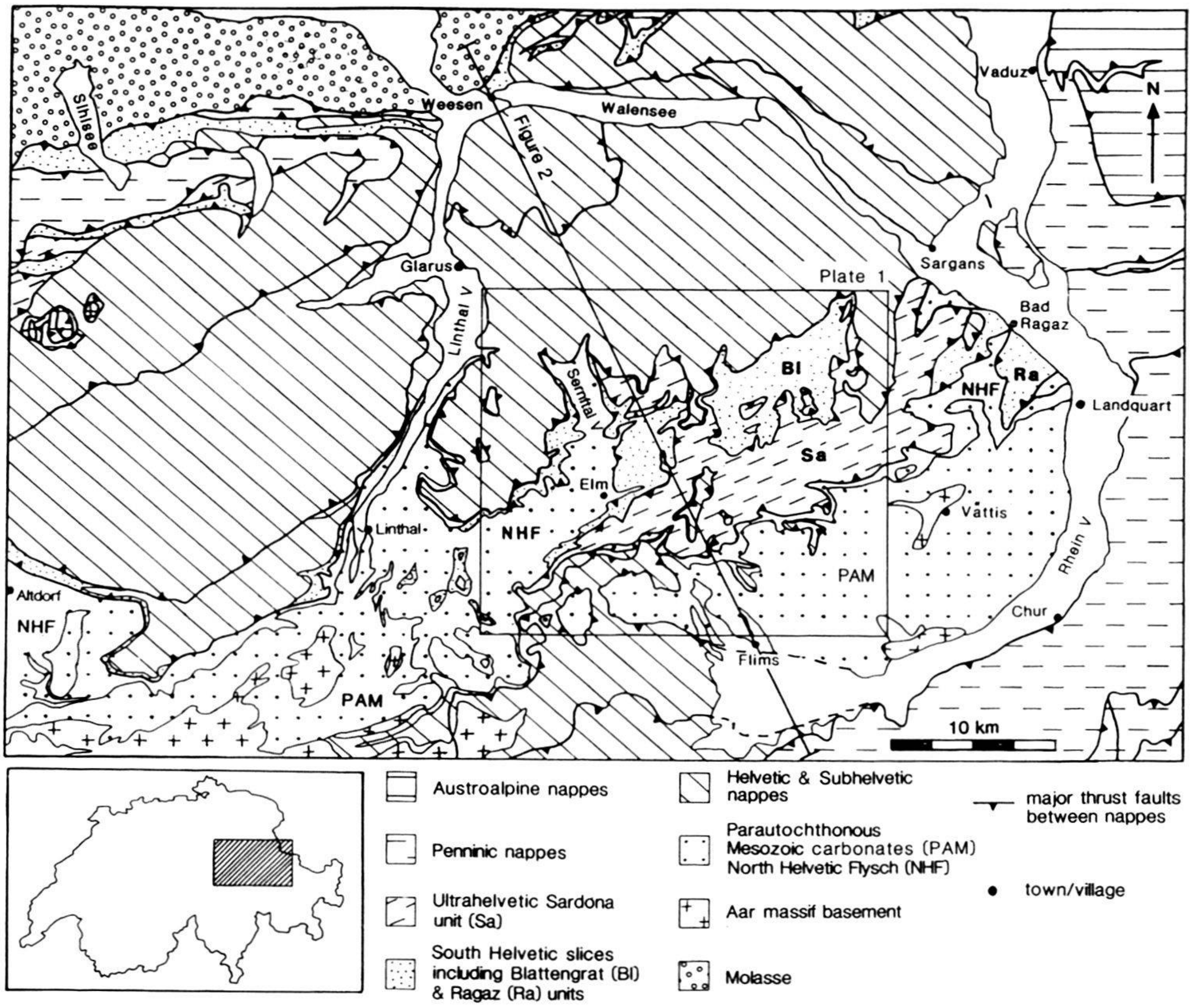

Fig. 1. Tectonic map of the Glarus Alps, adapted from Trümpy (1967) and Spicher (1980), showing the area illustrated in Plate 1 and the line of section for figure 2.

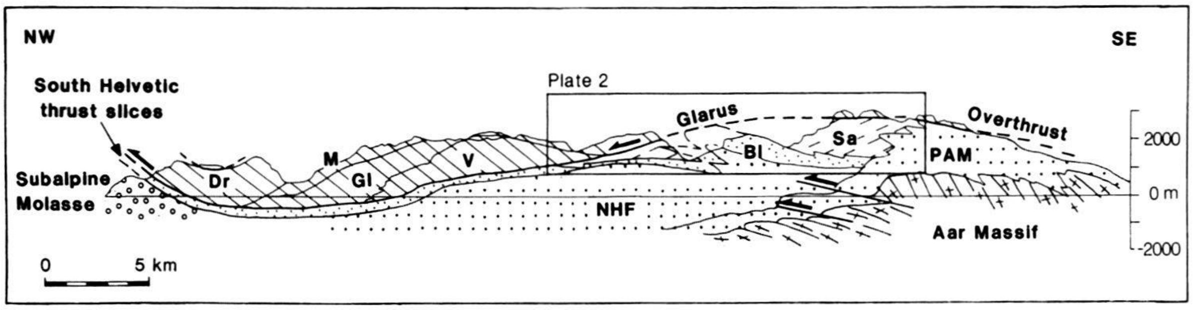

Fig. 2. Simplified structural cross-section through the Glarus Alps, eastern Switzerland, modified from Trümpy (1980) and Pfiffner (1986), also showing the cross-sectional area covered by Plate 2; key as in figure 1.
Bl – Blattengrat unit; Dr – Drusberg nappe; Gl – Glarus nappe; M – Mürtschen nappe; NHF – North Helvetic Flysch; PAM – Parautochthonous Mesozoic; Sa – Sardona unit; V – Verrucano.

units in the south of the area. A review of previous work, plus new personal observations regarding the structure and kinematics of the Infrahelvetic Complex are presented in this paper, together with an account of its early deformational history.

2. Structure of the Infrahelvetic flysch units

2.1 Structure of the Sardona and Blattengrat units

The Sardona unit, which has been assigned to the Ultrahelvetic paleogeographic realm, consists of Cenomanian-Campanian pelagic limestones and marls, plus Maastrichtian to Bartonian flysch (Lihou, in press). There are two important, competent marker horizons in the Sardona unit, the Cenomanian-?Santonian Globotruncana Limestone and the Paleocene-lower Eocene Sardona Quartzite Formation. The Blattengrat unit is composed of Upper Cretaceous marls, unconformably overlain by middle Eocene shallow marine and shelf sediments and upper Eocene flysch deposited on the South Helvetic margin, that have been attributed to an early North Alpine Foreland Basin (NAFB) (Lihou 1995). The Eocene Nummulitic Limestone provides the only marker horizon in the Blattengrat unit. The two units crop out in tectonic windows through the culmination in the Glarus Overthrust (Fig. 1).

The structure of the Infrahelvetic units is discordant with that of the overlying Helvetic nappes (Pl. 2). Wegmann (1961) envisaged the whole Sardona unit east of Elm as a large synform, with its lower limb formed by the Blattengrat and NHF units, and its upper limb partly formed by the parautochthonous Helvetic units, but truncated by the Glarus Overthrust; this geometry also appears in the profiles presented here (Pl. 2). The general configuration had already been deduced by Oberholzer (1933 in Trümpy 1980), whose profile through the Glarus Alps is reproduced in figure 2 and shows a second syncline to the north.

The new cross-sections (Pl. 2) illustrate a structural coherency within the Blattengrat and Sardona units: the faults between the flysch units are harmonically folded together into 'similar' (or Class 3 folds of Ramsay 1967), asymmetrical, N to NNW-vergent folds with wavelengths of 500 to 1500 m. These folds plunge gently to the ENE or WSW in the Elm district and Weisstannental, but are oriented more E-W in Calfeisental (Fig. 3a). In addition, some minor folds plunge to the SSE or SW and these may represent a second phase of folding. This second phase of gentle folding is only locally developed, but can be clearly seen in the field, for example, on the north slope of Calfeisental and at Heubützli Pass where it refolds D1 fold hinges into south-plunging open folds.

Axial planes to the major D1 folds are gently-inclined by 25–40° to the S to SSE, becoming less inclined and then recumbent further north in the Blattengrat unit (Plate 2B & C). Bedding/cleavage intersection lineation data collected from Weisstannental and Calfeisental show a close approximation to the calculated local D1 fold axial plunges, and poles to the measured cleavage planes produce a well-defined mean of 40/168, suggesting that the regional SSE-dipping D1 cleavage is axial planar (Fig. 3b). There is no separate cleavage associated with the D2 folds. Schmid (1975) also found that cleavage and axial planes in the Infrahelvetic flysch units in Sernftal had a uniform dip direction, with a

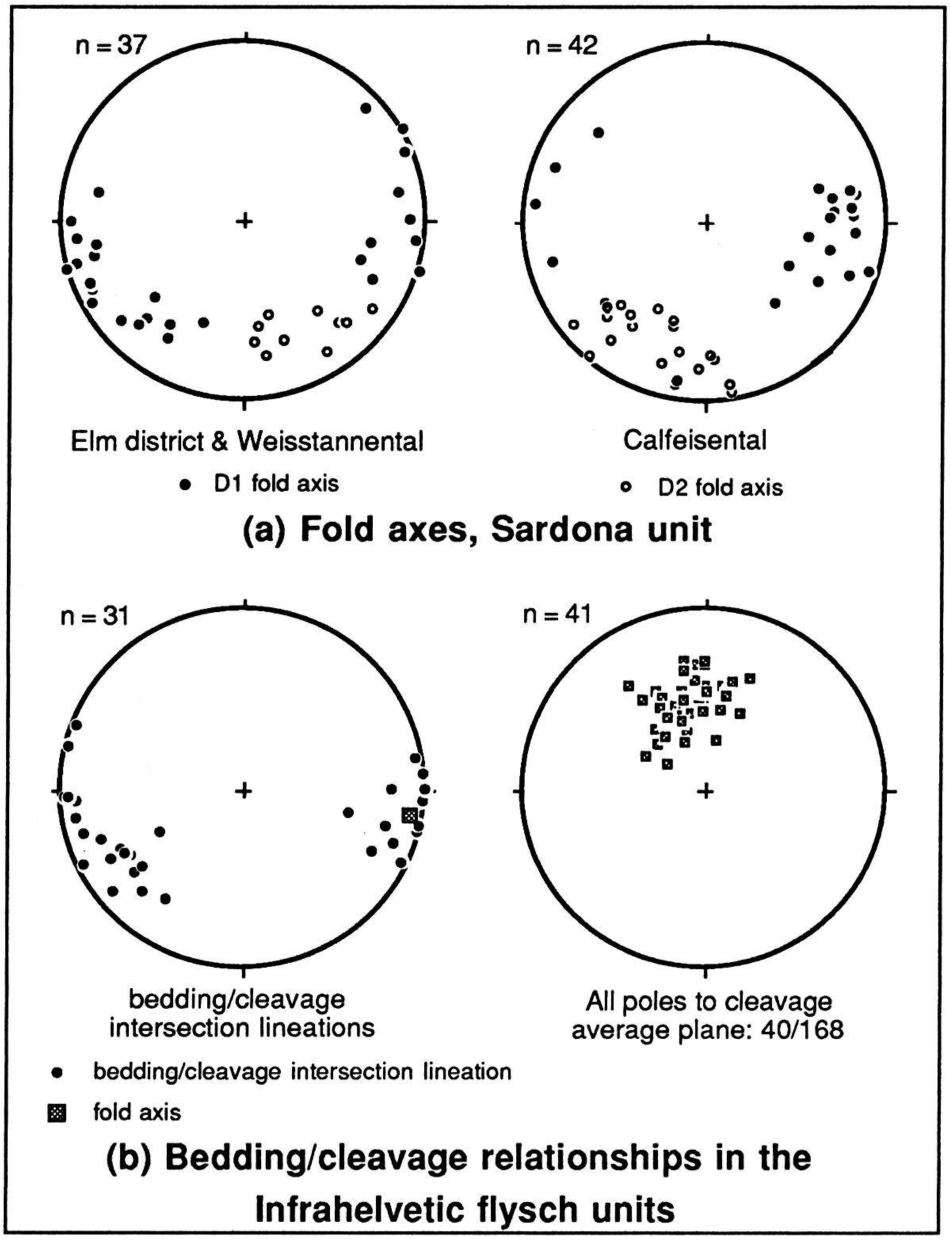

Fig. 3. (a) Plunge of all fold axes measured in the Sardona unit, differentiated into D1 (Calanda) and D2 (Ruchi) fold phases on the basis of field relationships; and (b) bedding/cleavage intersection lineations from minor folds in the Infrahelvetic Sardona and Blattengrat units, showing a close approximation to the calculated average D1 fold axis, plus the tight cluster of poles to measured D1 cleavages.

mean orientation of 40/147. However, he interpreted the same pattern of highly variable fold axis orientations in the NHF unit as indicative of variable bedding plane orientations prior to folding, i.e., resulting from an earlier phase of deformation. Although there is invariably some layer-parallel deformation visible within the competent strata of the Sardona and Blattengrat units, in the form of minor thrusts which locally repeat strata, this does not appear to predate the main D1 folding event. Also, the D1 folds appear to be approximately cylindrical on the outcrop scale, so the spread of fold axis data is probably not attributable to sheath folding and is therefore interpreted here as the result of an overprinting, N-S oriented D2 fold phase.

2.2 Strain estimates

Strain estimates for the Sardona unit can be obtained from line length measurements for the Sardona Quartzite Formation taken from the cross-sections (Pl. 2). The restored cross-sectional width of the Sardona unit is 9–10 km and folding within the unit accounts for approximately 23% shortening in profile B and 33% in profile C. The restored cross-sectional extent of the Blattengrat unit is also ~9 km and shortening within the Nummulitic Formation is ~40% for both profile B and C, i.e., greater than the estimates for the Sardona Quartzite. However, the upper limb of a cylindrical fold in the Nummulitic Limestone exposed at Englawand (742.0/202.2) is dissected by domino normal faults dipping at 50° to the NNE, and 2 km to the west at Prägelwand (738.7/202.7) the limestone is broken up into blocks by low-angle extensional faults. Beta values calculated using the rotating domino model of Le Pichon & Sibuet (1981), where $\beta \sin\theta_1 = \sin\theta_2$, indicate that these normal faults account for ~25–30% extension within the flat-lying fold limbs. This extension suggests that the flat-lying limbs migrated from the shortening into the extensional strain fields as deformation progressed, whilst the steeper limbs remained in the shortening strain field. This effect was probably produced by a shear strain being applied to already buckled layers (Fig. 4), so the phenomenon could have been associated with translation of the Helvetic nappes along the Glarus Overthrust.

In the Blattengrat unit between Ramintal and Chrauchtal to the east of Elm, few folds remain in the Nummulitic Limestone. Instead, upright competent limestone beds sandwiched between incompetent Upper Cretaceous and Tertiary marls are repeated in a series of five thrust slices (Pl. 2A) that may be dismembered isoclinal folds (Wegmann 1961). Wegmann (1961) estimated that the cumulative length of these thrust slices was 15–20 km, which would require 65–75% shortening to produce their present extent of approximately 5 km. This value for the original width of the Blattengrat realm would have to be decreased to account for the layer-parallel extension of the limestone within the thrust slices, but increased to account for the missing overturned limbs, so it is unreasonable to evaluate the amount of shortening in this way.

2.3 Calfeisen digitation of the Orglen thrust sheet

A similar arrangement of dismembered thrust sheets is preserved in three parautochthonous Helvetic slices exposed between the ridge demarcating the south of Calfeisental and Flims: here, recumbent fold hinges are preserved at the distal (northern) and proximal (southern) linkages of the thrust sheets (Bürgisser & Felder 1974; Pfiffner 1977; Trümpy & Trommsdorff 1980; Plate 2B). The thrust sheets are called the Calanda (or Panära), Mirutta and Tschep units, in ascending structural order (Bürgisser & Felder 1974; Pfiffner 1977). At the east end of Calfeisental, Pfiffner (1977, 1978) mapped two further thrust sheets beneath the Calanda unit, namely the Orglen and Kaminspitz units, with the latter overlying the autochthonous Vättner unit. The Orglen thrust may correlate with the thrust that extends the length of the south side of Calfeisental beneath Piz

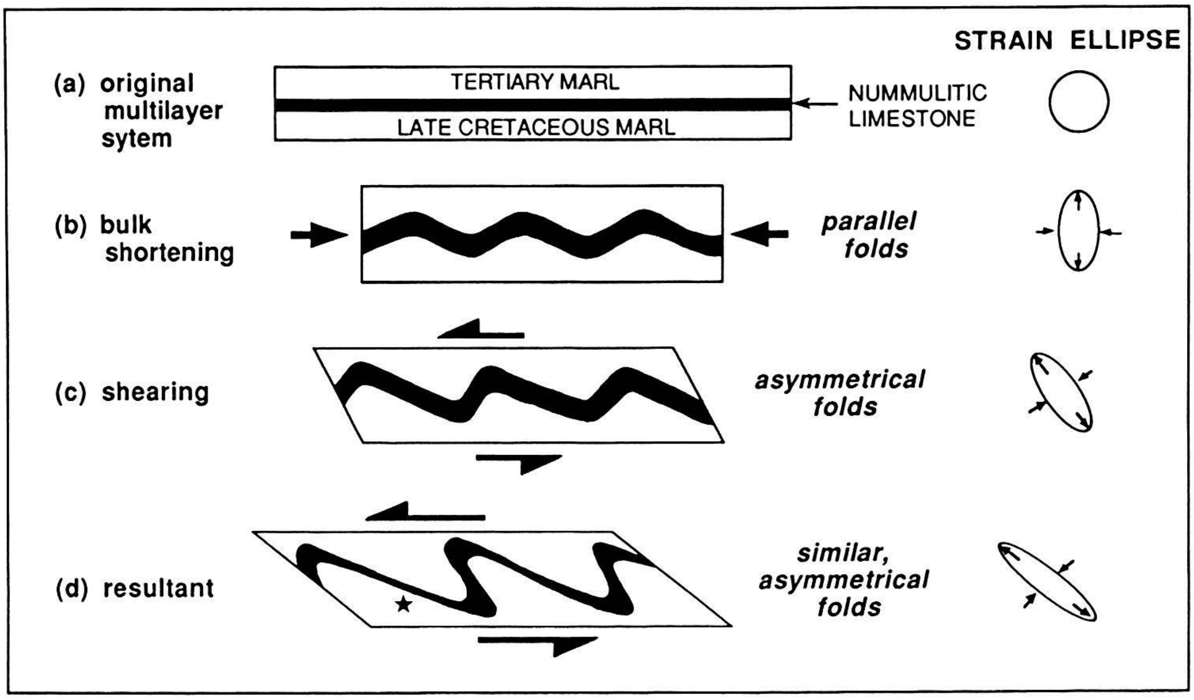

Fig. 4. Schematic diagram showing the anticipated evolution of 'similar' (or Class 3 folds of Ramsay 1967), asymmetrical folds in the Nummulitic Limestone of the Blattengrat unit.
* Shearing of the folded Nummultic Limestone in (d) causes tectonic thinning by extensional faulting in the normal fold limbs.

Sardona and as far as Segnas Pass (Pl. 1, 2B, C). It principally juxtaposes upright, highly strained Globotruncana Limestone and Marl over folded Sardona flysch sediments, and so its movement must post-date at least some of the folding in the Sardona unit. I have named the extension of the Orglen unit within the Sardona unit the Calfeisen digitation. Klippen of limestone also appear along the ridge between Calfeisental and Weisstannental, and beneath Pizol at the eastern end of Weisstannental (Pl. 1): these structures could be part of the same Orglen thrust sheet (Pl. 2B) which extends into Weisstannental (Pl. 2C). Rüefli (1959) was the first to discern the non-stratigraphic arrangement of the limestone in Weisstannental and represented it as a series of small, isolated thrust slices in his cross-sections. An alternative interpretation is that the limestone of the Calfeisen digitation is folded together with the underlying Sardona flysch sediments (Pl. 2C), implying that some folding post-dated its emplacement.

The minimum amount of displacement that the Orglen thrust accommodates is 4 km (Pl. 2B) but it may be more than twice that if it is continuous into Weisstannental (Pl. 2C). Compared with the 2–3 km of shortening calculated from the cross-sections for the folded Sardona Quartzite underlying the Calfeisen digitation, the displacement on this thrust is as important or more significant to bulk shortening in the Sardona unit as is folding. Duplication of the Sardona unit by the Orglen thrust means that the estimated 9–10 km minimum restored cross-sectional width of the basin must be increased by 4–8 km to 13–18 km.

The furthest east that Globotruncana Limestone and Marl in the Calfeisen digitation can be found is east of Pizol, at Laufböden (751/205). The contact with the underlying Sardona flysch sediments can easily be followed, appears to be flat-lying and is clearly discordant with the folded flysch.

2.4 Contacts between the flysch units

Whilst it is possible to quantify the minimum amount of translation on the late Orglen thrust, this is not feasible for the folded fault at the base of the Sardona unit, since the unit is completely allochthonous and its original paleogeographic relationships cannot be proven. However, the stratigraphic links between the Blattengrat and NHF units argue for them being closely related not just temporally, but also spatially (Lihou 1995). Trümpy's (1969) palinspastic reconstruction for the Glarus Alps showed the Blattengrat and NHF 'diverticules' adjacent to one another and separated by only 10 km, which provides an estimate for the minimum amount of translation on the fault between the Blattengrat and NHF units.

The fault contact between the Sardona and Blattengrat units probably climbs through progressively higher stratigraphic levels in the Sardona unit towards the north (Pl. 2), but this cannot conclusively be established from map relationships. In addition, this fault apparently follows progressively higher stratigraphic levels in the Blattengrat unit, this being clearest on Alp Foo (Pl. 2B). The proposed hangingwall relationships would imply that the fault originated as a low-angle thrust in the Sardona unit, similar to the less deformed, late Orglen thrust. The truncation of Blattengrat strata in the footwall means that the Sardona unit cannot have been emplaced onto the Blattengrat unit as an olisthostrome or 'diverticule' because the basal detachment would then follow one stratigraphic level or cut downwards through the Blattengrat unit. The interpretation that the Sardona unit was thrust onto the Blattengrat unit is not compatible with the gravity sliding model for the deformation of the Infrahelvetic Complex that was proposed by Trümpy (1969) (chapter 4).

Siegenthaler's (1974) illustrations of the internal structure of the NHF unit in northern Sernftal (Vorstegstock thrust slice), clearly show that the fault contact between the Blattengrat and NHF units also climbs through progressively higher stratigraphic levels in the NHF unit towards the north. In contrast to the basal Sardona thrust though, this fault appears to follow the oldest strata in the Blattengrat unit, the Upper Cretaceous marls, and the youngest strata in the NHF unit, the Engi 'Dachschiefer' slates, for at least 8 km in northern Sernftal (Wegmann 1961). This is probably because these mechanically weak horizons favoured detachment as opposed to imbricate thrusting. Eventually though, this detachment must cut up section through the Blattengrat unit, probably near Matt in Sernftal, and along strike to the east beneath the present topographic surface in Weisstannental (Pl. 2B, C). It is therefore envisaged that the fault contact between the Blattengrat and NHF units also represents a folded thrust, which originally had a ramp-flat structure that was governed by the mechanical properties of the different stratigraphic layers in the footwall and hangingwall. Trümpy (1969) believed that the Amden marls played a vital role in determining the location of the early detachments in the Helvetic paleogeographic realm because where they were thickest, they were included in the allochthonous thrust sheets, but where they were absent, or removed by pre-Wang Formation erosion, Blattengrat-equivalent strata remained attached to their Helvetic substrata.

At the south end of Sernftal, the internal deformation of the NHF unit results in stratigraphic duplication and can be best described as a series of S-dipping imbricate thrust sheets, whose basal detachments commonly occur in the Globigerina Marls (Sinclair 1989). These thrusts within the NHF unit displace an earlier structure, the Vorstegstock thrust, which divides the Tertiary NHF sediments into autochthonous strata in the footwall and parautochthonous strata in the hangingwall (Siegenthaler 1974; Pfiffner 1986). The Vorstegstock thrust is also cross-cut by the basal Blattengrat thrust (Fig. 3, Pfiffner 1986), implying that thrusting of the Blattengrat unit onto the NHF unit post-dates the onset of thrust deformation within the NHF unit (out-of-sequence thrusting). However, major thrust duplication within the NHF unit mainly occurred after the Sardona and Blattengrat units were emplaced onto it, probably at the same time as the Calfeisen digitation developed together with the parautochthonous thrust slices exposed to the south of the area. Thrust displacements within the Sardona and NHF units were in the order of a few kilometres (Sinclair 1989; section 2.3).

2.5 Other allochthonous Infrahelvetic units

The other allochthonous Helvetic units in the Infrahelvetic Complex were originally termed 'Subhelvetic'. Trümpy (1969 & refs. therein) introduced this term as a purely geometric description for the isolated thrust slices or nappes located immediately beneath the Glarus Overthrust, but the term gradually became synonymous for Mesozoic carbonates of Mid to North Helvetic affinities. The confusion between the term 'Subhelvetic' as a geometric and a paleogeographic term is best solved by simply referring to these thrust slices as 'allochthonous Infrahelvetic units' (Pfiffner 1977, 1978). The allochthonous Infrahelvetic thrust slices are thickest in the Clariden range, to the west of the study area, where they are subdivided into the Griesstock and Cavistrau nappes. East of Sernftal, they are preserved locally at Foostock (Pl. 2B), Tschingelhoren (Pl. 2A), and as klippen between Pizol and Bad Ragaz in the Rhine Valley.

The lower boundary of the allochthonous, Lower Cretaceous Schrattenkalk slice at Foostock is discordant with minor folds in the underlying Sardona flysch sediments, which may be a consequence of the different mechanical properties of the limestone and flysch, rather than indicating that its emplacement onto the Sardona unit post-dates the development of these folds. The interface between the allochthonous limestone and the Sardona Flysch appears to be lobate, forming flaser-like, NNE-vergent folds with rounded troughs and pinched crests where the underlying Sardona Flysch has been squeezed upwards.

A similar allochthonous lens at Tschingelhoren, mainly consisting of Upper Jurassic limestone (Schmid 1975), is clearly folded into a recumbent anticline and syncline pair (Fig. 5). The core of the syncline is composed of black, Upper Cretaceous Amden slate, which can be traced southwestwards into the Martinsmad cirque where it thickens into 300 m of Upper Cretaceous Amden and Tertiary Globigerina Marls, termed the 'Martinsmad Flysch', that contains banks of folded, detached, Tertiary, Helvetic greensand (Wegmann 1961). Bürgisser & Felder (1974) claimed that the limestone beneath Tschingelhoren was completely detached from, and apparently geometrically unrelated to, the subjacent parautochthonous Helvetic thrust slices. However, Pfiffner (1978) correlated it with the uppermost parautochthonous thrust slice, the Tschep nappe, which extends as

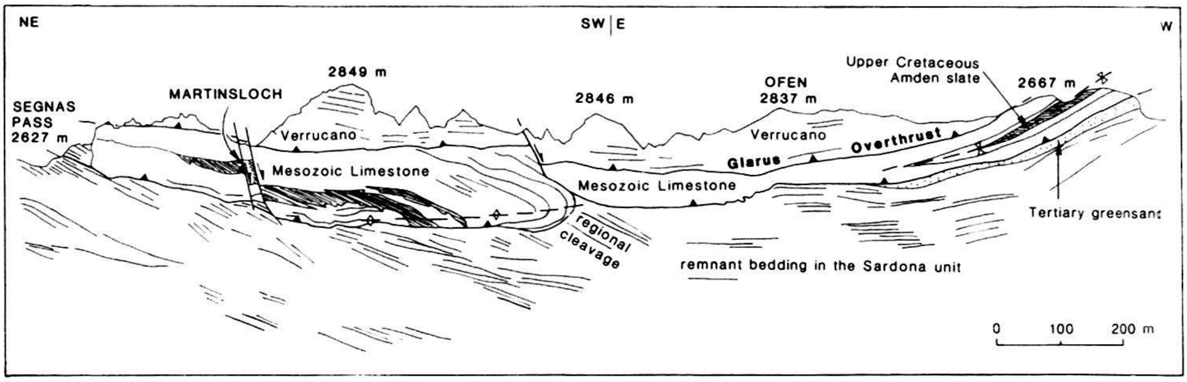

Fig. 5. Structure of the allochthonous Infrahelvetic limestone beneath Tschingelhoren, which Pfiffner (1978) correlated with the parautochthonous Tschep-nappe; field of view 2 km.

far southwest as Panix Pass (Pl. 1). He also claimed that the Martinsmad Flysch was the westernmost part of the parautochthonous Mirutta thrust slice (Pl. 1).

Trümpy (1969, 1980) proposed that the allochthonous (Subhelvetic) thrust slices were remnants of the inverted limb of a large recumbent fold cored by the Verrucano that is now preserved in the Glarus nappe. Related to this problem of the origins of the allochthonous thrust slices is the debate on the parentage of the Lochseitenkalk, a calc-mylonite that is associated with the main Glarus Overthrust and probably facilitated movement along it by acting as a ductile medium of reduced resistance (Hsü 1969; Trümpy 1969; Schmid 1975). The mylonite is 1-2 m thick and usually forms the interface between the Infrahelvetic units and the overriding Verrucano (Schmid 1975), extending over a N-S cross-sectional distance of at least 20 km (Pfiffner 1993). At Foostock, for example, the uppermost 1–2 m of the allochthonous limestone are mylonitised, but in other areas where the allochthonous limestone is extremely thin or absent, the mylonite forms an intermediate layer between the Infrahelvetic flysch and the Verrucano. Like the allochthonous limestone at Foostock, the lower boundary of the mylonite often shows a lobate interface in contact with Infrahelvetic flysch units (Schmid 1975), the classic example being found at its type locality near Schwanden (Trümpy & Trommsdorff 1980). Schmid (1975) proposed that the Lochseiten calc-mylonite was derived not only from the allochthonous limestone, but also from the Mesozoic limestones from the parautochthonous zone to the south of the study area. Pfiffner (1993) recently proposed that the Lochseiten calc-mylonite was the product of tectonic erosion in the footwall of the Glarus Overthrust, where it ramped up through mechanically strong parautochthonous Mesozoic limestone. He furthermore suggested that tectonic erosion at footwall ramps was principally responsible for the relatively smooth cross-sectional shape of thrusts within the Helvetic nappes.

2.6 Mud sheet of the North Helvetic Flysch unit

A deformed slate containing detached blocks of Taveyannaz Sandstone crops out beneath allochthonous Infrahelvetic Mesozoic strata between Chalchorn and Rotstock in the area of Panix Pass (Wegmann 1961; Pl. 1). Wegmann (1961) tentatively identified this

20–100 m thick strip as Sardona Flysch, much reduced in thickness compared with its development further northeast. Without diagnostic blocks of Globotruncana Limestone or Sardona Quartzite, there is no reason to conclude that this mud sheet belongs to the Sardona unit; it could equally be derived from the flysch of the Blattengrat unit, or be closely related to the NHF unit which it overlies, or even be unrelated to all three flysch units.

The mud sheet received considerable attention from Sinclair (1989, 1992), who believed that its initial transport and emplacement onto the underlying Taveyannaz Sandstone of the NHF unit occurred at, or near to, the sediment/water interface, terminating sedimentation within the NHF basin. He documented a number of deformational features associated with the contact between the mud sheet and the Taveyannaz Sandstone that he believed could be ascribed to soft sediment deformation, including Taveyannaz Sandstone dyke injections penetrating upwards into the mud sheet; subsequent dislocation and imbrication of the Taveyannaz Sandstone, with erosion of the upthrust sandstone to form an intraformational breccia; and deformation at the bases of dislocated Taveyannaz Sandstone blocks within the mud sheet, indicating that they slid downslope in advance of the bulk of the mud sheet.

There has been no direct dating of the mud sheet owing to its extreme deformation and low-grade metamorphism. Anyhow, it is likely that a mixed fauna would be preserved in the mud sheet if it incorporated semi-lithified NHF sediments. However, indirect evidence as to its age is that it post-dates deposition of the Taveyannaz Sandstone, and pre-dates sedimentation of the Engi slates (Sinclair 1989). Hornblende from basaltic and tonalitic material in the Taveyannaz Sandstone has recently produced radiometric ages of 32 Ma (i.e., early Oligocene) (Fischer & Villa 1990), whilst the fish-bearing Engi slates are also believed to be of early Oligocene age (Wettstein 1887; Trümpy 1980). The presence of Mesozoic limestone blocks within the mud sheet indicates that its emplacement may be related to the initiation of thrusting in the Helvetic realm (Sinclair 1989). Injections of mudstone into the overlying competent Mesozoic limestone (Tschep-nappe of Pfiffner 1978) at the main thrust contact suggest that the mud was still unconsolidated when it was buried by the advancing nappe pile.

3. Kinematic analysis

The Sardona and Blattengrat units have an arcuate outcrop pattern that is reflected in the orientation of their fold axial traces: these swing from NE-SW in Sernftal to ENE-WSW in Weisstannental and approximately E-W in Calfeisental (Pl. 1). One cannot assume from this that their principal shortening axis was perpendicular to the changing strike of the structures, especially when dealing with recumbent folds whose traces are likely to be significantly influenced by the present day topography of the area. Also, fold axes may form oblique to the mean transport direction. Therefore, it is necessary to undertake the collection of kinematic data, which in this case was provided by the solution of calcite (or occasionally quartz) and its regrowth as stepped fibre lineations in discrete slip planes within the sediments, usually approximating to the regional cleavage.

The data were collected in the context of local structures, sometimes relating to flexural slip in fold limbs, but, more usefully, when obtained from the immediate vicinity of minor faults, or close to the detachment between the Sardona and Blattengrat units. Sites in both flysch units were selected in order to evaluate whether there had been any diffe-

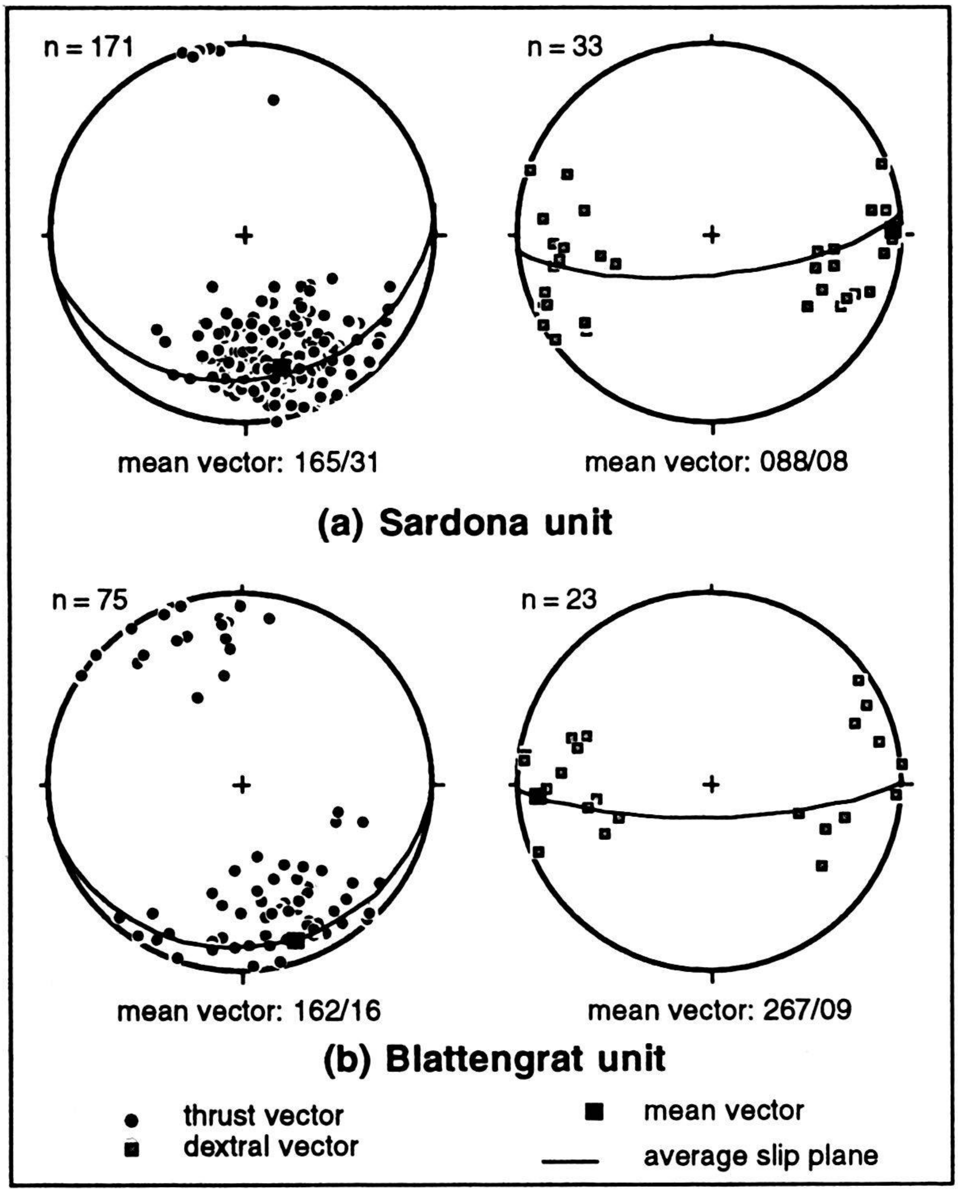

Fig. 6. Compilation of all kinematic data collected from (a) the Sardona unit and (b) the Blattengrat unit, demonstrating that the data from the two structural units is remarkably uniform: thrust lineations are directed towards the NNW in shallow, SSE-dipping planes and a second population of cross-cutting lineations are related to steep, E-W striking dextral faults.

rential rotational movement between the two units. Where possible, at least 12 lineations were collected at each site and more if two populations were present, in order to record a statistically valid sample. The mean vectors for each location are superimposed on the structural information in Plate 1; the structural data for these sites are compiled in Appendix 1. Compiling all the kinematic indicators illustrates that the data are remarkably uniform across the whole area (Fig. 6): thrust lineations in both structural units are directed towards the NNW in shallow, SSE-dipping planes and a second population of lineations are related to steep, E-W striking dextral faults.

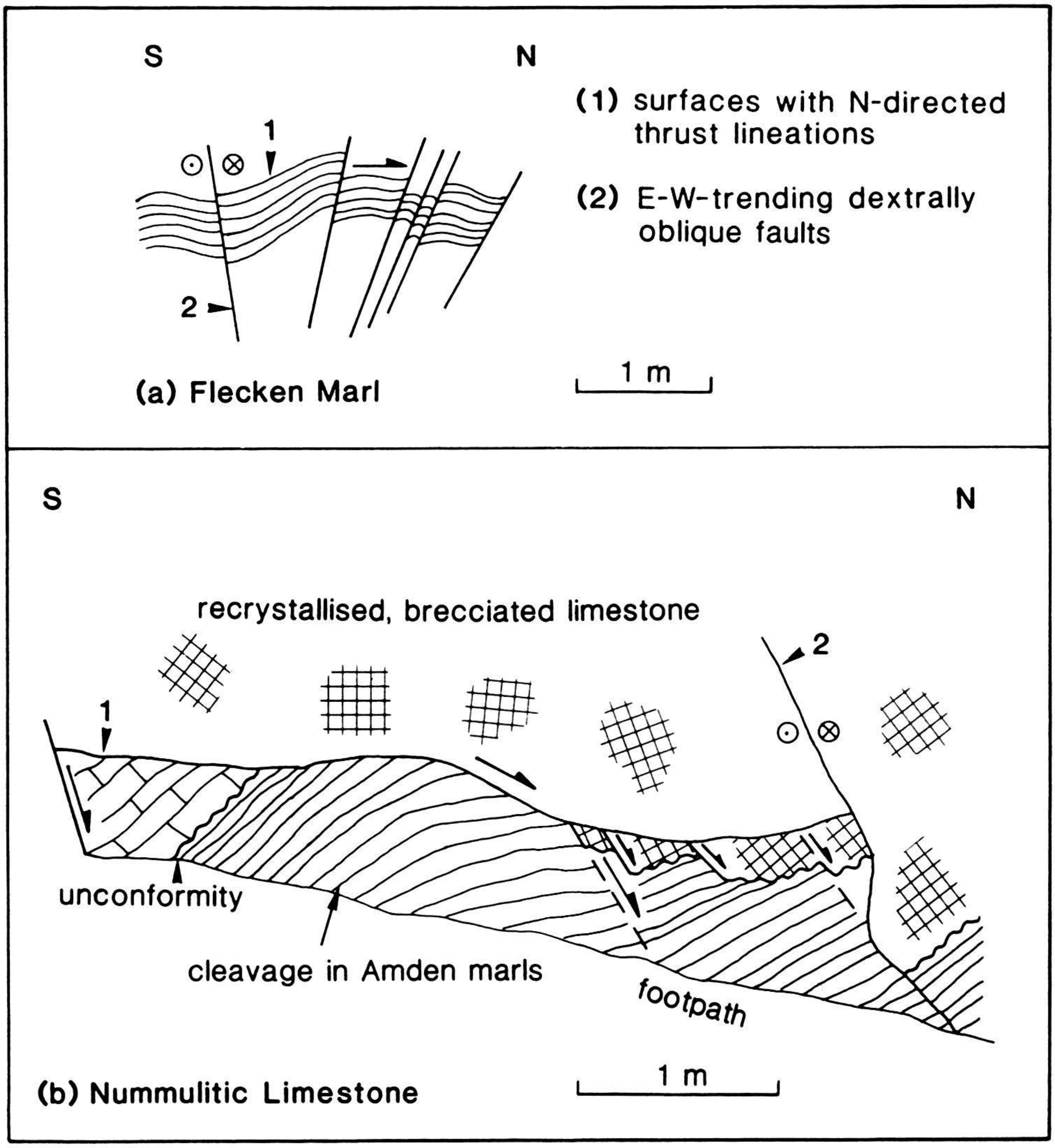

Fig. 7. Sketches of the cross-cutting relationship between dextrally oblique normal faults and reverse faults in the Blattengrat unit, at Prägelwand in Weisstannental (738.9/202.4).

Kinematic indicators from the NHF in the parautochthonous Mirutta thrust sheet to the south of the study area (site 23; Pl. 1) also indicate a NNW thrusting direction; data from the Lochseitenkalk nearby at Cassonsgrat (site 24; Pl. 1) are directed more towards the north, as are the data from the Verrucano above the Glarus Overthrust at Schwarze Hörner (site 17; Pl. 1). It can therefore be concluded that there has been penetrative deformation in the study area associated with N- to NNW-directed shortening. Previous kinematic studies have also concluded that the deformation was produced by N to NNW translation on the Glarus Overthrust (Pfiffner 1972, 1977, 1980, 1985; Schmid 1975; Sinclair 1989).

The additional population of dextral lineations has not been recognised in previous studies of the Infrahelvetic units. At some localities within the Blattengrat unit, dextrally oblique normal faults clearly post-date the folding, e.g., at Prägelwand (738.9/202.4) (Fig. 7), or at Chämmli (739.0/201.1) in Weisstannental. An E-W-trending fracture was found at the base of the Tschepp nappe near Panix Pass (727.8/190.7) which showed an oblique dextral offset with a throw of ~5 m. However, examination of E-W-trending fractures affecting the Glarus Overthrust to the east of the Schwarze Hörner (749/206-7) revealed that these fractures were a regularly-spaced, late, extensional cleavage probably related to arching of the Overthrust (Lihou et al. 1995), that experienced minor normal displacements of up to a few metres, but rarely showed dextral offsets. Other normal faults with this trend that affect the Glarus Overthrust have been mapped by Helbling (1948). Therefore, despite the fact that a late phase of dextrally oblique normal faulting would be expected to affect the Helvetic nappes as well, my observations only allow me to conclude that these faults were apparently confined to the Infrahelvetic units.

4. Deformational phases

The Helvetic zone and Infrahelvetic Complex were deformed during the Oligocene-Miocene Neo-Alpine Orogeny. Trümpy (1969) was the first to produce a palinspastic reconstruction for the Helvetic nappes of eastern Switzerland, in which progressively structurally higher nappes were derived from progressively further south. He distinguished three phases of deformation, which were part of a continuum process that amounted to 40–55 km of shortening – the early movement of 'superficial strip sheets' or 'diverticules', namely the allochthonous Infrahelvetic units; a main phase of folding and thrusting under high overburden to produce the Helvetic nappes; and minor, late phase movements under low overburden. Since then, Pfiffner (1977) has developed a four phase deformational model by subdividing Trümpy's main phase; this model has subsequently appeared in a number of publications (Milnes & Pfiffner 1977, 1980; Groshong et al. 1984; Pfiffner 1978, 1981, 1985, 1986). The individual 'phases' can be traced over large domains, but do not define chronologically distinct events since the deformation was probably diachronous (Groshong et al. 1984; Pfiffner 1986). The four phases can be summarised as follows:

Pizol phase: The first phase was the initial emplacement of the 'exotic strip sheets' (Sardona and Blattengrat units) onto the NHF unit, during which time the Sardona and Blattengrat thrust sheets are supposed to have travelled more than 30 km (Pfiffner 1978). The Sardona unit was considered to have more southerly (Ultrahelvetic) paleogeographic origins than the Blattengrat unit, which was thought to originate from the South Helvetic margin (Rüefli 1959; Wegmann 1961). Recently, Crampton (1992) and Lihou (1995, in press) ascribed the Infrahelvetic flysch sediments (NHF, Blattengrat and Sardona units) to an early NAFB setting. Foreland basin sediments originally more proximal to the thrust wedge, i.e., the Sardona Flysch, are now located at the top of the Infrahelvetic nappe pile, and the more distal foreland basin sediments in the Blattengrat and NHF units, are found beneath them, indicating that there is a structural inversion in the nappe pile that was probably brought about by telescoping of the early NAFB during Pizol phase deformation.

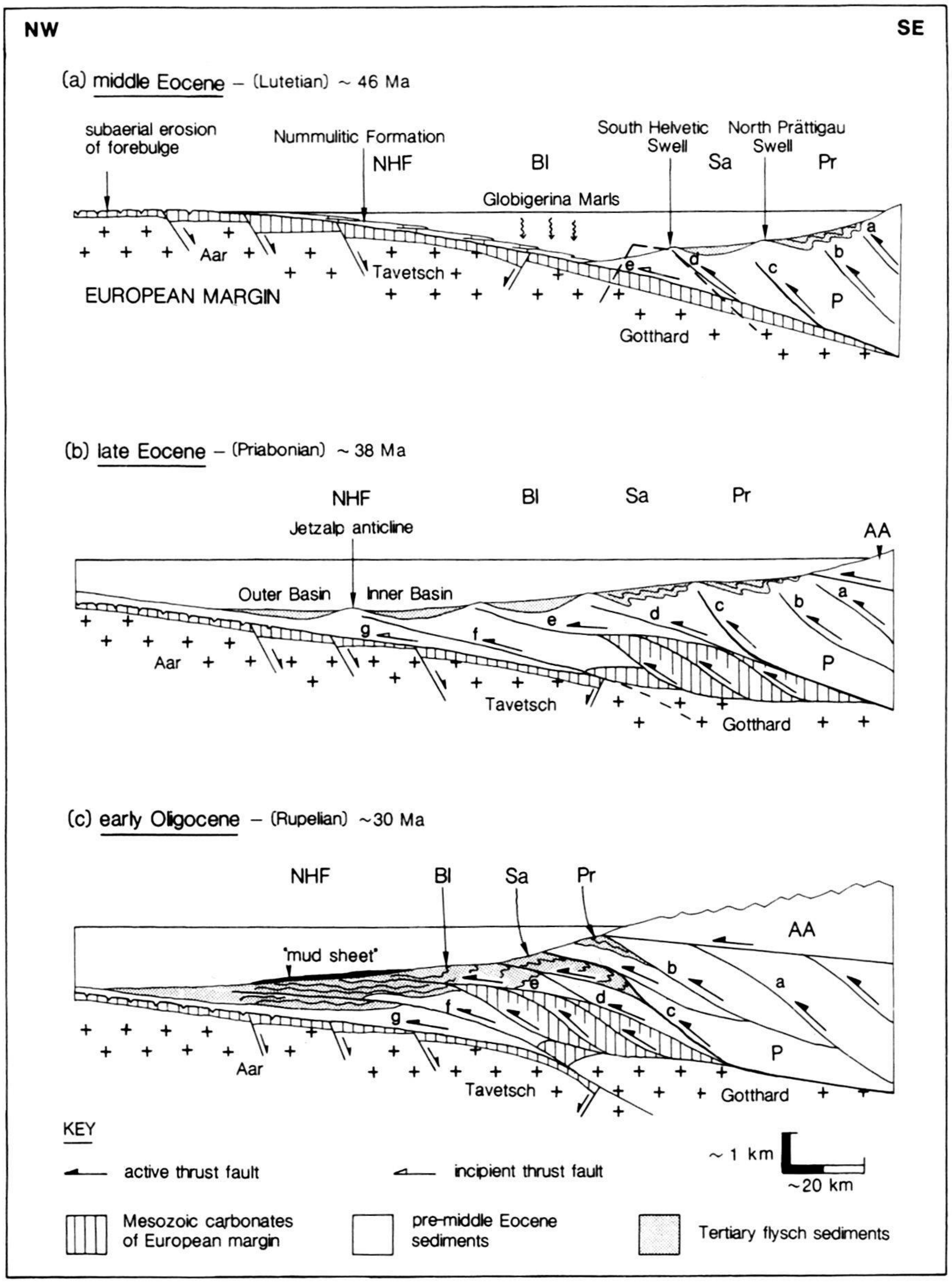

Fig. 8. *Schematic representation* of the early, pre-Pizol phase deformation within the North Alpine Foreland Basin (NAFB); for subsequent steps, refer to Pfiffner (1986).
a – g: sequence of thrusts propogating towards the foreland, where c (bold line) marks the Penninic frontal thrust; AA – Austroalpine cover sediments; Bl – Blattengrat Flysch (South Helvetic); NHF – North Helvetic Flysch; P – Penninic cover sediments; Pr – Prättigau Flysch (North Penninic); Sa – Sardona Flysch (Ultrahelvetic).
Note that the South Helvetic and North Prättigau Swells in (a) are shown as a thrust-cored anticlines, but could equally have been Mesozoic normal fault blocks reactivated by compressional/transpressional stresses within the NAFB – dashed alternative.

Trümpy (1969), and more recently Herb (1988), restored the Blattengrat unit to an original position on top of the Drusberg nappe, with its basement formed by the Gotthard massif (Pfiffner 1985; Fig. 8a). It was detached from its substratum within the Amden marls and displaced 10 km or more northwards during the Pizol phase (Fig. 8c). Remnants of Blattengrat-equivalent strata can be found on top of the Drusberg nappe, while similar thrust slices are found along the Alpine border near Einsiedeln (Trümpy 1980; Herb 1988; Fig. 2). The southerly part of the NHF unit was also sheared off its Cretaceous substratum during the early deformation (Trümpy 1969 & refs. therein) and is now preserved as the Wageten slices, also in the Subalpine chain. However, the NHF unit is parautochthonous, partly retaining its association with its basement, the Aar massif, and so underwent less translation than the other two units (Trümpy 1969).

The timing of the onset of deformation was thought by several authors to be constrained by the end of sedimentation in the NHF unit, which continued until the early Oligocene with the deposition of the Engi slates (Trümpy 1969; Schmid 1975; Milnes & Pfiffner 1980). However, Sinclair (1989, 1992) showed that deformation initiated somewhat earlier, during deposition of the Taveyannaz Sandstone, when thrusting close to the sea floor created the Jetzalp anticline, a paleohigh that ponded sediment in an inner, southern basin and starved the outer, northern basin (Fig. 8b). He also documented the pre-Pizol emplacement of the 'mud sheet' onto semi-lithified Taveyannaz Sandstone, that terminated sedimentation within the NHF basin (section 2.6; Fig. 8c). Continued thrust movement on the southern margin of the basin led to exposed Jurassic limestone blocks slipping off the hangingwall culmination, to be incorporated into the mud sheet (Sinclair 1989). This early deformation in the NHF unit also only shortly post-dates final flysch sedimentation in the Sardona and Blattengrat units during the Bartonian and Priabonian, respectively (Lihou 1995, in press). The end of sedimentation in these units may also be linked to the onset of deformation and thereby reflects its northward propagation onto the foreland, with the Sardona unit first being thrust onto the Blattengrat unit, and then in a piggy-back fashion onto the NHF unit (Fig. 8c). If the mud sheet was emplaced at or near the sediment/water interface (Sinclair 1989, 1992), there must have been little or no overburden during its emplacement, and by implication, during the Pizol phase emplacement of the Blattengrat and Sardona units.

Overprinting by later deformational phases has meant that until now no penetrative structures associated with the earliest phase of deformation have yet been recognised (Trümpy 1969; Milnes & Pfiffner 1977), and therefore Milnes and Pfiffner (1980) believed that it was impossible to determine the exact deformation mechanism for the Pizol phase. However, Trümpy (1969) favoured tectonic uplift during compression to trigger gravity sliding down a north-facing slope, whereby the allochthonous thrust sheets travelled downslope under the influence of gravity. Schmid (1975) believed that high pore pressures in the unconsolidated sediment aided the gravity sliding mechanism. However, two observations of the current structure argue against this mechanism of emplacement: firstly, neither the Blattengrat nor the Sardona unit can be described as a chaotic mélange of beds created whilst still semi-lithified, since their internal structures can be traced laterally over a few kilometres (section 2.1; Pl. 1) and lithostratigraphic relationships are internally consistent; and secondly, detachments between the flysch units can be restored to southerly-dipping thrust planes (section 2.4). Therefore, the suggestion of Groshong et al. (1984) that Pizol phase structures formed under horizontal compression seems more plausible. A thrust wedge of Penninic and Austroalpine material migrating towards the foreland might have provided the necessary horizontal force to shear off the 'exotic strip sheets' and move them along at the toe of the wedge (Fig. 8). Gravitational stresses associated with a north-facing surface slope to the thrust wedge probably aided thrust movements (Platt 1986).

Cavistrau phase: The Infrahelvetic Complex was subsequently overthrust by Helvetic Mesozoic limestone transported along out-of-sequence thrusts. It has been proposed that these allochthonous Infrahelvetic slices were early large-scale recumbent folds, that were sheared off the southern Aar massif and translated more than 5 km northwards as the deformation progressed across the Helvetic zone (Trümpy 1969; Milnes & Pfiffner 1977; Pfiffner 1978, 1985). The Panix Pass 'transverse line' running SSE from Chalchorn marks a change in the structural organisation of the allochthonous Infrahelvetic nappes and is considered to have acted as a lateral ramp during Cavistrau folding and thrusting (Pfiffner 1978; Sinclair 1989). A similar N-S-trending structure can be found to the southwest of the study area at Kunkels Pass (Pfiffner 1978). The lateral limits of younger thrust slices also coincide with these transverse faults, suggesting that they had a long-lived influence on the structural development of the Helvetic nappes (Pfiffner 1978).

However, the Cavistrau phase is considered to be of local importance (Pfiffner 1986), and is perhaps better considered as an integral part of the main, Calanda phase of deformation.

Calanda phase: The whole Infrahelvetic Complex was overthrust by the Helvetic nappes during the main deformational phase. Jurassic normal faults in the Helvetic paleogeographic zone were reactivated, following established zones of weakness and causing basin inversion (Trümpy 1969; Pfiffner 1993). Thrusting initiated within the Aar massif then subsequently migrated towards the foreland (Pfiffner 1986). The Helvetic nappes (Glarus, Mürtschen, Axen and Drusberg-Säntis nappes, in ascending structural order) were the autochthonous cover originally to the Tavetsch and Gotthard massifs, which lay to the south of the Aar massif (Pfiffner 1985, 1986). They were stacked into an imbricate structure by progressive splaying off the main Glarus Overthrust, which initiated between the Aar and Tavetsch massifs (Pfiffner 1985). Milnes and Pfiffner (1980) estimated that there had been up to 50 km of movement on the Glarus Overthrust in order to translate the Helvetic nappes from their original position south of the Aar massif to their present position north of it.

Penetrative ductile deformation in the whole Infrahelvetic Complex is associated with movement on the Glarus Overthrust (Milnes & Pfiffner 1977, 1980; section 2.2). A regional cleavage formed that cross-cuts all units and their contacts (Schmid 1975), and is associated with widespread folding and thrusting (Milnes & Pfiffner 1977, 1980). Earlier Cavistrau structures were refolded (Pfiffner 1985) and the Infrahelvetic flysch units were sliced up by out-of-sequence thrusts developed in the footwall of the Glarus Overthrust, a process known as 'Entwicklung' in Alpine literature (Pfiffner 1986). Imbrication of the parautochthonous thrust slices to the south of the flysch units created the Calfeisen digitation in the Sardona unit, truncating the older detachment between the Sardona and NHF units, and translating it 4–8 km northwards (section 2.3; Pl. 2). Folding accounts for another 2–3 km of shortening in the Sardona unit (section 2.3).

Burial by the Penninic/Austroalpine thrust wedge led to low-grade metamorphism in the Infrahelvetic Complex and the Helvetic nappes following the Calanda phase (Frey et al. 1973, 1980; Groshong et al. 1984). Metamorphism in the Helvetic nappes has been dated as early to middle Oligocene (30–35 Ma), using concordant K/Ar and Rb/Sr mineral ages (Frey et al. 1973; Hunziker et al. 1986). Trümpy (1969) estimated that as a result of the deformation, the overburden for the Infrahelvetic Complex was in the order of 5–6 km, based upon stratigraphic thickness estimates for the overriding nappes. Palinspastic reconstructions by Pfiffner (1986, fig. 4,) suggest a much greater overburden, in the order of 10 km, and recent metamorphic studies substantiate this estimate. Paleotemperatures derived from vitrinite reflectance values for a profile through the Axen nappe suggest that a paleogeothermal gradient of 35°C/km existed during peak metamorphism (Erdelbrock 1994). This compares well with the paleogeothermal gradient of 24–32°C/km for the NHF unit calculated using P/T conditions deduced from fluid inclusion data (Rahn et al. 1994). Using these data and the peak paleotemperature of ~300°C obtained for the Infrahelvetic units in the south of the study area (Erdelbrock 1994), it can be estimated that the overburden for the Infrahelvetic flysch units was in the order of 8–12 km. Hence, these units were once buried beneath the Helvetic, Penninic and Austroalpine nappes, the bulk of which have since been eroded. Their Miocene-Pliocene exhumation history has been documented by Rahn (1994) and Lihou et al. (1995) using apatite fission-track analysis.

Ruchi phase: There was continued northward movement on the Glarus Overthrust during the final phase of deformation, and the development of a crenulation cleavage in the Infrahelvetic Complex (Milnes & Pfiffner 1977, 1980). Rahn et al. (1995) and Erdelbrock (1994) were able to estimate the post-metamorphic offset across the Glarus Overthrust, by mapping iso-reflectance lines derived from vitrinite reflectance values. Both groups estimated the horizontal offset to be in the order of 5–10 km. In addition, Rahn et al. (1995) detected post-metamorphic offsets across imbricate thrust slice boundaries within the NHF unit that were mapped by Sinclair (1989). None of these studies identified a post-metamorphic discontinuity at the tectonic boundary between the Penninic and Helvetic nappes.

A thin film of fault gouge developed within the Lochseiten calc-mylonite due to frictional sliding as opposed to its earlier ductile deformation (Hsü 1969), which implies that late phase movements on the Glarus Overthrust occurred under less overburden, after uplift and erosion of the Penninic and Austroalpine nappes (Trümpy 1969). Radiometric dating of metamorphism of the Lochseiten calc-mylonite gave ages of ~23 Ma, i.e., the Oligocene-Miocene boundary (Hunziker et al. 1986), although this does not date final movement along the Glarus Overthrust. A later, Miocene metamorphic phase was dated at 14-20 Ma (Frey et al. 1973; Hunziker, in Pfiffner 1986) which indicates that post-metamorphic, Ruchi phase, movements on the Glarus Overthrust are post-mid-Miocene. Recently, Rahn (1994) discovered a discontinuity in apatite fission-track ages across the Glarus Overthrust, which may indicate that there has been thrust movement along this thrust since the late Miocene.

5. Conclusions

Structural mapping has revealed that there is a structural coherency within the Sardona and Blattengrat units. These flysch units are harmonically folded together into similar, asymmetrical, N- to NNW-vergent folds with wavelengths of 500 to 1500 m, associated with an axial planar cleavage; these folds plunge gently to the ENE/WSW or E/W. A second, N-S-trending phase of open folding has been recognised, which produced minor folds plunging to the SSE or SW. Folding accounts for 20–40% shortening within competent stratigraphic layers. Flat-lying fold limbs in the Blattengrat unit are extended by 25–30%, suggesting that buckled layers progressively migrated into the extensional strain field during emplacement of the Helvetic nappes along the Glarus Overthrust during Calanda phase deformation.

An important late thrust has been identified within the Sardona unit, which defines a hangingwall block that I have named the Calfeisen digitation; this thrust probably correlates with the basal thrust of the parautochthonous Orglen unit. Imbrication of the parautochthonous and allochthonous Infrahelvetic thrust slices was also associated with Calanda phase deformation, but these structures were eventually truncated by continued, Ruchi phase movement on the Glarus Overthrust. Compared with the 2–3 km of shortening within the folded Sardona Quartzite underlying the Calfeisen digitation, the 4–8 km displacement on the Orglen thrust is as important or more significant to bulk shortening in the Sardona unit as is folding. Based upon shortening estimates from the enclosed cross-sections, the preserved cross-sectional width of the Sardona basin is 13–18 km, whilst only a 9 km wide cross-section of the Blattengrat basin is preserved.

The collection of kinematic data revealed a remarkably uniform pattern across the whole area: thrust lineations in both structural units are directed to the NNW in shallow, SSE-dipping planes, and a second population of lineations are related to steep, E-W – striking dextral faults. It was concluded that penetrative compressive deformation associated with N-NNW – directed Calanda phase movement on the Glarus Overthrust was followed by dextrally oblique normal faulting affecting the Infrahelvetic units. The significance of these dextral faults has not been resolved.

Overprinting by later deformational phases has meant that until now no penetrative structures associated with the earliest, Pizol phase of deformation, in which the embryonic NAFB was telescoped onto the European (Helvetic) foreland, were recognised. However, the faulted contacts between the Sardona, Blattengrat and NHF units appear to climb through progressively higher stratigraphic levels towards the north in both their footwalls and hangingwalls, which suggests that they originated as low-angle, southward-dipping thrusts under horizontal compressive forces. Deformation propagated towards the foreland such that the Sardona unit was thrust onto the Blattengrat unit, before the Blattengrat unit was thrust onto the NHF unit. A thrust wedge of Penninic and/or Austroalpine material migrating towards the foreland might have provided the necessary horizontal force to detach these units and translate them northwards. The overburden for the Infrahelvetic flysch units once they were incorporated into the thrust wedge was in the order of 8–12 km. The foreland basin sediments originally more proximal to the thrust wedge, that are preserved in the Sardona unit, are now located at the top of the Infrahelvetic nappe pile, and the more distal foreland basin sediments in the Blattengrat and NHF units, are found beneath them; hence, there is a structural inversion in the nappe pile arising from the early deformation of the NAFB.

Acknowledgements

This work was undertaken as a part of a D.Phil. research project at the University of Oxford, England, supervised by John Platt and Philip Allen, and funded by a student sponsorship provided by Shell International Petroleum Company Limited. I would like to thank Martin Burkhard and Adrian Pfiffner, who provided speedy and throrough reviews of the manuscript, and Meinert Rahn who provided assistance with translation of the abstract. I also wish to thank Prof. Rudolf Trümpy for a stimulating discussion of these ideas at the Second Alpine Workshop in Basel, although in the end, we chose to differ regarding some of the interpretations.

REFERENCES

BISIG, W. 1957: Blattengratflysch und Sardonaflysch im Sernftal nördlich der Linie Richtelpass-Elm-Ramintal-Grosse Schiebe. PhD. thesis Univ. Zürich.

BÜRGISSER, H.M. & FELDER, T.E. 1974: Zur Geologie der Südabdachung der Segnas-Ringel-Gruppe (Vorderrheintal, Graubünden). Eclogae geol. Helv. 67, 457–467.

CRAMPTON, S.L.E. 1992: Inception of the Alpine Foreland Basin: Basal unconformity and Nummulitic Limestone. PhD. thesis, Univ. of Oxford (unpublished).

ERDELBROCK, K. 1994: Diagenese und schwache Metamorphose im Helvetikum der Ostschweiz (Inkohlung und Illit-'Kristallinität'). PhD. thesis Univ. Aachen.

FISCHER, H. & VILLA, I.M. 1990: Erste K/Ar- und Ar/Ar-Hornblende-Mineralalter des Taveyannaz-Sandsteins. Schweiz. mineral. petrogr. Mitt. 70, 73–75.

FREY, M. 1978: Progressive low-grade metamorphism of a black shale formation, central Swiss Alps, with special reference to pyrophyllite and margarite bearing assemblages. J. Petrol. 19, 95–135.

– 1988: Discontinuous inverse metamorphic zonation, Glarus Alps, Switzerland: evidence from illite 'crystallinity' data. Schweiz. mineral. petrogr. Mitt. 68, 171–183.

FREY, M., HUNZIKER, J.C., ROGGWILLER, P. & SCHINDLER, C. 1973: Progressive niedriggradige Metamorphose glaukonitführender Horizonte in den helvetischen Alpen der Ostschweiz. Contrib. Mineral. Petrol. 39, 185–218.

FREY, M., TEICHMÜLLER, M., TEICHMÜLLER, R., MULLIS, J., KÜNZI, B., BREITSCHMID, A., GRUNER, U. & SCHWIZER, B. 1980: Very low-grade metamorphism in the external parts of the Central Alps: illite crystallinity, coal rank and fluid inclusion data. Eclogae geol. Helv. 73, 173–203.

GROSHONG, R.H.JR., PFIFFNER, O.A. & PRINGLE, L.R. 1984: Strain partitioning in the Helvetic thrust belt of Eastern Switzerland from the leading edge to the external zone. J. Struct. Geol. 6, 5–18.

HELBLING, R. 1948: Photogeologische Karte der Tödikette vom Bifertenstock bis Calanda, 1: 25 000 (7 Tafeln). Geol. Spezialkarte Nr. 120, Schweiz. Geol. Kommission.

HERB, R. 1988: Eocene Paläogeographie und Paläotektonik des Helvetikums. Eclogae geol. Helv. 81, 611–657.

HSÜ, K.J. 1969: A preliminary Analysis of the Statics and Kinetics of the Glarus Overthrust. Eclogae geol. Helv. 62, 143–154.

HUNZIKER, J.C., FREY, M., CLAUER, N., DALLMEYER, R.D., FRIEDRICHSEN, H., FLEHMIG, W., HOCHSTRASSER, K., ROGGWILLER, P. & SCHWANDER, H. 1986: The evolution of illite to muscovite: mineralogical and isotopic data from the Glarus Alps, Switzerland. Contrib. Mineral. Petrol. 92, 157–180.

LE PICHON, X. & SIBUET J. 1981: Basin margins: a model of formation. J. geophys. res. 86, 3708–3720.

LIHOU, J.C. 1995: A new look at the Blattengrat unit of eastern Switzerland: Early Tertiary foreland basin sediments from the South Helvetic realm. Eclogae geol. Helv. 88, 91–114.

– (in press): Stratigraphy and Sedimentology of the Sardona unit, Glarus Alps: Upper Cretaceous–middle Eocene deep marine sediments from the Ultrahelvetic realm. Eclogae geol. Helv.

LIHOU, J., HURFORD, A. & CARTER, A. 1995: Preliminary fission-track ages on zircons and apatites from the Sardona unit, Glarus Alps, eastern Switzerland: late Miocene-Pliocene exhumation rates. Schweiz. mineral. petrogr. Mitt. 75, in press.

MILNES, A.G. & PFIFFNER, O.A. 1977: Structural development of the Infrahelvetic Complex, eastern Switzerland. Eclogae geol. Helv. 70, 83–95.

– 1980: Tectonic evolution of the Central Alps in the cross section St. Gallen-Como. Eclogae geol. Helv. 73, 619–633.

OBERHOLZER, J. 1933: Geologie der Glarneralpen, mit Atlas. Beitr. Geol. Karte Schweiz. N.F. 28, Schweiz. Geol. Kommission.

PFIFFNER, O.A. 1972: Neue Kenntnisse zur Geologie östlich und westlich des Kunkelpasses (GR). Eclogae geol. Helv. 65, 555–562.
- 1977: Tektonische Untersuchungen im Infrahelvetikum der Ostschweiz. PhD. thesis Univ. Zürich.
- 1978: Der Falten- und Kleinendeckenbau im Infrahelvetikum der Ostschweiz. Eclogae geol. Helv. 71, 61–84.
- 1980: Strain analysis in folds (Infrahelvetic Complex, Central Alps). Tectonophysics 61, 337–362.
- 1981: Fold and thrust tectonics in the Helvetic nappes (East Switzerland). In: Thrust and Nappe Tectonics (Ed. by McCLAY, K.R. & PRICE, N.J.). Geol. Soc. spec. publ. 9, 319–327.
- 1985: Displacements along thrust faults. Eclogae geol. Helv. 78, 313–333.
- 1986: Evolution of the north Alpine foreland basin in the Central Alps. In: Foreland Basins (Ed. by ALLEN, P.A. & HOMEWOOD, P.). Int. Assoc. Sediment. Spec. Publ. 8, 219–228.
- 1993: The structure of the Helvetic nappes and its relation to the mechanical stratigraphy. J. struct Geol. 15, 511–521.

PLATT J.P. 1986: Dynamics of orogenic wedges and the uplift of high-pressure metamorphic rocks. Bull. geol. Soc. Am. 97, 1037–1053.

RAHN, M. 1994: Incipient Metamorphism of the Glarus Alps: Petrology of the Taveyanne Greywacke and Fission Track Dating. PhD. thesis Univ. Basel.

RAHN, M., MULLIS, J., ERDELBROCK, K. & FREY, M. 1994: Very low-grade metamorphism of the Taveyanne greywacke, Glarus Alps, Switzerland. J. metam. Geol. 12, 625–641.
- 1995: Alpine Metamorphism in the North Helvetic Flysch of the Glarus Alps, Switzerland. Eclogae geol. Helv. 88, 157–178.

RAMSAY, J.G. 1967: Folding and Fracturing of Rocks. Mc-Graw-Hill, London, England.

RÜEFLI, W.H. 1959: Stratigraphie und Tektonik des eingeschlossenen Glarner Flysches im Weisstannental (St.Galler Oberland). PhD. thesis Univ. Zürich.

SCHMID, S.M. 1975: The Glarus Overthrust: field evidence and mechanical model. Eclogae geol. Helv. 68, 247–280.

SIEGENTHALER, C.H. 1974: Die nordhelvetische Flysch-Gruppe im Sernftal (Kt. Glarus). PhD. thesis Univ. Zürich.

SINCLAIR, H.D. 1989: The North Helvetic Flysch of Eastern Switzerland: foreland basin architecture and modelling. PhD. thesis Univ. Oxford (unpublished).
- 1992: Turbidite sedimentation during Alpine thrusting: the Taveyannaz sandstone of eastern Switzerland. Sedimentology 39, 837–856.

TRÜMPY, R. 1967: Geologischer Führer der Schweiz. Heft 7, Wepf & Co., Basel, Switzerland, 649–696.
- 1969: Die helvetischen Decken der Ostschweiz: Versuch einer palinspastischen Korrelation und Ansätze zu einer kinematischen Analyse. Eclogae geol. Helv. 62, 105–142.
- 1980: Geology of Switzerland, a Guide-Book. Wepf & Co., Basel, Switzerland.

TRÜMPY, R. & TROMMSDORFF, V. 1980: Excursion No. IV: Alps of Eastern Switzerland. In: Geology of Switzerland, a Guide-Book (Ed. by TRÜMPY, R.). Wepf & Co., Basel, Switzerland, 211–260.

WEGMANN, R. 1961: Zur Geologie der Flyschgebiete südlich Elm. PhD. thesis Univ. Zürich.

WETTSTEIN, A. 1887: Über die Fischfauna des Tertiären Glarnerschiefers. Abh. Schweiz. Paläont. Ges. 13, 1–103.

Manuscript received April 28, 1995
Revision accepted Juni 19, 1995

Appendix 1. Compilation of structural data collected from sites in the Infrahelvetic units between Sernftal and Pizol; mean vectors are plotted on Plate 1.
Structural units: (Bl) Blattengrat unit; (Gl) Glarus nappe; (Sa) Sardona unit. Mean vectors are given as plunge direction/amount of plunge and fault planes as dip direction/amount of dip.

Structural site no.	Location Grid Ref.	Altitude (m)	Stratigraphic & (Structural) unit	Number of measurements	Av. thrust vector Av. dextral vector	Av. fault plane(s)
1	Martinsmad (733.3/194.8)	2000	Glt. Marl (Sa)	12	165/26 —	177/23 —
2	Segnas Pass (736.1/196.1)	2627	Infraqtzite Fl. (Sa)	30	153/53 091/08	178/56
3	Brüschegg (734.7/196.2)	1920	Sardona Qtzite (Sa)	11	157/25 —	191/31 —
4	Biflen (734.2/196.6)	1700	Glt. Lst. & Marl (Sa)	16	154/29 243/02	168/31
5	Mattlirüs (733.5/196.8)	1440	Numm. Lst. & Flecken Marl (Bl)	19	167/35 290/13	177/34 191/75
6	Unter Falzüber (734.3/197.8)	1450	Flecken Marl (Bl)	14	137/07 —	153/09 —
7	Chalberweid (734.7/197.7)	1600	Infraqtzite Fl. (Sa)	12	166/03 267/36	 207/52
8	Falzüber (735.1/197.5)	1790	Glt. Lst. (Sa)	14	156/27 —	171/26 —
9	Foo Pass (736.9/201.3)	2300	Sardona Qtzite (Sa)	14	170/38 308/07	177/40 036/84
10	Foobach (737.5/200.9)	2040	Flecken Marl (Bl)	9	157/31 086/02	163/32 008/67
11	Heitelkopf (738.3/200.7)	2000	Sardona Qtzite (Sa)	9	175/23 —	174/22 —
12	Unter Stich (738.9/202.3)	1700	Numm. Lst. & Flecken Marl (Bl)	33	344/31 257/31	316/18 178/72
13	Heitel Pass (744.2/201.2)	2388	Sardona Qtzite (Sa)	10	161/20 —	157/19 —
14	Guetental (745.2/202.3)	1910	Glt. Lst. & Infraqtzite Fl. (Sa)	13	159/15 —	149/13 —
15	Lavtinarus (745.1/204.3)	1500	Flecken Marl (Bl)	14	142/38 —	132/36 —
16	Gafarratobel (746.6/206.8)	1250	Flecken Marl (Bl)	10	190/07 —	182/13 —
17	Schwarze Hörner (748.5/205.7) (749.8/206.7) (749.9/207.7)	 2480 2160 1500	Verrucano (Gl)	10	167/10 —	200/07 —
18	Pizolgebiet (750/205)	2000 -2240	Glt. Lst. & Marl (Sa)	28	184/39 —	170/40 —
19	Sunntigweid (744.5/200.3)	2100	Infraqtzite Fl. (Sa)	15	166/39 —	177/38 —
20	Ebnitros (743.0/198.3)	1800	Sardona Qtzite (Sa)	13	156/26 —	170/61 —
21	Hexenbühel (740.6/198.1)	1854	Supraqtzite Fl. (Sa)	8	158/08 —	235/11 —
22	Segnas Sura (738/195)	2460 -2600	Glt. Lst. (Sa)	15	163/50 100/17	174/52
23	Fuorcla Rascaglius (738.6/194.5)	2580	North Helv. Flysch	8	166/39 —	185/32 —
24	Cassonsgrat (739.1/193.8)	2660	Verrucano (Gl)	12	191/14 —	178/08 —

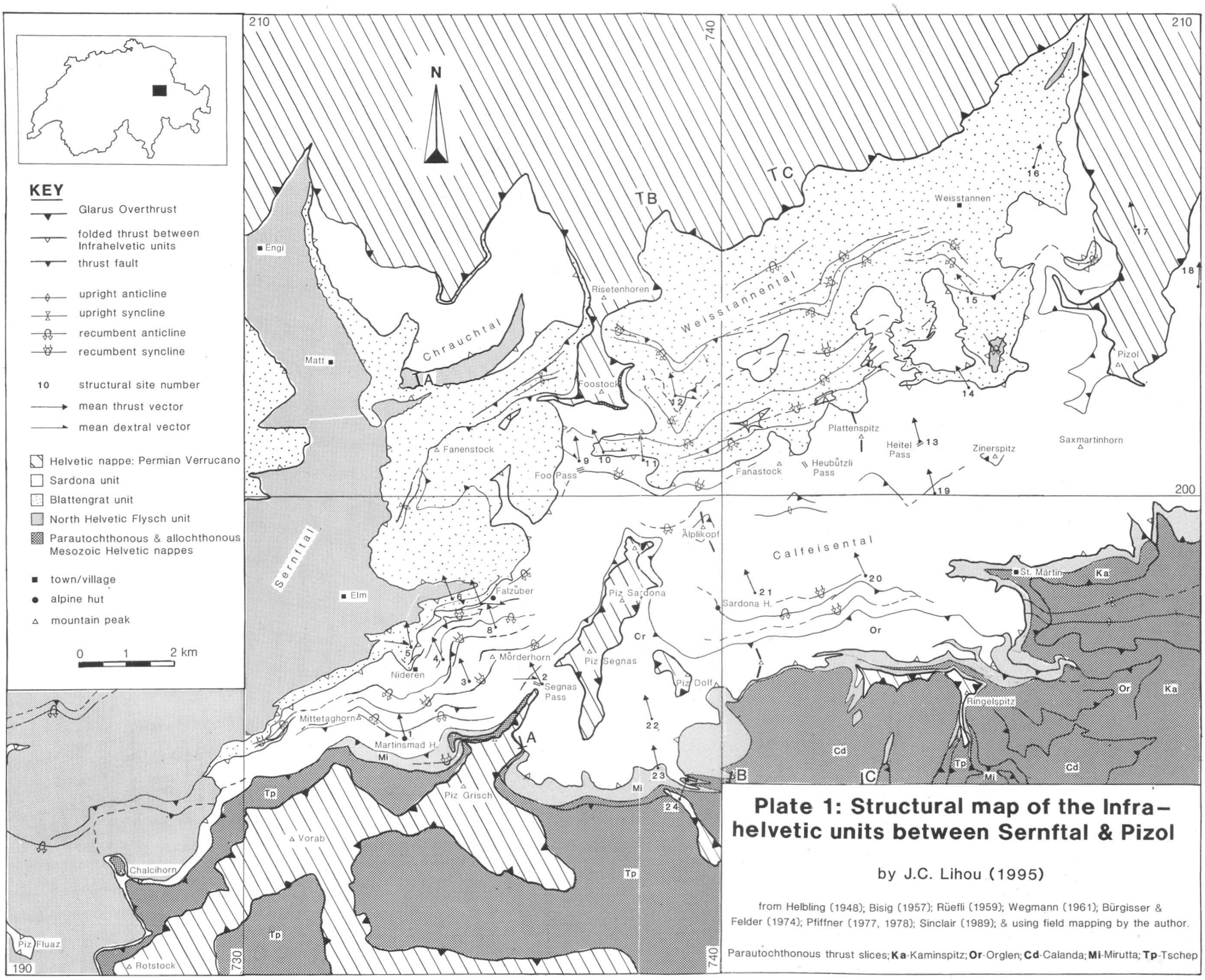

Plate 1: Structural map of the Infrahelvetic units between Sernftal & Pizol

by J.C. Lihou (1995)

from Helbling (1948); Bisig (1957); Rüefli (1959); Wegmann (1961); Bürgisser & Felder (1974); Pfiffner (1977, 1978); Sinclair (1989); & using field mapping by the author.

Parautochthonous thrust slices; **Ka**-Kaminspitz; **Or**-Orglen; **Cd**-Calanda; **Mi**-Mirutta; **Tp**-Tschep

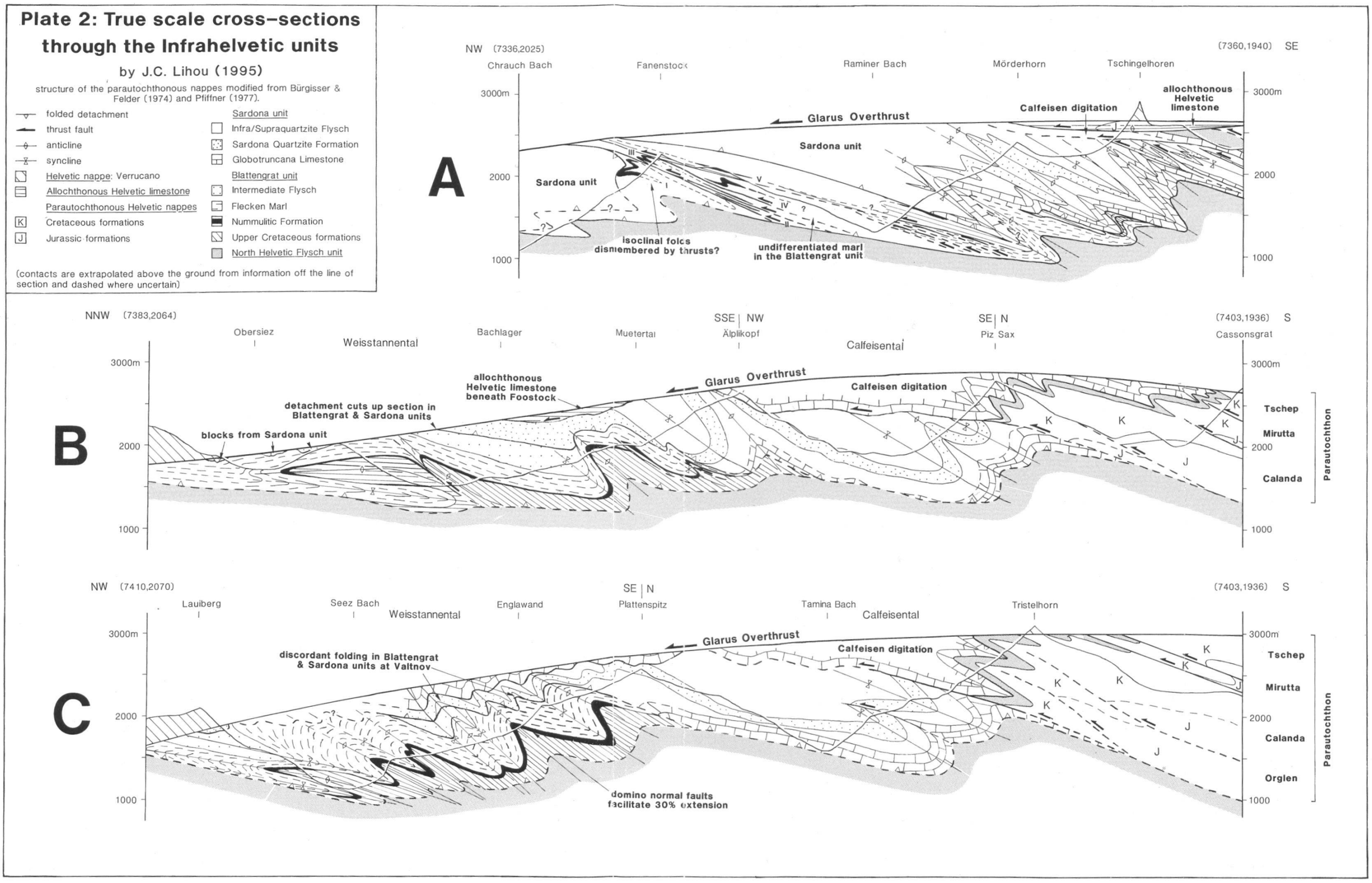

Plate 2: True scale cross-sections through the Infrahelvetic units

by J.C. Lihou (1995)

structure of the parautochthonous nappes modified from Bürgisser & Felder (1974) and Pfiffner (1977).

(contacts are extrapolated above the ground from information off the line of section and dashed where uncertain)