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The structure of the Helvetic nappes and its relation to the mechanical stratigraphy

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Abstract—This paper discusses structure and variations in structural style due to changes in mechanical stratigraphy of the Helvetic nappes based on five cross-sections. The ratio, n, of the thickness of mechanically weak to the thickness of adjacent mechanically strong layers is of particular importance. A low value of n favours imbricate thrusting and harmonic folding, a high value favours detachment and disharmonic folding. The transition at around $n = 0.5$ is characterized by polyharmonic folding. Stratigraphic thickness variations due to local basin subsidence resulted in arcuate fold hinges and important plunges upon basin inversion. Lateral variations in the overall structure of the Helvetic nappes is largely controlled by the initial irregular arrangements of the various small basins. One more or less coherent thrust sheet, the Cretaceous stockwerk of the Wildhorn–(Drusberg–) Säntis nappe can be traced along the entire fold-and-thrust belt.

INTRODUCTION

THE Helvetic zone extends along the northern margin of the Alps all the way across Switzerland and into the adjoining countries to the east (Austria) and west (France). In the framework of Alpine tectonics the nappes of the Helvetic zone are overlain to the south by the Penninic and Austroalpine nappe systems (Fig. 1). To the north the Helvetic nappes override the Oligocene–Miocene clastics of the adjoining Molasse basin, a foredeep which formed during the later stages of the Alpine collision. The Mesozoic sediments making up the largest part of the Helvetic zone comprise essentially a carbonate shelf sequence of the northern European margin of Tethys. In contrast, the Mesozoic rocks of the Penninic and Austroalpine nappes represent a thinned European continental margin interlayered with oceanic rocks, and the thinned Adriatic margin of Tethys, respectively. In the course of the Alpine collision the Penninic nappes were thrust onto the Helvetic zone, carrying the Austroalpine nappes piggy-back. The rocks of the Helvetic zone were buried in this process, metamorphosed up to greenschist facies conditions and deformed.

The Helvetic nappes offer the possibility to study the influence of mechanical stratigraphy on the style of large-scale structures. The aim of this paper is to give a general overview of the structure and to analyse the variation in structural style along the strike of the chain in the light of changes in mechanical stratigraphy.

In a general way the Helvetic zone is subdivided by major thrust faults into the Helvetic nappes (above) and the Infrahelvetic complex (below). This subdivision is particularly useful in eastern and central Switzerland, where the displacements along the basal thrusts (Glarus and Axen) are much larger than the ones along thrusts in their footwalls and hangingwalls. The basal thrust faults of the Helvetic nappes are given in Fig. 1. They carry the name of the nappes in their hangingwalls. In the Infrahelvetic complex the pre-Triassic crystalline basement is involved in the nappe structure to a large degree. In contrast, the Helvetic nappes represent classic detachment tectonics. This paper will mainly deal with the structure of the Helvetic nappes and factors influencing this structure. For a more detailed discussion of the Infrahelvetic complex the reader is referred to Pfiffner (1978) for eastern Switzerland, and to Burkhard (1988), Coward & Dietrich (1989) and Ramsay (1989) for western Switzerland. The kinematic and metamorphic evolution of the Helvetic zone is given in Groshong *et al.* (1984) and Pfiffner (1986) for eastern Switzerland, Frey *et al.* (1980) and Breitschmid (1982) for central Switzerland, and Ramsay (1981, 1989), Burkhard (1988), Dietrich & Casey (1989) and Coward & Dietrich (1989) for western Switzerland.

The Mesozoic stratigraphic sequence of the Helvetic zone is summarized in Fig. 2. Although individual formations can be traced along the entire fold-and-thrust belt, marked variations in thickness and composition occur. Figure 2 illustrates some of the major variations: the Lower Jurassic lacking in the Infrahelvetic complex of central and eastern Switzerland; thickness variations of the Middle Jurassic; the Upper Jurassic being thin in the west; and the Cretaceous being thin and purely calcareous in the Infrahelvetic complex as opposed to in the Helvetic nappes. The bearing of these variations on structural style will be discussed in a later section. A summary stratigraphic sequence displaying the mechanical stratigraphy is given as an inset in Fig. 3 and serves as a legend for the cross-sections. The mechanically dominant layers are the thick Upper Jurassic and Cretaceous carbonate formations. As is evident from Fig. 2 the main detachment horizons are located in the shaly or marly horizons at the base of the Lower Jurassic and the Middle Jurassic, the base of the Lower Cretaceous, in a Triassic evaporite layer and (inset in Fig. 3) in an unknown lithology (Carboniferous shale or schistose basement?) at the base of the Verrucano. For more

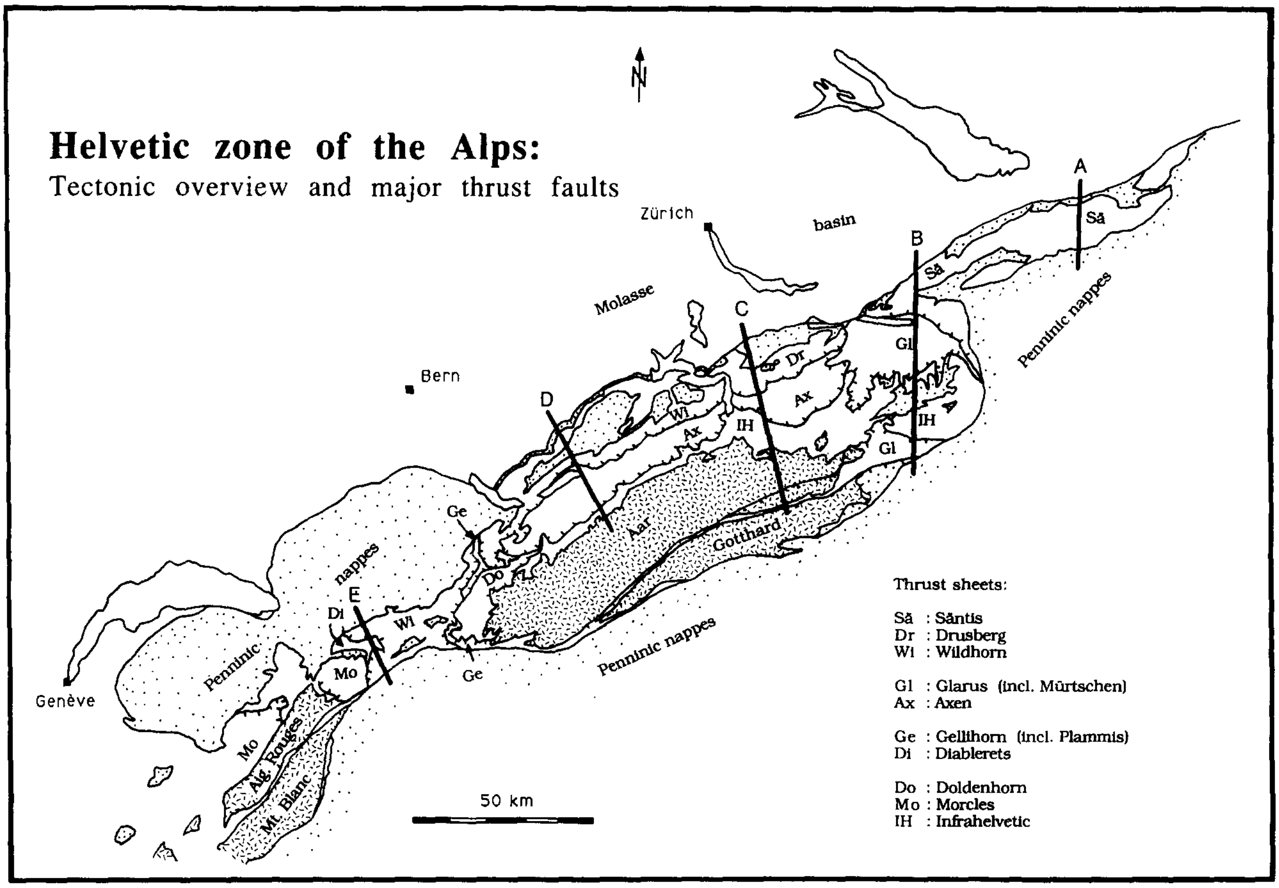


Fig. 1. Simplified tectonic map of the Helvetic zone. A–E: traces of the cross-sections in Fig. 3. Random dashes: pre-Triassic crystalline basement of the external massifs (Aar, Gotthard, Mt. Blanc, Aiguilles Rouges).

information on the stratigraphy the reader is referred to Funk *et al.* (1987) and references therein.

STRUCTURAL OVERVIEW

The Helvetic zone forms a classic fold-and-thrust belt with an intricate interplay between thrusting, leading to extensive imbrications, and folding, leading to large-scale recumbent folds. As will be shown, not only does the contrast in mechanical strength seem to play a key role in the development of the structures, but the relative thickness of individual rock formations seems to also. Since the latter are subject to pronounced lateral variations (Fig. 2) it is no surprise that the structure varies considerably along the strike. It would be beyond the scope of this paper to discuss all these variations. Rather, I attempt to show the spectrum of structural styles using five evenly spaced cross-sections (shown in Fig. 3) thought to be representative for the purpose. These sections will be discussed proceeding from east to west.

Transect A

Section A in Fig. 3 is located in Austria and is in part based on Wyssling (1985). The large-scale antiform beneath Kanisfluh is shown to be cored by very thick Middle Jurassic. This is hypothetical since the basal (Säntis) thrust fault and the deeper part of the section is nowhere exposed due to the lack of substantial axial plunges. In this sense section A is the least constrained of all the sections. Inspection of section A in Fig. 3 reveals that there is some polyharmonic folding of the Upper Jurassic and Cretaceous limestones rendered possible by a shaly–marly lowermost Cretaceous. The thickness of the latter was, however not sufficient for a complete detachment, as is the case in the neighbouring section B. The overturned limb of the anticline beneath Niedere and the presence of Upper Jurassic limestones in its core is constrained by surface and subsurface data. The absence of such limestones in the folds beneath this anticline is speculative and inspired by the structural style of the neighbouring section B. The southward continuation of the Helvetic zone in this section is completely buried by the higher tectonic units (see Fig. 1). The position of the autochthonous Mesozoic was obtained from extrapolation of surface data.

Transect B

Section B in Fig. 3 extends all the way across the Helvetic zone. Due to significant axial plunge and seismic data (Pfiffner *et al.* 1990a) it is particularly well constrained. The Helvetic nappes, whose basal thrust fault is the famous Glarus thrust, are subdivided into two major nappe complexes in this transect (see also Pfiffner 1981). The Upper Glarus nappe complex—also referred

thickness ratios	A	B		C		D	E		
	Sä	Sä + Gl	Autochth.	Ax	Dr	Wi - Ax	Wi + Di	Mo	Autochth.
Palfris/Cretac. / Palfris/Malm	0.2 / 0.5 P	0.35 / 1.17 D	0 / 0 H	0.16 / 0.3 H	0.44 / - D	0.33 / 2 D	0.25 / 1.5 D	0.7 / 0.44 P	0.5 / 0.2 H
Dogger/Malm	1.5 D	1 P	0.06 H	0.37 H	-	6 D	10 D	1.9 D	0 H

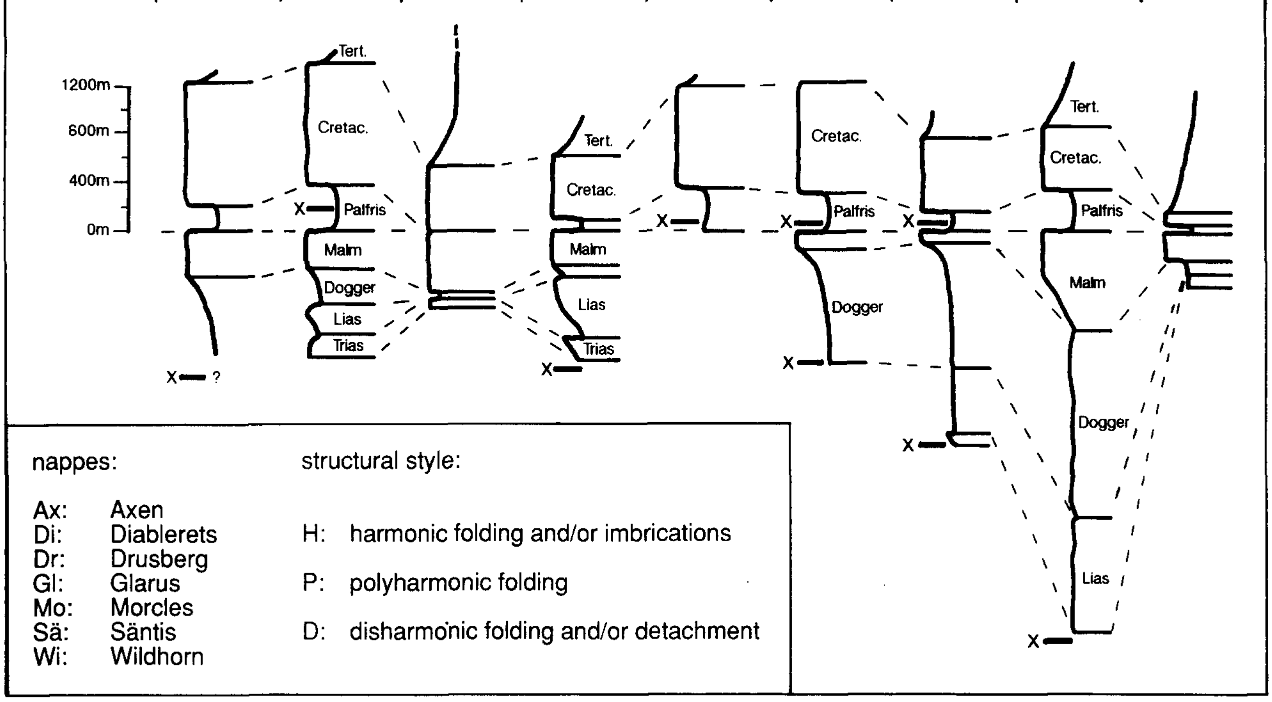


Fig. 2. Stratigraphic sections for the transects A–E (Fig. 3) showing thickness variations of structural lithic units and their bearing on structural style. Detachment horizons are marked with X.

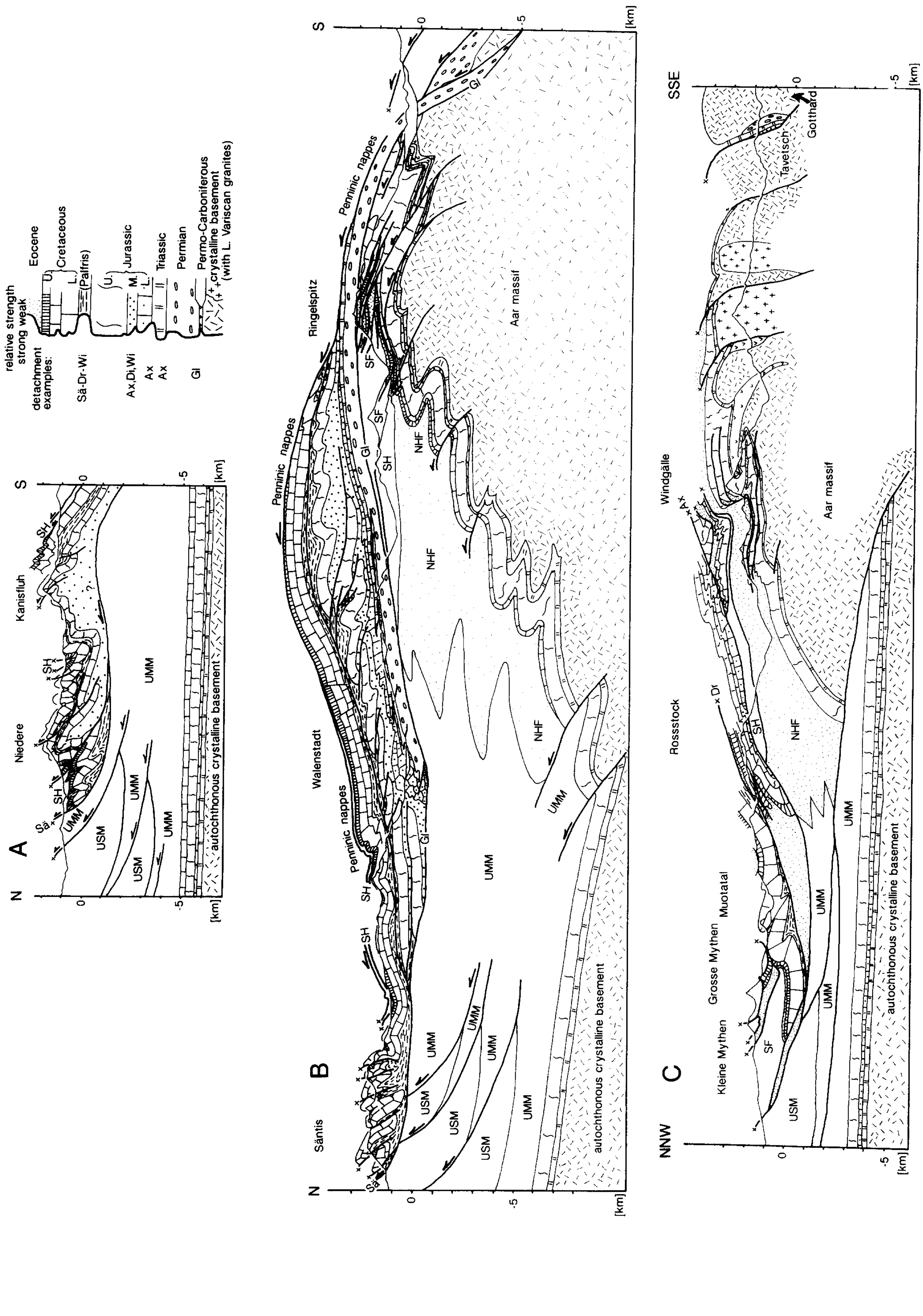
to as the Säntis nappe—consists of Cretaceous limestones which were detached from their Jurassic substratum (Säntis), which give way to a series of fold structures towards the south (north of Walenstadt). This change in style coincides with an increase in stratigraphic thickness of the shaly–marly detachment horizon (Palfris Formation), which is in part due to the replacement of calcareous facies by muddy facies equivalents. It thus seems that the thick, mechanically weak horizon favoured detachment and buckle folding, with the incompetent layer being able to accommodate space problems associated with the buckling of single strong layers. The trailing edge of the Säntis nappe (south of Walenstadt) in contrast shows some signs of layer-parallel extension above the detachment horizon.

The Lower Glarus nappe complex consists of two structurally distinct levels in this transect. The lower level, a rigid block of Verrucano and Trias, is an upright sequence whose simple structure reflects the mechanical stiffness of these units. The upper level is characterized by imbricate thrusting of the thick Upper Jurassic limestones, which grades into folding southwards. The difference in style between north and south can be attributed to the drastic increase in thickness of the Middle Jurassic whose lower shaly part also accounts for the disharmony in structure between upper and lower levels.

The structure of the Infrahelvetic complex beneath the Glarus thrust is constrained by seismic data from line NFP20-EAST which passes 5 km to the east of this cross-section (Pfiffner *et al.* 1990a, Stäuble & Pfiffner 1991). The style of recumbent folding and thrusting on steeply dipping faults, both involving basement, can actually be observed at the surface farther west along strike (see also sections C and D in Fig. 3). In fact the pre-Triassic, Variscan structure had a pronounced influence on the Alpine deformation. For example, the Late Variscan magmatic complexes behaved as rigid blocks in some instances and were squeezed up into the cores of antiformal structures (see also Pfiffner *et al.* 1990b).

Transect C

In section C of Fig. 3, based in part on Schmid in Funk *et al.* (1983), the Helvetic nappes consist of the Säntis nappe (also called Drusberg nappe in this transect; see Fig. 1) and the Axen nappe. The Axen thrust follows a detachment horizon in Triassic cargneules. The front of the Axen nappe consists of plunging (synformal) anticlines, the northernmost of which is associated with a


A
N
S
Niedere
Kanisfluh
Sä
SH
UMM
USM
autochthonous crystalline basement
[km]
0
-5
relative strength
strong weak
detachment examples:
Sä-Dr-Wi
Ax,Di,Wi
Ax
Ax
Gl
Eocene
U.
L.
Cretaceous
(Palfris)
U.
M.
L.
Jurassic
Triassic
Permian
Permo-Carboniferous
crystalline basement
(with L. Variscan granites)
B
Säntis
Walenstadt
Ringelspitz
Penninic nappes
SF
Gl
NHF
Aar massif
C
NNW
SSE
Kleine Mythen
Grosse Mythen
Muotatal
Rossstock
Dr
Windgälle
Tavetsch
Gotthard

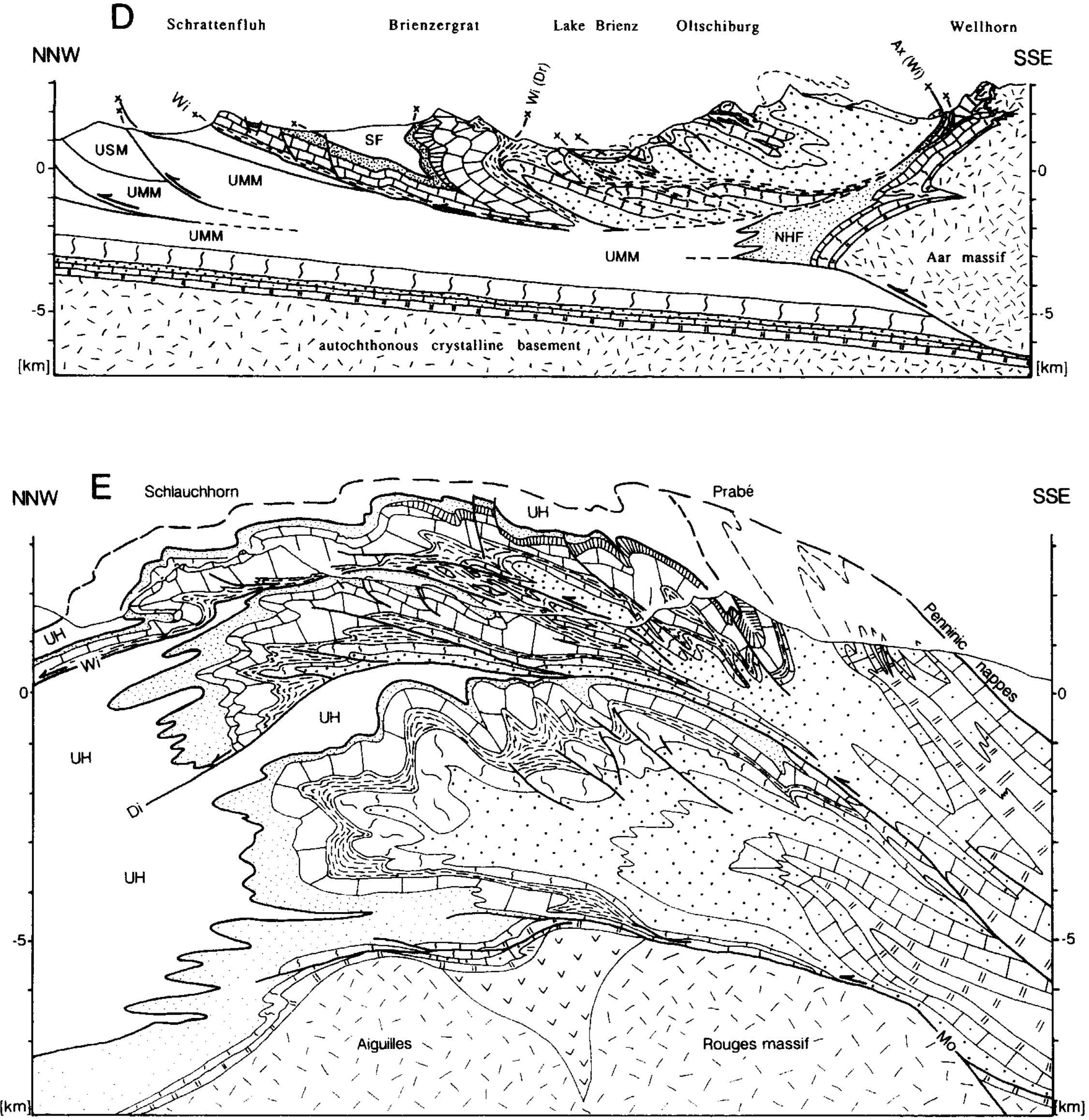


Fig. 3. Five representative cross-sections through the Helvetic zone. The traces are given in Fig. 1. Abbreviations for the thrust faults are as in Figs. 1 and 2. NHF, North-Helvetic Flysch; UMM, Lower Marine Molasse; USM, Lower Freshwater Molasse; SF, Sardona and Schlieren Flysch (Penninic); SH, South-Helvetic units; UH, Ultra-Helvetic units.

hanging-wall ramp of the Axen thrust. The Säntis thrust, on the other hand, follows the lowermost Cretaceous detachment horizon. As is evident on section C the trailing edge of the Helvetic nappes is eroded. It is thus not clear whether the Jurassic substratum of the Säntis nappe is to be sought in the southern, eroded Axen nappe or in the Jurassic Bündnerschiefer above the Gotthard massif. It is interesting to note in this context that the Lower Jurassic of the Axen nappe (beneath Rossstock in section C, Fig. 3) compares closely with the Lower Jurassic found just to the north of the Gotthard massif (Trümpy 1949), which would speak for a rather internal origin of the Axen nappe.

A characteristic of this transect is the occurrence of overridden slices of mainly Upper Jurassic–Cretaceous limestones in the footwall of the Axen thrust (north of Windgälle in section C; see von Schumacher 1928, Frey 1965). Truncation of fold structures within these allochthonous Infrahelvetic slices points toward out-of-sequence thrusting. Folding of the basal thrust of these slices by the Windgälle fold, however, suggests in-sequence thrusting at a later stage.

The Aar massif is shown to be thrust over the autochthonous Mesozoic (unpublished seismic data) over a distance of about 10 km. This (compared with that in section B) additional shortening explains the higher position of the top of the Aar massif and might be responsible for the local steep dip of the Axen thrust and the rotation of the folds mentioned above.

Transect D

Section D in Fig. 3 shows a style in strong contrast to that in section C. Traditionally the whole complex above the basal thrust fault is called Wildhorn nappe. However there are clearly two structurally independent levels (or stockwerk) distinguishable, namely the Cretaceous and the Jurassic. The thick lowermost Cretaceous Palfris shales are responsible for the disharmony, and this detachment horizon can easily be traced eastward and linked to the Säntis thrust in the transect of section C. One could therefore just as well call the Cretaceous stockwerk the (Drusberg–) Säntis nappe. Since this Cretaceous can also be traced westward (into the transect of section E) it follows that the Cretaceous of the Wildhorn–(Drusberg–) Säntis nappe represents an almost coherent thrust sheet extending all the way through Switzerland and into Austria.

The Jurassic stockwerk of the Wildhorn nappe, which can be linked to the Axen nappe farther east (and could thus just as well be called Axen nappe) is characterized by high-amplitude recumbent folding (see also Günzler-Seiffert 1944). Inspection of section D reveals that this structural style is related to the great thickness of the Middle Jurassic, the shaly lower part of which acted as a basal detachment horizon and accommodated the contact strains related to folding. The great thickness of the Middle Jurassic characteristic of this transect (Pilloud 1990) rapidly decreases northward from Oltschiburg, as well as eastward and westward along strike. The lowermost imbricates of Upper Jurassic limestones (beneath Oltschiburg) were introduced for reasons of balancing, but are not constrained by other data. In fact this could also be drawn as an inverted sequence (similar to the structure of the Wildhorn nappe in section E, Fig. 3).

The structure of the Cretaceous stockwerk in this transect is dominated by a deep syncline with an overturned limb. This syncline seems to be related to the structural relief caused by shortening within the underlying Jurassic. It thus seems that the detachment and northward transport of the Cretaceous occurred in an early stage of internal deformation. As in transect C the southern extension of the Wildhorn nappe in transect D is completely eroded.

Deformation in the footwall of the Axen–(Wildhorn) thrust, i.e. shortening within the Aar massif, steepened the thrust and locally even overturned it. To the west of this section this thrust is deformed by the internal deformation of the underlying Gellihorn nappe (Burkhard 1988) and the Gellihorn thrust is locally deformed by the internal deformation of the underlying, Infrahelvetic Doldenhorn fold-nappe. This suggests that thrusting progressed from higher to lower levels, i.e. in-sequence. For a detailed discussion of the structures in the area between profiles D and E in Fig. 3 the reader is referred to Burkhard (1988).

Transect E

In transect E of Fig. 3 the Helvetic nappes form an antiformal stack above the recumbent Morcle fold and the antiformal structure of the Aiguilles Rouges massif. This structure has also been discussed in detail by Ramsay (1981, 1989) and Dietrich & Casey (1989). The internal structure of the Wildhorn nappe is governed by isoclinal folds in the south and a buckled normal sequence of Cretaceous in the north. The isoclinal folds again coincide with a relatively thick Middle Jurassic sequence. Locally these isoclinal folds are also associated with thrust faults and large-scale boudinage (see also Ramsay 1981). The Upper Jurassic limestones of the Wildhorn nappe are very thin and thus probably did not influence the structural style much. The Cretaceous limestones were detached from their Jurassic substratum and hence were not involved in this isoclinal folding north of Prabé. The structure linking the Diablerets and Wildhorn nappes is a thrust fault in the northern part, and a tight isoclinal fold in the south ('synclinal de raccord', see Ramsay 1981, 1989, Dietrich & Casey 1989). The basal Diablerets thrust follows the shaly Middle Jurassic detachment horizon (between Prabé and Schlauchhorn) and then ramps up into the Ultrahelvetic. A cascade of folds in the Cretaceous occurs in the hanging wall of this ramp (see also Masson *et al.* 1980). The structure at the southern end comprises a thick pile of Triassic dolomites and Lower Jurassic marls and limestones pertaining to all three nappes. The southerly dip of this structure is drawn such as to line it up with a band of strong reflections visible in a seismic

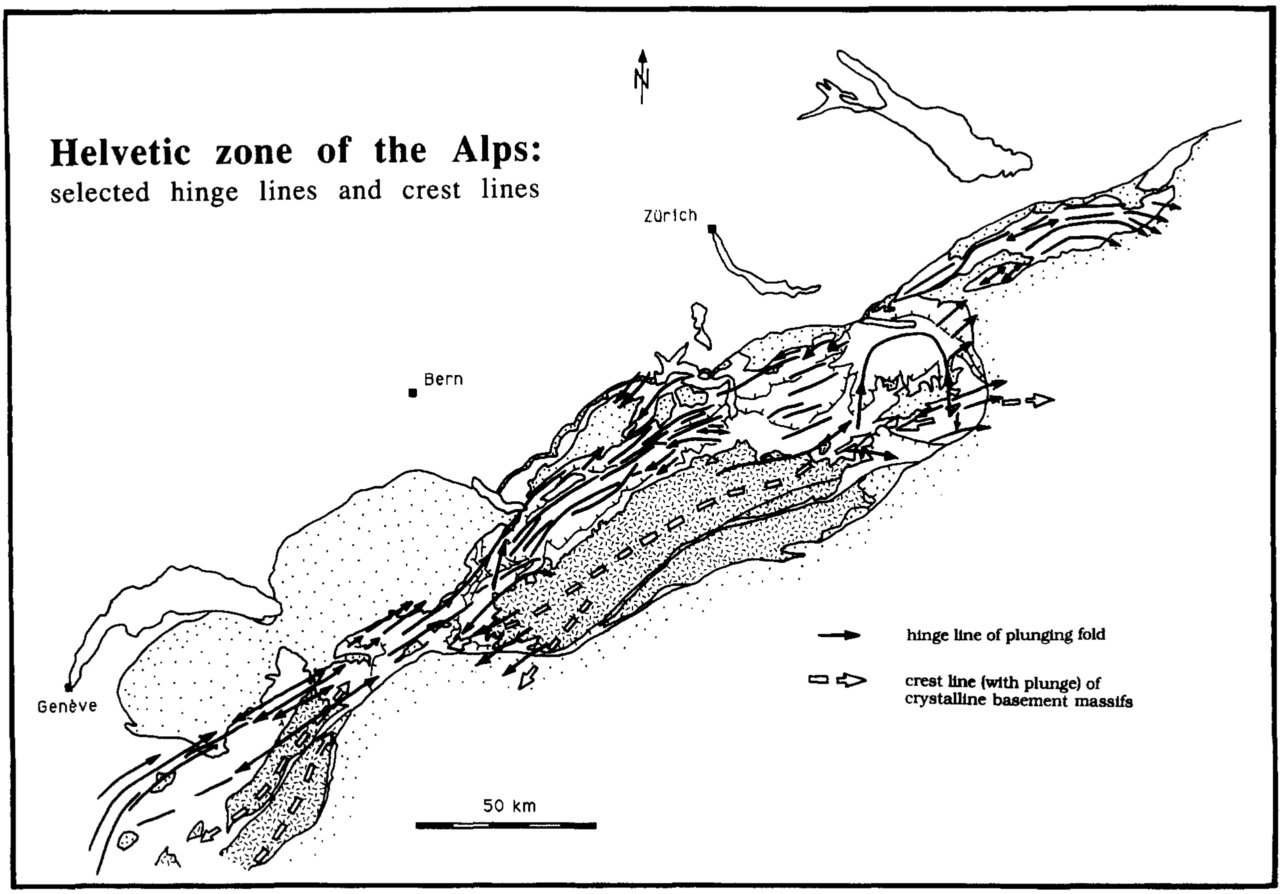


Fig. 4. Map showing the orientations of selected hinge lines of major folds and crest lines of basement uplifts. Note the curved hinge lines and en échelon pattern of crest lines. Tectonic units as in Fig. 1.

section situated in the southern extension of profile E in Fig. 3 (DuBois *et al.* 1990).

The Morcles fold (also called Morcles nappe or fold-nappe in the literature) has been discussed in great detail by Badoux (1972), Ramsay (1981, 1989), Casey & Huggenberger (1985), Dietrich & Casey (1989) and Langenberg *et al.* (1987). Common to the models of these authors is the general structure of a recumbent fold, but the models show differences in thickness of the whole structure due to the difficulty in projecting the different plunges of the two limbs. The geometry given in section E (Fig. 3) corresponds to the one by Langenberg *et al.* (1987) who performed a computer-aided projection along curved lines, but the section was extended southward and northward. One of the peculiarities of the Morcles fold is that a clear thrust can be mapped at its base in the south. Displacement along this Morcles thrust can be estimated at 4.5 km with reference to the top of the Jurassic. However, to the north this thrust fault discontinues and at the interface between the Tertiary strata and the Ultrahelvetic units (which were emplaced in an early stage onto the future Helvetic nappes and Morcles fold) the map pattern can be interpreted in terms of a tight syncline (as in section E, Fig. 3). The geometry of a thrust losing displacement and terminating in the core of a fold resembles the situation of a fault-propagation fold (Suppe & Medwedeff 1990) in which the tip of the propagating fault would be located within the Tertiary.

As is evident from section E in Fig 3 the thickness of the Lower and Middle Jurassic in the core of the Morcles fold greatly exceeds that of the underlying (originally neighbouring) cover of the Aiguilles Rouges massif. This drastic thickness change points to syn-sedimentary faulting associated with Tethyan rifting. As Gillcrist *et al.* (1987) postulated, the Morcles recumbent fold probably represents an 'inverted basin'. This point will be discussed below.

Second-order folding of the mechanically strong Upper Jurassic and Cretaceous limestones in the Morcles fold is seen to be somewhat harmonic in the hinge, becoming more polyharmonic on the normal limb. This change seems to coincide with an increase in thickness of the lowermost Cretaceous marls. The normal fault cutting the Upper Jurassic limestones at exactly that location might suggest that this thickness increase was associated with syn-sedimentary faulting.

LARGE-SCALE FOLD HINGE LINES

The fold structures discussed in the previous section can be traced along strike over considerable distances (see also Ramsay 1989). Hinge lines of some of the major folds are shown in Fig. 4. It follows from Fig. 4 that several hinge lines are arcuate and parallel to the cut-off point tie lines (Fig. 5). The most prominent arc is in eastern Switzerland (section B in Fig. 3) and it makes

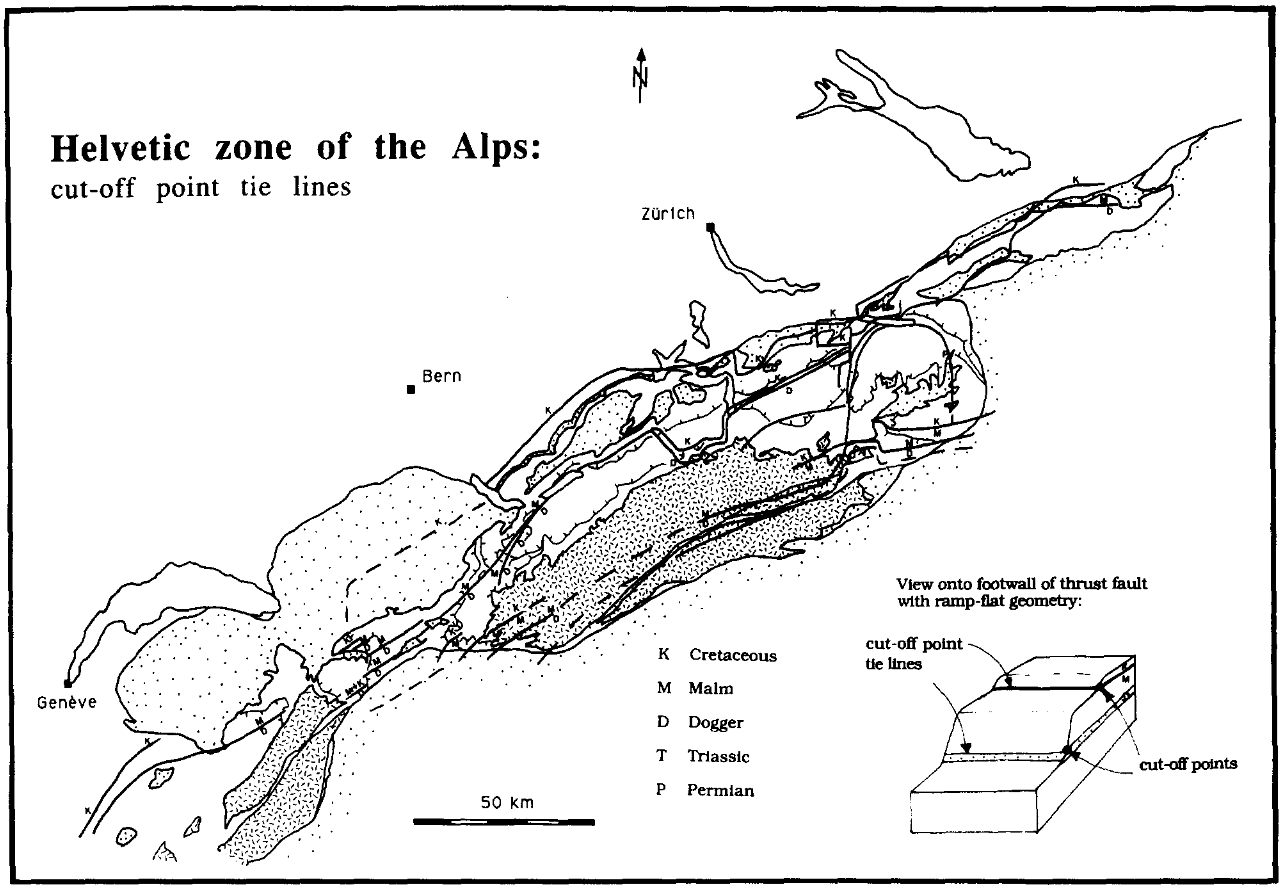


Fig. 5. Map showing orientations of cut-off point tie lines. Note parallelism between these tie lines and the hinge lines of major folds (Fig. 4). Tectonic units as in Fig. 1.

a full 180° turn. This fold arc matches precisely the occurrence of Verrucano in the Lower Glarus nappe complex. The Verrucano forms the core of anticlinal structures closing outward from the center of the fold arc. It is thus concluded that this fold arc is due to the original shape of the Verrucano basin which, upon inversion, was shoved out of the graben in a northerly direction along the steeply dipping eastern and western graben margins.

In a similar way the N-dipping hinge line south-southeast of Bern which turns into an east-northeast direction to the northeast can be explained by the western and northwestern margins of the Middle Jurassic basin. The thick basin infill was thrown into recumbent folds upon inversion (section D in Fig. 3). The location of the eastern end of this basin is at present not known.

The fold arc in the extreme east (section A in Fig. 3) could be interpreted in the same way. Although the arc itself is real, the subsurface geology is ill-constrained and its interpretation as being due to an inverted basin of Early Jurassic age speculative.

As Ramsay (1989) has shown the hinge lines of the (second-order) Morcles folds bend around into a N–S orientation in the Chaînes Subalpines of the Western Alps (south of Genève in Fig. 4). As mentioned above (see section E, Fig. 3) and discussed by Gillcrist *et al.* (1987) the Morcles fold resulted from the inversion of a Lower and Middle Jurassic basin. The hinge lines in Fig. 4 are from the Upper Jurassic and Cretaceous limestones and straddle the western margin of the Lower and Middle Jurassic sediments in the Chaînes Subalpines. Published cross-sections through the Chaînes Subalpines (Epard, 1989, Guellec *et al.* 1990, Huggenberger & Wild 1991) support the explanation that the fold arc reflects the primary shape of the inverted basin.

Figure 4 reveals that axial plunges vary along strike, forming culminations and depressions. A culmination in the Upper Jurassic–Cretaceous stockwerk in eastern Switzerland and Austria is related to the inversion of the underlying basins. In other instances plunges result from deformation within the underlying external massifs. The Aar massif shows opposing plunges at its eastern and western ends, which simply reflects the general geometry of this dome-shaped body (see also the structure contour map in Pfiffner *et al.* 1990b). The northward-plunging hinge line south-southeast of Bern (marking the western margin of the Middle Jurassic basin discussed above) owes its orientation to the fact that this hinge line continues southward, climbing over the basement uplift. In a similar way plunges of the hinge lines of the Morcles folds are related to the Aiguilles Rouges and Mt. Blanc massifs which they cross at a shallow angle (indicated by the crest lines given in Fig. 4).

It will be noted from Fig. 4 that the crest lines of the Aiguilles Rouges–Mt Blanc massifs, on the one hand, and those of the Aar massif on the other hand, are arranged en échelon. This en échelon pattern emerges also for the hinge lines of the Morcles and the Doldenhorn folds and thus precludes the connection of these folds at depth as faintly suspected by Ramsay (1989). Another en échelon pattern can be detected within the Cretaceous level of the Wildhorn–Drusberg–Säntis nappes. If one traces the frontal folds southeast of Bern towards the east one ends up in the folds of the Pilatus mountain near Lucerne (50 km southwest–south-southwest of Zürich) which trend out into the Molasse basin. Folds which are more internal than Pilatus then evolve eastwards to become the frontal folds south of Zürich. The en échelon pattern in both the crest lines of the basement massifs and the hinge lines just discussed points to a component of dextral transpression. Such movements might be related to the anticlockwise rotation of the Adriatic plate (Heller *et al.* 1989) in the course of the Alpine collision.

FOLDING VS THRUSTING

The cross-sections in Fig. 3 reveal that the Helvetic nappes were shortened by imbricate thrusting (sections B and C), buckle folding (section B south) or recumbent folding (sections D and E). These contrasting styles are closely related to the ratios of incompetent to competent layers. In Fig. 2 stratigraphic thickness variations are compiled and from these, thickness ratios, n, of incompetent to competent units are derived. As Ramsay & Huber (1987) point out, this parameter, along with the viscosity ratio, controls the wavelength of folds in a multilayer. For low n-values adjacent layers interfere with each other and lead to harmonic folding. High values on the other hand favor disharmonic or polyharmonic folding. In addition the thickness ratio n is also an important factor controlling the development of thrusts. Woodward & Rutherford (1989) discuss this aspect and conclude that mechanically weak layers act as detachments only if their thickness exceeds a certain critical value. This study suggests that detachments and associated, disharmonic folding necessitate n-values greater than about 0.5 (see Fig. 2). For n-values smaller than 0.5 either harmonic folds develop, or else thrust faults ramp through the weak layer.

The influence of stratigraphic thickness variations on structural style are particularly evident within the Jurassic strata. The Upper Jurassic limestones represent a mechanically strong and thick layer. This layer is made up of micritic limestones which are not particularly well bedded. Strains within it are often accommodated by pressure solution and fracturing (see Burkhard 1986, Dietrich 1989, Pfiffner 1990). The Middle Jurassic strata, on the other hand, are composed of shales at the base followed by interlayered shales and sandstones and capped by thin, well-bedded limestones (Dollfus 1965, Tröhler 1965, Pilloud 1990). These rocks were better suited for folding at outcrop scale and very often exhibit a pervasive axial-planar cleavage. In the example of section D (Fig. 3) the incompetent Middle Jurassic was of sufficient thickness to serve as a detachment horizon and to fill the cores of the large amplitude anticlines in the Upper Jurassic limestones. Limb rotations in the course of basin inversion and subsequent overthrust shear lead to the development of recumbent folds. The close relationship between recumbent folds in the Upper Jurassic stockwerk and anomalously thick Lower or Middle Jurassic strata can be observed throughout the Helvetic nappes. Examples include the Morcles and Wildhorn nappes in transect E, and the Axen nappe in transect D and between transects D and C (Engelberg area). The transition in style associated with progressively lower n-values is particularly well visible in transect B: asymmetric folds in the Lower Glarus nappe complex (north of Ringelspitz) pass northward into imbricate thrust sheets (around Walenstadt).

The Cretaceous is made up of limestone formations interlayered with marly–shaly strata (Funk 1985). The thickness of these marly–shaly formations, including the lowermost Cretaceous detachment horizon (Palfris shales), increases southward towards the external shelf. In the (in a palaeogeographical sense) extreme north, which corresponds to the autochthonous cover of the Aar massif, the whole sequence is calcareous and directly overlying the Upper Jurassic limestones. The structural style here is given by harmonically folded Upper Jurassic and Cretaceous limestones (section B, north of Ringelspitz, and section D) and imbrications (section B, south of Ringelspitz, and section C). Where the thickness ratio, n, of the incompetent Palfris shales to the mechanically strong layers beneath and above reaches about 0.5, polyharmonic folding can be observed. Examples include the Morcles and Diablerets nappes (sections A and E). At still higher values of n, detachment with disharmonic deformation in the hanging wall and footwall is observed (Säntis–Drusberg)–Wildhorn nappe in sections B, C, D and E, Fig. 3).

The Verrucano, present in transect B only, is folded at its contact with the Triassic, but elsewhere it forms a long upright slab unaffected by folding. This might be due to several reasons: (a) the coarse clastic and ill-bedded lower part, which is unsuited for folding; (b) the lateral facies variations of this continental sequence, which makes it the extreme opposite of a multi-layered sequence; and (c) the absence of a basal detachment horizon of any significant thickness. The last point is sustained by the Lochseiten calc-mylonite. This mylonite (see, e.g., Schmid 1975) represents the lubricating layer at the base of the Verrucano. It is derived from limestones that occur in the footwall of the Glarus thrust where it ramps up through the Mesozoic. The limestones were smeared out by the overthrust movement over at least 20 km to a layer of 1–2 m thickness. Similar mylonites accompany other thrust faults.

The development of such lubricating layers can be explained by tectonic erosion of a footwall ramp in the course of the passage of a mechanically strong layer. The relatively smooth shape of the majority of the thrust faults in the Helvetic nappes (see Fig. 3) suggests that tectonic erosion and ductile shearing substantially modified the initial geometry (see also the cross-sections in figs. 5, 6 and 7 in Pfiffner 1978). Stair-case geometries, such as preserved in the Southern Alps (Doglioni 1990), the Rocky Mountains (e.g. Price 1981) or the Appalachians (Milici 1975) are rather the exception than the rule in the case of the Helvetic zone of the Alps. However, imbrications of the type observed in transects B (Cretaceous stockwerk in the Säntis area, the Upper Jurassic near Walenstadt), C (the Upper Jurassic stockwerk in the Infrahelvetic complex, the Cretaceous in the Axen nappe) and D (cover of the Aiguilles Rouges massif), suggest that for low n-values thrust faults originally did develop in a ramp–flat fashion. In addition, the parallelism between cut-off point tie lines and hinge lines of major folds (cf. Figs. 4 and 5) supports a link between thrust-fault geometry and folds. An example of a fault-bend fold resulting from this process is discussed in Pfiffner (1981). Dietrich & Casey (1989) put forward a model of overthrust shear to explain the geometric shapes of the Morcles, Diablerets and Wildhorn nappes in transect E. In this model pervasive distributed shear takes up thrust displacement in the internal part of the nappes. Many of the internal folds originated possibly from oblique shear according to Casey & Huggenberger (1985). Nevertheless the Morcles thrust loses displacement northwards. The distributed shear taking up this displacement manifests itself by the folded surface of the basal Ultrahelvetic thrust. In this sense the Morcles fold nappe can be interpreted as a fault-propagation fold substantially overprinted by ductile overthrust shearing.

CONCLUSIONS

The interplay between folding and thrusting in the Helvetic nappes is seen to be largely controlled by thickness variations of the mechanically strong and weak layers. In particular the ratio n of the thickness of the mechanically weak layers acting as detachment horizons to the thickness of the overlying strong layers is of importance. A low ratio favours harmonic folding and/or imbricate thrusting. Ratios of around 0.5 lead to polyharmonic folding, and ratios greater than 0.5 to disharmonic deformation, buckle or detachment folding of the competent layers, and detachment of the upper part of the multilayer.

In the Helvetic zone primary thickness variations due to local basin subsidence influenced the present structure. Basin inversions led to the formation of fold arcs, controlled by the basin geometry, and to important axial plunges. Although folds due to ramps in thrust faults exist, many of the thrust faults at present exhibit relatively smooth surfaces due to tectonic erosion, and pervasive strains associated with overthrust shear modified the folds substantially.

The Cretaceous stockwerk can be traced as an almost coherent thrust sheet along the entire fold-and-thrust belt. In central and eastern Switzerland it is entirely detached from its Jurassic substratum, as opposed to the situation in western Switzerland and Austria. Also the front of the Jurassic stockwerk reaches progressively farther north going eastward. Its obliquity with regard to the strike of the basement massifs suggests an overall increase in displacement along the basal thrust of the Helvetic nappes going east. This, combined with the observed large-scale en échelon arrangement of the hinge lines within the Cretaceous stockwerk might be associated with the anticlockwise rotation of the Adriatic plate, which was pushing and overriding the Helvetic nappes.

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REFERENCES

Badoux, H. 1972. Tectonique de la nappe de Morcles entre Rhône et Lizerne. *Matér. Carte Géol. Suisse, 27.*

Breitschmid, A. 1982. Diagenese und schwache Metamorphose in den sedimentären Abfolgen der Zentralschweizer Alpen (Vierwaldstättersee, Urirotstock). *Eclog. geol. Helv.* **75**, 331–380.

Burkhard, M. 1986. Déformation des calcaires de l'Helvétique de la Suisse occidentale (Phénomènes, mécanismes et interprétations tectoniques). *Rév. Géol. dyn. géogr. phys.* **27**, 281–301.

Burkhard, M. 1988. L'Helvétique de la bordure occidentale du massif de l'Aar (évolution tectonique et métamorphique). *Eclog. geol. Helv.* **81**, 63–114.

Casey, M. & Huggenberger, P. 1985. Numerical modelling of finite-amplitude similar folds developing under general deformation histories. *J. Struct. Geol.* **7**, 103–114.

Coward, M. & Dietrich, D. 1989. Alpine tectonics—an overview. In: *Alpine Tectonics* (edited by Coward, M. P., Dietrich, D. & Park, R. G.). *Spec. Publs geol. Soc. Lond.* **45**, 1–29.

Dietrich, D. 1989. Fold-axis parallel extension in an arcuate fold-and-thrust belt: the case of the Helvetic nappes. *Tectonophysics* **170**, 183–212.

Dietrich, D. & Casey, M. 1989. A new tectonic model for the Helvetic nappes. In: *Alpine Tectonics* (edited by Coward, M. P., Deitrich, D. & Park, R. G.). *Spec. Publs geol. Soc. Lond.* **45**, 47–63.

Doglioni, C. 1990. Anatomy of an overthrust. *Annales Tectonicae* **4**, 68–82.

Dollfus, S. 1965. Ueber den Helvetischen Dogger zwischen Linth und Rhein. *Eclog. geol. Helv.* **58**, 453–554.

DuBois, L., Levato, L., Besnard, J., Marchant, R., Olivier, R., Ouwehand, M., Sellami, S. & Wagner, J. J. 1990. Aspects particuliers du traitement sismique des profils alpins suisses du PNR-20. In: *Deep structure of the Alps* (edited by Roure, F., Heitzmann, P. & Polino, R.). *Mém. Soc. géol. Fr.* **156**, 47–54.

Epard, J.-L. 1989. Stratigraphie du Trias et du Lias dauphinois entre Belledonne, Aiguilles Rouges et Mont Blanc. *Bull. Géol. Lausanne.* 304.

Frey, F. 1965. *Geologie der östlichen Claridenkette.* Vjschr. natf. Ges., Zürich.

Frey, M., Teichmüller, M., Teichmüller, R., Mullis, J., Künzi, B., Breitschmid, A., Gruner, U. & Schwizer, B. 1980. Very low-grade metamorphism in external parts of the Central Alps: illite crystallinity, coal rank and fluid inclusion data. *Eclog. geol. Helv.* **73**, 173–203.

Funk, H. P. 1985. Mesozoische Subsidenzgeschichte im Helvetischen Schelf der Ostschweiz. *Eclog. geol. Helv.* **78**, 249–272.

Funk, H. P., Labhard, T., Milnes, A. G., Pfiffner, O. A., Schaltegger, U., Schindler, C., Schmid, S. M. & Trümpy, R. 1983. Bericht über die Jubiläumsexkursion "Mechanismus der Gebirgsbildung" der Schweizerischen Geologischen Gesellschaft in das ost- und zentralschweizerische Helvetikum und in das nördliche Aarmassiv vom 12. bis 17. September 1982. *Eclog. geol. Helv.* **76**, 91–123.

Funk, H. P., Oberhänsli, R., Pfiffner, A., Schmid, S. & Wildi, W. 1987. The evolution of the northern margin of Tethys in eastern Switzerland. *Episodes* **10**, 102–106.

Gillcrist, R., Coward, M. & Mugnier, J. -L. 1987. Structural inversion and its controls: examples from the Alpine foreland and the French Alps. *Geodinamica Acta* **1**, 5–34.

Groshong, R. H., Pfiffner, O. A. & Pringle, L. R. 1984. Strain partitioning in the Helvetic thrust belt of E Switzerland from the leading edge to the internal zone. *J. Struct. Geol.* **6**, 5–18.

Guellec, St., Mugnier, J.-L., Tardy, M. & Roure, F. 1990. Neogene evolution of the western Alpine foreland in the light of ECORS data and balanced cross-section. In: *Deep Structure of the Alps* (edited by Roure, F., Heitzmann, P. & Polino, R.). *Mém. Soc. géol. Fr.* **156**, 165–184.

Günzler-Seiffert, H. 1944. Ueber den Mechanismus einiger liegender Falten. *Eclog. geol. Helv.* **37**, 433–437.

Heller, F., Lowrie, W. & Hirt, A. M. 1989. A review of paleomagnetic and magnetic anisotropy results from the Alps. In: *Alpine Tectonics* (edited by Coward, M. P., Dietrich, D. & Park, R. G.). *Spec. Publs geol. Soc. Lond.* **45**, 399–420.

Huggenberger, P. & Wildi, W. 1991. La tectonique du massif des Bornes (Chaînes Subalpines, Haute-Savoie, France). *Eclog. geol. Helv.* **84**, 125–149.

Langenberg, W., Charlesworth, H. & La Rivière, A. 1987. Computer-constructed cross-sections of the Morcles nappe. *Eclog. geol. Helv.* **80**, 655–667.

Masson, H., Baud, A., Escher, A., Gabus, J. & Marthaler, M. 1980. Compte rendu de l'excursion de la Société Géologique Suisse du 1 au 3 octobre 1979: coupe Préalpes–Helvétique–Pennique en Suisse occidentale. *Eclog. geol. Helv.* **73**, 331–349.

Milici, R. C. 1975. Structural patterns in the southern Appalachians: evidence for a gravity slide mechanism for Alleghenian deformation. *Bull. geol. Soc. Am.* **86**, 1316–1320.

Pfiffner, O. A. 1978. Der Falten- und Kleindeckenbau im Infrahelvetikum der Ostschweiz. *Eclog. geol. Helv.* **71**, 61–84.

Pfiffner, O. A. 1981. Fold-and-thrust tectonics in the Helvetic nappes (E Switzerland). In: *Nappe Tectonics* (edited by McClay, K. R. & Price, N. J.). *Spec. Publs geol. Soc. Lond.* **9**, 319–327.

Pfiffner, O. A. 1986. Evolution of the north alpine foreland basin in the Central Alps. In: *Foreland Basins* (edited by Allen, P. A. & Homewood, P.). *Spec. Publ. Int. Ass. Sedim.* **8**, 219–228.

Pfiffner, O. A. 1990. Kinematics and intrabed-strain in mesoscopically folded limestone layers: examples from the Jura and the Helvetic zone of the Alps. *Eclog. geol. Helv.* **83**, 585–602.

Pfiffner, O. A., Frei, W., Valasek, P., Stäuble, M., Levato, L., DuBois, L., Schmid, S. M. & Smithson, S. B. 1990a. Crustal shortening in the Alpine orogen: results from deep seismic reflection profiling in the eastern Swiss Alps, line NFP 20-EAST. *Tectonics* **9**, 1327–1355.

Pfiffner, O. A., Klaper, E. M., Mayerat, A.-M. & Heitzmann, P. 1990b. Structure of the basement-cover contact in the Swiss Alps. In: *Deep Structure of the Alps* (edited by Roure, F., Heitzmann, P. & Polino, R.). *Mém. Soc. géol. Fr.* **156**, 247–262.

Pilloud, A. 1990. Bau und jurassische präorogene Tektonik der helvetischen Hauptschubmasse im Berner Oberland. Unpublished Ph.D. thesis, University of Bern.

Price, R. A. 1981. The Cordilleran foreland thrust and fold belt in the southern Canadian Rocky Mountains. In: *Thrust and Nappe Tectonics* (edited by McClay, K. R. & Price, N. J.). *Spec. Publs geol. Soc. Lond.* **9**, 427–448.

Ramsay, J. G. 1981. Tectonics of the Helvetic nappes. In: *Thrust and Nappe Tectonics* (edited by McClay, K. R. & Price, N. J.). *Spec. Publs geol. Soc. Lond.* **9**, 293–309.

Ramsay, J. G. 1989. Fold and fault geometry in the western Helvetic nappes of Switzerland and France and its implication for the evolution of the arc of the Western Alps. In: *Alpine Tectonics* (edited by Coward, M. P., Dietrich, D. & Park, R. G.). *Spec. Publs geol. Soc. Lond.* **45**, 33–45.

Ramsay, J. G. & Huber, M. I. 1987. *The Techniques of Modern Structural Geology, Volume 2: Folds and Fractures*. Academic Press, London.

Schmid, S. M. 1975. The Glarus overthrust: Field evidence and mechanical model. *Eclog. geol. Helv.* **68**, 247–280.

Stäuble, M. & Pfiffner, O. A. 1991. Evaluation of the seismic response of basement fold-and-thrust geometry in the Central Alps based on 2-D ray tracing. *Annales Tectonicae* **5**, 3–17.

Suppe, J. & Medwedeff, D. A. 1990. Geometry and kinematics of fault-propagation folding. *Eclog. geol. Helv.* **83**, 409–454.

Tröhler, B. 1965. Geologie der Glockhaus-Gruppe. Mit besonderer Berücksichtigung des Eisenoolithes der Erzegg-Planplatte. *Beitr. Geol. Karte Schweiz, Geotech. Ser.* **XIII**.

Trümpy, R. 1949. Der Lias der Glarner Alpen. *Mitt Geol. Inst. ETH & Univ. Zürich, Serie* C36, *Denkschriften Schweiz. Natf. Ges.* **79**.

von Schumacher, P. 1928. Der geologische Bau der Claridenkette. *Beitr. geol. Karte Schweiz, N.F.* **50/IV**, 1–47.

Woodward, N. B. & Rutherford, E., Jr. 1989. Structural lithic units in external orogenic zones. *Tectonophysics* **158**, 247–267.

Wyssling, G. 1985. Palinspastische Abwicklung der helvetischen Decken von Vorarlberg und Allgäu. *Jb. Geol. B.-A.* **127**, 701–706.