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# Evolution and internal structure of the Helvetic nappes in the Bernese Oberland

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*Key words:* Fold-and-thrust structures, synsedimentary faulting, Helvetic nappes, western Switzerland

ABSTRACT

During the last century, many detailed field studies have been carried out in the Bernese Oberland. Data from these studies were combined with new field data to restore the Axen and the Drusberg nappes in three cross sections. The criteria for validating retrodeformable cross sections were used to extend the limits of interpretation. Results show that synsedimentary normal faults played a key role in the evolution of the nappes. Retrodeforming the nappes suggests that Cretaceous synsedimentary faults within the Drusberg nappe had reactivated Jurassic faults within the Axen nappe. Alpine compression partly reactivated these faults once again but simultaneously developed conjugate reverse faults; subsequent folding and shearing lead to the hitherto enigmatic Bürgle-Sylere structure. The Schilthorn thrust fault was found to be an important out-of-sequence thrust, causing complex nappe internal structures such as the tectonic isolation of individual thrust slices. The Kiental-phase folding of the Schilthorn fault clearly indicates a polyphase deformation history of the Drusberg and the Axen nappes.

ZUSAMMENFASSUNG

Im vergangnenen Jahrhundert ist die lokale Geologie im Berner Oberland in zahlreichen Arbeiten detailiert untersucht worden. Darauf aufbauend und kombiniert mit neuen Felduntersuchungen wurden die Drusberg-Decke und die Axen-Decke in drei Querschnitten abgewickelt. Die Berücksichtigung geometrischer Kriterien für abwickelbare Profile erlaubte dabei eine erhebliche Einschränkung des Interpretationsspielraums in erodierten Deckenteilen. Es stellte sich heraus, dass kretazische synsedimentäre Normalbrüche in der Deckenkinematik eine Schlüsselrolle spielten. Derartige Brüche findet man in der Drusberg-Decke; die Deckenabwicklungen lassen vermuten, dass bei ihrer Entstehung jurassische Normalbrüche in der Unterlage, der heutigen Axen-Decke, reaktiviert wurden. Während der alpinen Kompression wurden diese Brüche teilweise reaktiviert und führten in Kombination mit konjugierten Rückaufschiebungen und anschliessender Faltung und Scherung zu der lokal gut bekannten Bürgle-Sylere Struktur. Die Schilthorn-Überschiebung ist eine bedeutende out-of-sequence Überschiebung und führte zu komplexen deckeninternen Strukturen in Form tektonisch vollständig isolierter Schuppen. Die Verfaltung der Schilthorn-Überschiebung während der Kiental-Deformationsphase zeugt von der mehrphasigen Verformungsgeschichte der Drusberg- und der Axen-Decke.

## Introduction

The Helvetic zone of Central Switzerland and the Bernese Oberland is composed of two nappe complexes separated by a major thrust fault with several tens of kilometers of displacement. This major thrust fault is the basal thrust of the Helvetic nappes proper. The Helvetic nappes are characterized by a complex interplay of folds and faults involving Mesozoic-Cenozoic cover rocks. The Axen nappe (Fig. 1) contains essentially Jurassic sediments and is overlain by the Drusberg nappe, which is built of Cretaceous–Cenozoic strata (Pfiffner 1993). The units in the footwall of the basal thrust of the Helvetic nappes are referred to as Infrahelvetic complex. To the south, this Infrahelvetic complex is a thick-skinned fold-and-thrust belt involving pre-Triassic crystalline basement rocks (Aar massif) and their autochthonous-parautochthonous Mesozoic-Cenozoic cover (e.g. Doldenhorn nappe). Further north, this complex contains allochthonous cover sheets (Subalpine Flysch and Subalpine Molasse).

The sediments of the Helvetic zone were deposited on the European margin of Tethys. In the course of the Alpine orogeny these sediments were thrust and transported to the north and northwest. As a general rule, the paleogeographically southern Helvetic units experienced a larger amount of displacement than the northern ones, which resulted in the development of an antiformal stack on top of the Aar massif in the transect of the Bernese Oberland (Fig. 1). The Doldenhorn nappe contains recumbent folds with a crystalline core forming part of to the Aar massif. Across the Lauterbrunnen Valley to the east, the separation between the Mesozoic cover and the

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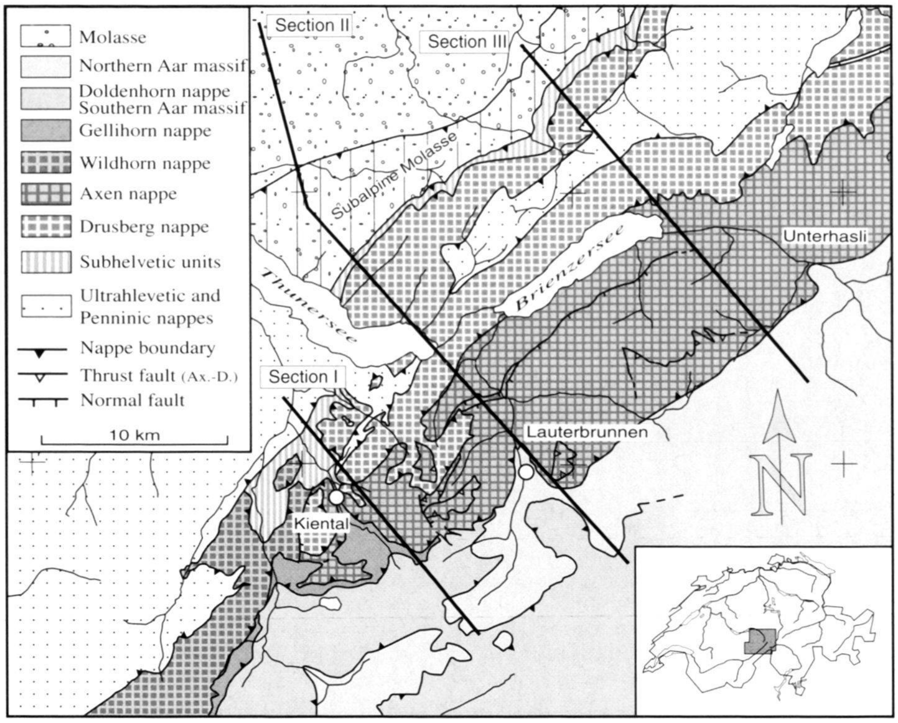


Fig. 1. Tectonic sketch map of the Bernese Oberland. Thick lines are traces of cross sections shown on plate I.

crystalline core diminishes and the Doldenhorn nappe passes into the autochthonous-parautochthonous units typical of the central and eastern Aar massif.

From the Kander Valley to the west, the Gellihorn nappe separates the Wildhorn nappe from the underlying Doldenhorn nappe. To the east, the Gellihorn nappe quickly diminishes in volume along strike until its complete disappearance east of the Kiental Valley.

The Jurassic and Cretaceous parts of the Wildhorn nappe ("stockwerks") exhibit an increasing tectonic independence going east, resulting in the eventual separation into two distinct nappes which can be traced into eastern Switzerland (see also Pfiffner 1993), the Drusberg nappe (Cretaceous stockwerk), and the Axen nappe (Jurassic stockwerk).

The Jurassic stockwerk has been shown to contain a number of tight to nearly isoclinal folds (Arbenz 1922; Günzler-Seiffert 1925; Hänni et al. 1997) cut by numerous tear faults (Pilloud 1990) and low angle reverse faults (Schilthorn, Männlichen).

The Cretaceous stockwerk is disharmonically folded above the Jurassic stockwerk owing to the thick, incompetent Palfris marls separating the two stockwerks (cf. Pfiffner 1993). As will be shown later the two stockwerks experienced a displacement of up to 10 km by bedding parallel thrusting on this detachment horizon.

The Helvetic nappes are overlain by Ultrahelvetic and Penninic units of a more internal origin, which outcrop as erosional relics or "klippen" (Fig. 1).

As a rough estimate, about half of the net volume of the Helvetic nappes is missing in the Bernese Oberland owing to erosion. In order to completely reconstruct the eroded and subsurface parts of the nappes, results of former investigations had to be puzzled together. Fieldwork focussed on the upper parts of the Helvetic nappes, which are particularly important for the tectonic interpretation of the eroded part of the nappes. Three balanced sections were constructed along with their restored counterparts.

The aim of this paper is to analyse the importance of synsedimentary extensional structures for section retrodeformation and to discuss their effect on the evolution of nappe internal structures in subsequent Alpine compression.

## 2. Cross sections

### 2.1. *Construction method*

Three digitized sections across the study area were balanced and retrodeformed using suitable computer software such as Geosec 4.0. Despite these powerful tools, section balancing and retrodeformation requires a lot of iterative work by hand. Inevitably, the reconstruction of eroded structures and subsurface extrapolation demands a certain amount of interpretation. However, section balancing allows testing of a profile's geometrical correctness by comparing volumes and line-lengths before and after deformation. In addition, a retrodeformable cross section not only has to be geometrically correct but it also has to be kinematically plausible. Only the contradiction-

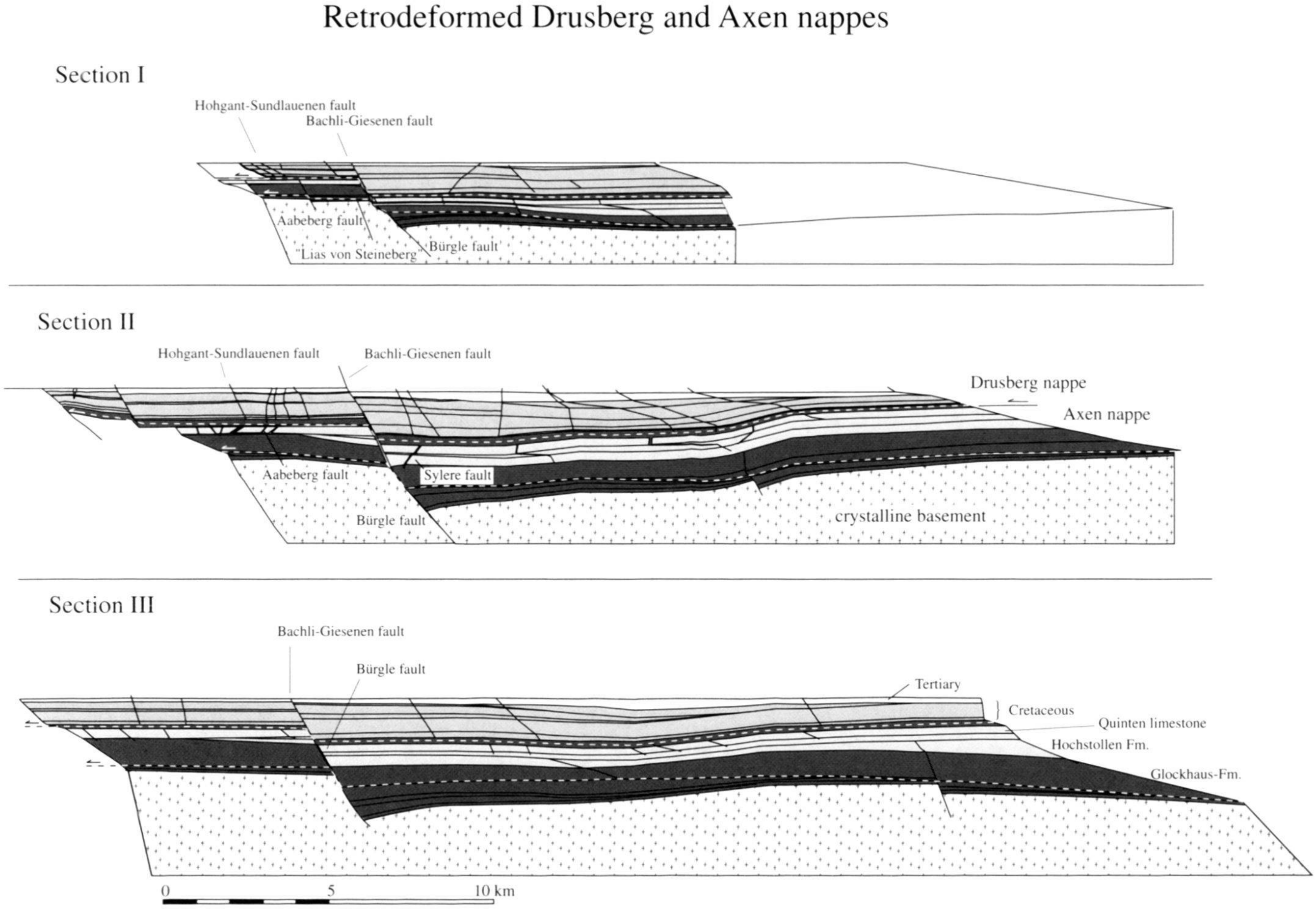


Fig. 2. Volume and line-length balanced restoration of the sections shown on plate I. The Axen and Drusberg nappes have been independently retrodeformed and correlated using the Bachli-Giesenen fault as a common feature. White dotted lines indicate the future basal thrusts of the nappes. Note the location of the "Lias von Steineberg" in section I and the vicinity of the Hohgant-Sundlauenen and the Aabeberg fault in section II.

less return of a cross section to its undeformed state can guarantee a viable interpretation. Finally the cross sections were checked for consistency with the structural style observed in this segment of the Alpine orogen.

The sections were constructed using a field map at the scale of 1:25 000 and numerous literature sources (see below). In addition, the results of the NRP 20 research project (Pfiffner et al. 1997) were used to constrain the Helvetic nappes within a large-scale tectonic framework. Each section exhibits certain features that affect the construction and interpretation of the neighbouring section. Therefore, the 3D structural geometry with its lateral changes has to be taken into account to achieve mutual consistency amongst the cross sections. The retrodeformed sections (Fig. 2) show the initial state of the Drusberg and Axen nappes before deformation. In section II, the Drusberg and Axen nappes are entirely line-length and volume balanced. In sections I and III, these nappes are entirely volume balanced and line-length balanced with respect to the stratigraphic tops of the Glockhaus-Fm., Quinten limestone, Kieselkalk-Fm. and Schrattenkalk-Fm. For completeness Triassic and lower Jurassic beds were added to the retrodeformed section although the volumes of these strata are not accessible to direct observation. The Molasse in section II is drawn after Schlunegger et al. (1993) using heavy mineral boundaries as stratigraphic markers.

### 2.2. *Section I (plate I)*

This easternmost section runs SSE along the right-hand side of the Kiental Valley (Fig. 1). The map by Krebs (1925), and the work by Liechti (1930), Zwahlen (1986) and Schürch (1991) supplied valuable information for this section. The unbalanced geometry shown for the Doldenhorn nappe reflects

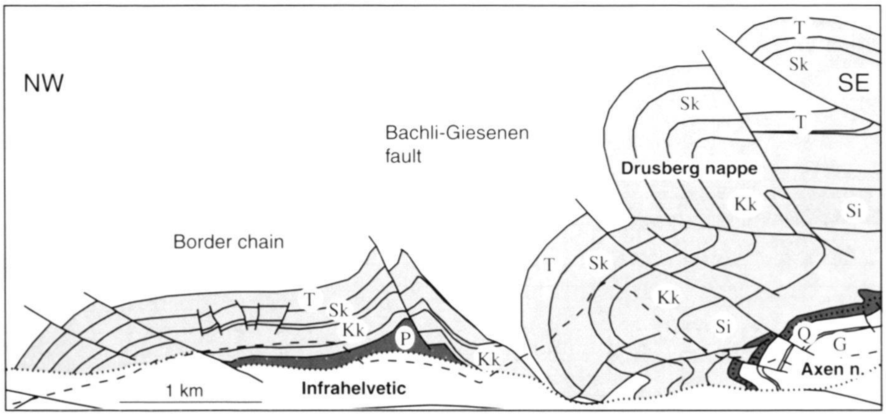


Fig. 3a. Enlargement of section I, showing the present-day geometry of the Bachli-Giesenen growth fault (Kiental valley). T: Tertiary Sk: Schrattenkalk-Fm. Kk: Kieselkalk-Fm. Si: Sichel/Diphyoides limestone. P: Palfris-Fm. Q: Quinten limestone. G: Glockhaus-Fm. For location see plate I.

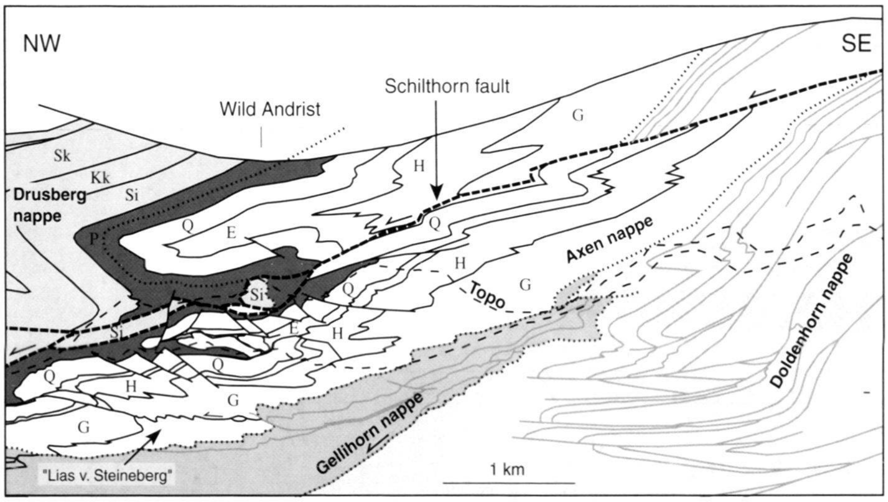


Fig. 3b. Enlargement of section I, showing the internal structure of the Axen and Drusberg nappes. The Schilthorn fault (dotted line) offsets the hangingwall for about 2.5 km and isolates Sichel limestone at Wild Andrist. Note the small lens of Upper Jurassic at the roof thrust of the Lower Jurassic "Lias von Steineberg". Sk: Schrattenkalk-Fm. Kk: Kieselkalk-Fm. Si: Sichel/Diphyoides limestone. P: Palfris-Fm. Q: Quinten limestone. E: Erzegg-Fm. H: Hochstollen-Fm. G: Glockhaus-Fm. For location see plate I.

new fieldwork that was partly carried out together with Jenni (1999).

Important lateral changes in nappe structure occur on either side of section I. To the SW of the section, a lower unit ("Bundstock element", Zwahlen 1986) underlies the Wildhorn nappe and consists of lower Jurassic to Teritary sediments that indicate a more northerly origin for this unit. Along strike toward the east, the Gellihorn nappe wedges out and the Doldenhorn nappe loses its nappe character, grading into imbricate thrusting within the Aar massif and its core (Infrahelvetic compex). In section I, the more internal part of the Axen nappe rests on the Doldenhorn nappe and was overprinted owing to shortening of the latter (Kiental phase, Günzler-Seiffert 1941b), whereas further east the Axen nappe rests on the Intrahelvetic thrust sheets. Despite the differences in the footwall, individual folds within the Axen nappe are generally quite continuous and can be traced along strike for distances of 10 km and more.

As mentioned by Liechti (1930), the northern part of the Drusberg nappe ("Border Chain") is separated from its southern counterpart by the Bachli-Giesenen fault. This Mesozoic growth fault runs parallel to strike and outcrops in the Kiental Valley. On its southern hanging wall block, the strata end discordantly on the horizontal basal thrust fault of the Drusberg nappe, indicating a rotated hanging wall ramp (Fig. 3a). This point will be discussed in more detail in section 4.

The southern part of the Axen nappe is cut by the relatively young, gently dipping Schilthorn fault that causes a displacement of the hanging wall of some 2.5 km to the northwest (Fig. 3b). This fault, which was probably caused by early shortening of the Doldenhorn nappe, cuts across the Axen nappe and merges into the Drusberg thrust, thereby increasing the displacement of the latter.

Tectonically higher Ultrahelvetic and Penninic units of more internal origin are locally wrapped beneath the basal Helvetic thrust (Zwahlen 1993). The same is true for the "Kiental Flysch" ("KF" in section I), a tectonic mélange at the base of the Penninic Niesen nappe. These findings point to out-of-sequence thrusting (i.e. younger, more external thrusts cut older thrusts of more internal origin).

*2.3. Section II (plate I)*

The section line links the two wells Linden-1 and Thun-1 in a straight line trending 345° and continues at 317° after a kink at Thun-1.

It is based on our own field data, maps by Günzler-Seiffert (1933, 1938), Collet & Paréjas (1928, 1931), Beck (1910), Haldemann et al. (1980) and work by Pilloud (1990), Goldschmid (1926), Günzler-Seiffert & Wyss (1938), and Herb (1980).

Owing to the wells Linden-1 (Maurer et al. 1978), Thun-1 (Micholet 1992), seismic lines (Vollmayr 1992) and sedimentological investigations (Schlunegger et al. 1993; Diem 1986), the structure of the Subalpine Molasse is quite well-known for this section. The youngest sediments in the footwall of the Hilfern thrust, the early Aquitanian Gitzischöpf Conglomerate (Schlunegger et al. 1996), indicate that the Hilfern thrust did not reach the present-day surface before about 23 Ma. The Blueme thrust is drawn with a complete hanging wall to illustrate the total thrust displacement. Supposedly, the front of the Blueme thrust sheet was being eroded during its emplacement by thrusting. The youngest sediments in the footwall of the Blueme thrust sheet (15 Ma) pertain to the very diachronous Gunten Quartzite Conglomerate of the Plateau Molasse. Shortening of the Subalpine Molasse is estimated to be at least 19 – 20 km. In cross section II (plate I), this amount of shortening is shown to be compensated by imbrications on the northern flank of the allochthonous Aar massif. This solution was chosen because it is difficult to merge the thrust displacements from the Aar massif into the Triassic detachment horizon beneath the Molasse Basin. On the other hand, the sedimentary cover of the Aar massif is hardly detached from the basement in the Lauterbrunnen Valley. However, there remains the question where to take the additional 12 km (Laubscher 1965, Burkhard 1990) of shortening which are required for the Jura mountains, a subject that is still under debate (Burkhard 1999). We favour the idea of a detachment horizon that starts with relatively little displacement near the Aar massif. The hangingwall of the detachment fault is thought to be stiffened by thick Molasse sediments such that any increase in displacement along the detachment requires the footwall to be shortened (e.g. by partial inversion of Permo-Carboniferous grabens).

Projection errors are minimal for the northern part of the Drusberg nappe ("Border Chain"). The Bachli-Giesenen fault below Lake Thun and the southern eroded part of the Drusberg nappe are projected into the section plane from the west. The Bürgle and Sylere faults are located precisely on the section line. In this section, the Gellihorn nappe is absent and the Axen nappe rests directly on the Infrahelvetic complex. Compared to section I, the volume of middle Jurassic sediments is considerably larger. Unlike the interpretation by Louis (1924), the southern part of the Axen nappe (Männlichen) is cut by a relatively young fault corresponding to the Schilthorn fault. Before joining the basal thrust of the Drusberg nappe, this fault causes an imbrication of upper Jurasic limestones and is folded by a later deformation event (see section 7 and Fig. 6). The exact geometry of the southernmost nappe parts (below "Lütschine") is uncertain. Normal faults on the inverse limb of the Middle Jurassic anticline are projected from the east (Menkveld 1995).

Within the Doldenhorn nappe, apart from the nappe-like "digitation supérieure" (Collet & Paréjas 1931), the sediments are not detached from their crystalline basement. As a result, the structures within the Doldenhorn nappe in section II can be traced into the folded basement-cover contact of the parautochthonous Aar massif. This is an important difference compared to section I, where thick incompetent lower to middle Jurassic marls form the core of the Doldenhorn nappe and acted as a detachment horizon.

*2.4. Section III (plate I)*

Section III establishes a structural link between the two sides of the Unterhasli Valley. Because of the easterly dip of the fold axes, information about tectonically lower parts must be taken from the west, whereas higher parts are projected from the east. The section line runs from the subalpine Molasse to the crystalline basement in a 139° direction (Fig. 1). Unpublished maps were at our disposal for profile construction (sheet Brienz, sheet Innertkirchen, Dräyer 1999). For the Drusberg nappe we considered the work by Schider (1912) Michel (1921), Jost-Stauffer (1993) and Staeger (1944), for the Axen nappe Günzler-Seiffert (1925, 1934a, 1938, 1952), Günzler-Seiffert & Müller (1934), Günzler-Seiffert & Wyss (1938), Staeger (1944), Dr. von Moos (1978), Kellerhals & Häfeli (1983), Pilloud (1990), Rowan (1993), Menkveld (1995) and Hänni et al. (1997). Finally the deep part of the section relies on seismic data (Pfiffner et al. 1997). According to latest mapping by Schwizer (sheet Brienz, oral commun.), the second Quinten limestone above km 174 in the cross section ("Quinten limestone 5a" according to Günzler-Seiffert 1925) is overturned. This new finding greatly improves the structural coherence across the Unterhasli Valley. The structure of the Infrahelvetic complex is drawn according to Furrer (1949), Haldemann et al. (1980), Scabell (1926) and Kammer (1989).

In the southern part of the Axen nappe, the upper Jurassic Quinten limestone is detached from the middle Jurassic, forming a stockwerk of its own within the Axen nappe ("Malm-stockwerk der Axen-Decke", Menkveld 1995). Analogous to section I and II, the internal part of the Axen nappe is cut by a gently dipping fault that can be traced to the west (Fig. 1) and which is therefore considered to be identical with the Schilthorn fault. In section III this fault runs close above the topographic surface (to the north of "Rosenlaui" in section III).

Large parts of the Drusberg nappe are hidden in the subsurface and the correct geometry is difficult to assess (Jost-Stauffer 1993; Michel 1921). As a consequence, there is a certain leeway in the interpretation of the Drusberg nappe. In the

Infrahelvetic complex of section III between Rosenlaui and Urbachsattel, a tectonic slice with large offset occurs along the basal Helvetic thrust (Läsistock-Schuppe; Scabell 1926).

## 3. The Axen and the Drusberg nappes

The Wildhorn nappe of the Wildhorn area, located 25 km to the west of the study area, consists of a Jurassic and a Cretaceous-Tertiary stockwerk. Going east, two nappes individualize: the Axen nappe containing the Jurassic beds and the Drusberg nappe containing the Cretaceous and Tertiary sediments. As discussed by Pfiffner (1993), this change in structural style is controlled by the mechanical stratigraphy at which incompetent shales of the Palfris-Fm. played an important role as a stratiform detachment horizon. The lateral emergence of these two nappes is rather continuous, which makes it difficult to fix the eastern limit of the Wildhorn nappe. On the tectonic map of Fig. 1, the eastern limit of the Wildhorn nappe is chosen to follow the Bachli-Giesenen (Kandertal) fault. This interpretation is favoured because the synsedimentary fault causes an abrupt lateral increase in Cretaceous sediment thickness toward the east and therefore an important change in structural style (Zwahlen 1986). Stratigraphically, the Drusberg nappe represents the Cretaceous cover of the Jurassic Axen sediments.

### *3.1. The Axen nappe*

The Axen nappe contains a sedimentary sequence from lower Jurassic to Berriasian. The shales of the lower Aalenian Mols-Fm. occur along the basal thrust and are restricted to the southernmost part of the Axen nappe. Their volume is difficult to assess owing to erosion. The main volume of middle Jurassic sediments consists of sandy limestones of the Glockhaus-Fm. The Bajocian (Hochstollen-Fm.) is made up of alternating marls and limestones and increases in thickness toward the south. Bathonian and Callovian marls (Erzegg-Fm.) together with the Oxfordian marls (Schilt-Fm.) form the incompetent footwall of the Quinten limestone (Kimmeridgian-Tithonian), a thick massive limestone sequence. The roof thrust of the Axen nappe follows the Berriasian Palfris-Fm. and is identical with the floor thrust of the Drusberg nappe.

Many structures within the Axen nappe change their appearance quite quickly and it is often difficult to trace them laterally over large distances. The competent Quinten limestone is an important structural marker horizon and easily recognizable in the field. The thickness. of incompetent marls above and below the Quinten limestone generally increases toward the south and east, which leads to enhanced folding of the Quinten limestone within its incompetent host rock. A drastic increase in thickness of the incompetent middle Jurassic leads to disharmonic folding between the Quinten limestone and the Hochstollen-Fm. in the southern part of the Axen nappe from section III to the east (Menkveld 1995; Hänni et al. 1997). The Callovian-Oxfordian marls, which reach their maximum thickness to the east of the Unterhasli Valley, thereby play an important role as detachment horizon. Within the Axen nappe, the middle Jurassic Glockhaus-Fm. in particular exhibits significant lateral thickness changes across the Unterhasli valley. This variation in thickness is held to be responsible for the development of distinctly different structures that are not easily correlated from one side of the valley to the other.

As shown in Fig. 2, the basal thrust of the Axen nappe forms a flat at the base of the Glockhaus-Fm., stepping over synsedimentary faults (e.g. Bürgle fault). To the north, the basal thrust forms a ramp through the entire Mesozoic sequence. This ramp may well correspond to a major synsedimentary fault initiated in Early Jurassic times, separating the "Alemanic high" (Trümpy 1952) from a subsiding basin. This high was approximately located at the site of the future Aar massif. The sedimentary cover of the northern part of the Aar massif is mainly composed of carbonates and lacks shaly units of sufficient thickness to act as a detachment horizon, with the result that this sedimentary sequence has remained attached to its crystalline basement. A noteable exception occurs at the western end of the Aar massif. Here, a basin of Early and Middle Jurassic age accumulated shales interlayered with limestones and sandstones which now form the Doldenhorn nappe.

### *3.2. The Drusberg nappe*

The Drusberg nappe contains the lower Cretaceous and Teritary sediments, detached along the shales and marls of the Berriasian Palfris-Fm. The lower Cretaceous sediments up to the Barremian consist of platform carbonates. Younger Cretaceous units (Garschella-, Seewer-, Amden- and Wang-Fm.) only occur in the SE part of the nappe where they have escaped pre-Eocene erosion.

The part of the Drusberg nappe to the north of the synsedimentary Bachli-Giesenen fault is also called the "Randkette" or Border Chain. As a morphotectonic unit, the Border Chain is a relatively coherent rigid plate compared to the rest of the Drusberg nappe. This can be explained by the relative lack of incompetent units separating the competent ones in the Border Chain. In contrast, within the southern Drusberg nappe carbonates are interlayered with marls and here the nappe internal structure is characterized by folds.

There is a kinematic relationship between the Axen and Drusberg nappes because of their simultaneous shortening and transport. As a general rule, thrust faults from the Axen nappe join the basal thrust of the Drusberg nappe, increasing the displacement of the Drusberg nappe relative to the Axen nappe.

## 4. The Bachli-Giesenen fault

The Bachli-Giesenen fault separates the Border Chain from the southern part of the Drusberg nappe. In detail, it is a complex fault system rather than one single fault (Zwahlen 1986). It is well exposed in the Kiental Valley, where the strata of the

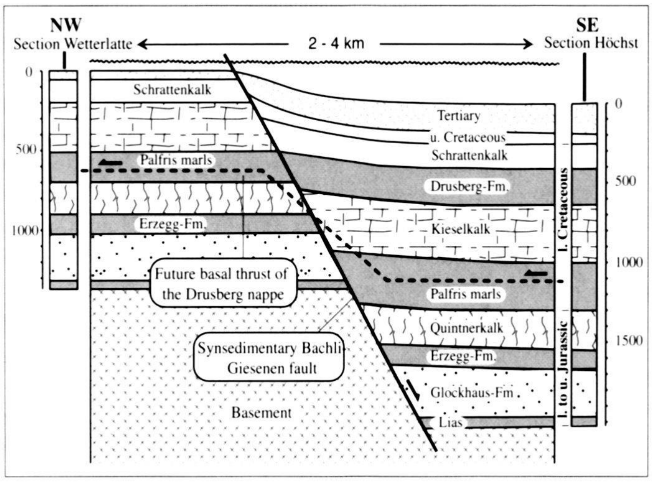


Fig. 4. Schematic section across the Bachli-Giesenen growth fault before Alpine overprint. To the south of the fault, the thickness of the stratigraphic sequence is increased by at least 640m. The upper Cretaceous and the Drusberg-Fm. are missing from the northern block. The future basal thrust of the Drusberg nappe, indicated by the dashed line, must form a ramp to overcome the offset of the Berriasian Palfris marls. Incompetent units are shown in grey shading.

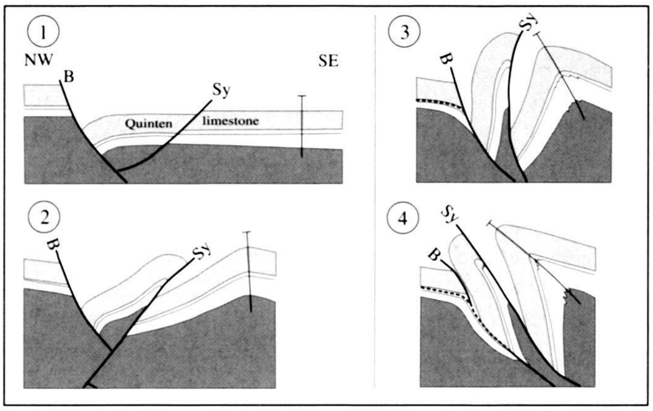


Fig. 5. Sketch of the kinematic evolution of the Bürgle-Sylere structure. The initial geometry is given by two synsedimentary faults: the Bürgle fault and the smaller, probably conjugate Sylere fault. In the course of Alpine shortening, the competent Quinten limestone (light grey) between the two faults is squeezed and rotated into its present-day position. The Sylere fault was inverted as a thrust fault and rotated into parallelism with the Bürgle fault. The Bürgle fault itself was not or only partly reactivated as a thrust fault.

southern Drusberg nappe end discordantly against a subhorizontal, gently dipping thrust surface (section I, plate I). The southern end of the Border Chain is bounded by a normal fault that rejoins this thrust surface. The northern part of the Drusberg nappe south of the Bachli-Giesenen fault shows a ramp anticline, where steeply dipping and even overturned strata abut the gently dipping Drusberg thrust. The restored geometry of this structure is shown in Fig. 4. The future (Drusberg) thrust fault formed a ramp at the site of the former growth fault. Juxtaposition of the two flats led to the formation of a fault-bend anticline in the southern block and opened a V-shaped space between the Tertiary strata of the two blocks. This means that there is a structural discontinuity between the Border Chain and the southern part of the Drusberg nappe and, as Liechti (1930) pointed out, there exists no synclinal link between the two. Comparing the sediments on each side of the Bachli-Giesenen fault, there is strong evidence for a synsedimentary origin of this fault.

The total increase in sediment thickness caused by the Bachli-Giesenen growth fault is about 640 meters. To judge from facies differences in the Tertiary, the total vertical displacement along this fault had to be even larger. The displacement on the Bachli-Giesenen fault is therefore far larger than the displacement on any other synsedimentary fault reported from the Drusberg nappe (e.g. Liechti 1930; Colombi 1960). The Bachli-Giesenen fault is a feature common to both the Axen and the Drusberg nappe an therefore can be used to fix the initial relative position of the two nappes. Considering the large displacement along the Bachli-Giesenen fault, its continuation within the Axen nappe must have had a comparable offset (see sections 5 and 6).

## 5. The Bürgle and Sylere faults

The Bürgle and Sylere faults are two well-known faults in the Axen nappe (Stauffer 1920; Goldschmid 1926; Staender 1943; Günzler-Seiffert 1933, 1934b, 1941a, 1944; Herb 1980; Pilloud 1990; Rowan & Kligfield 1992; Rowan 1993). They both run parallel to strike, with the Bürgle fault being the one further to the north (Fig. 5). The two faults cross the lower Lauterbrunnen Valley, where they form two spectacular, steeply south dipping normal faults. A hook-shaped piece of Quinten limestone is clamped between the two faults. Until now, two contradictory theories about the evolution of this structure have been proposed. Pilloud (1990) considered both faults to be initially parallel synsedimentary faults with approximately equal displacements, which have been passively folded during nappe shortening. In contrast, Rowan (1993) interpreted the structure to have evolved from two south vergent backthrusts that subsequently rotated into their current subvertical orientation due to a large amount of simple shear that affected the Axen nappe as a whole. Neither explanation is in accord with our field data and we suggest an alternative kinematic scenario in the following section (see Fig. 5).

As discussed in section 4, the Bachli-Giesenen fault was a synsedimentary normal fault with a vertical displacement of at least 640 m, affecting the Cretaceous and Tertiary strata of the Drusberg and the Jurassic strata of the Axen nappe (Fig. 4). We consider the Bürgle fault to be the continuation of the Bachli-Giesenen fault in the Axen nappe. Synsedimentary activity of the Bürgle fault during the middle Jurassic was postulated by Günzler-Seiffert (1941a) and the present-day geometry of the Bürgle fault is readily explained as a reactivated normal fault. It is plausible that the Bürgle fault was initiated during lower Jurassic rifting and was thereafter repeatedly active up into the Tertiary as a so-called "persistent fault" (Günzler-Seiffert 1941a). The restored lengths of the top of the Quinten limestone and top of the Glockhaus-Fm. reveal the original geometry of the two faults, suggesting the Sylere fault may be interpreted as a smaller, conjugate fault to the Bürgle fault (Fig. 2, section II, and Fig 5). The Sylere fault was subsequently inverted as a south vergent backthrust and then rotated into its present orientation. To explain the rotation, we consider the Quinten limestone as a competent and discontinuous single layer embedded in less competent middle Jurassic and lower Cretaceous marls. We envisage a passive rotation under subhorizontal compression of the competent Quinten limestone together with the Sylere fault. During this movement, the Bürgle fault was not or only partly inverted. We find that the simple shear model postulated by Rowan & Kligfield (1992) does not explain the parallelism of the two faults.

## 6. The relative position of the retrodeformed Drusberg and Axen nappes

In a first step, the Drusberg and the Axen nappes were independently retrodeformed along the three cross sections. In a second step, the retrodeformed nappes were positioned relative to each other in a way that the Bachli-Giesenen fault of the Drusberg nappe and the Bürgle fault of the Axen nappe merge into one single fault (Fig. 2). This correlation is consistent with NW-directed thrusting along the Drusberg thrust, as indicated by field observations. In addition, the vertical displacement of the Bachli-Giesenen fault of at least 640 m is in accordance with the displacement along the Bürgle fault of about 700 m. The reconstruction shown in Fig. 2 displays the synsedimentary normal faults as running down into the pre-Triassic crystalline basement. This is in analogy with eastern Switzerland were equivalent faults are associated with synfault breccias containing components of Triassic dolomites (Trümpy 1952). The retrodeformed section (Fig. 2) also answers an old local problem concerning the origin of the "Lias von Steineberg" (Fig. 3b). These lower Jurassic strata are in tectonic contact with their middle Jurassic hangingwall, as is evident from the occurrence of a lens of upper Jurassic limestone between the lower and middle Jurassic strata (Künzi 1975). The lower Jurassic strata have therefore been taken to form an independent tectonic element by Zwahlen (1993). A much simpler explanation is offered by the retrodeformed section of Fig. 2: The synsedimentary Bachli-Giesenen fault juxtaposed the "Lias von Steineberg" and the upper Jurassic (Quinten) limestone of the southern block. Subsequent reactivation plucked off a piece of Quinten limestone and brought middle Jurassic strata on top of lower Jurassic strata.

Another interesting feature of the retrodeformed section is the resulting proximity of the Hohgant-Sundlauenen fault, which is a synsedimentary normal fault in the northern part of the Drusberg nappe, and the Aabeberg fault of the Axen nappe. A synsedimentary origin of the Aabeberg fault was postulated by Günzler-Seiffert (1941a). Within the errors of our quantitative retrodeformation, it can be suggested that the Aabeberg fault was the continuation of the Hohgant-Sundlauenen fault. This possibility is supported by recent findings of speleologists (Häuselmann, oral commun.), which suggest that the synsedimentary displacement of the Hohgant-Sundlauenen fault is significantly larger than the 50 to 100 m proposed by Colombi (1960). In this case, the Hohgant-Sundlauenen fault should have a continuation within the Axen nappe, which we consider to be the Aabeberg fault.

## 7. The Schilthorn thrust fault

The Schilthorn thrust (Figs. 3b and 6) is a relatively gently dipping thrust fault in the southern part of the Axen nappe with a thrust displacement of about 2.5 km. The type locality of this thrust (Schilthorn) is located between sections I and II. Slices of Quinten limestone mark the thrust surface and indicate the repetition of thick Middle Jurassic Glockhaus limestones (the cableway station "Birg" stands on such a Quinten limestone slice). The deep-water facies of the middle Jurassic in the hangingwall of the thrust underlines its southerly origin (Pilloud 1990). This southerly, internal facies led Günzler-Seiffert (1934a) to the opinion that the upper block was derived from the Ultrahelvetic realm. Pilloud (1990) called this block the "Schilthorn element of the Axen nappe" to emphasize its tectonic independence from the underlying Axen nappe. The thrust concept outlined by Rowan (1993) is worked out and displayed in the cross sections (Figures 3b and plate I).

In section I of plate I the Schilthorn thrust cuts across the middle and upper Jurassic and finally merges into the Palfris marls, contributing to a further displacement of the Drusberg nappe. The piece of Sichelkalk that forms today's Wild Andrist (in section I) was plucked off from the base of the Drusberg nappe and was then overridden by the Drusberg nappe during motion on the Schilthorn thrust. The solution presented in section II (plate I) brings together field information from both sides of the Lauterbrunnen Valley. The Schilthorn thrust is shown to cut a recumbent syncline consisting mainly of middle Jurassic sediments and produces a repetition of the Quinten limestone on the normal limb of the syncline. As shown in Fig. 6, the repeated Quinten limestone was subsequently folded, indicating a later compressive deformation phase. The Schilthorn thrust cannot be traced continuously from section II towards the NE. Nevertheless, we can find a very similar thrust fault in section III (plate I), which runs closely above the surface from "Rosenlaui" to the north.

The Schilthorn thrust cuts the basal thrust of the Axen nappe as an out-of-sequence thrust (Fig. 3b). It probably originates from the southern part of the Doldenhorn nappe and was folded during the main shortening phase of the Doldenhorn nappe (Kiental phase, see below).

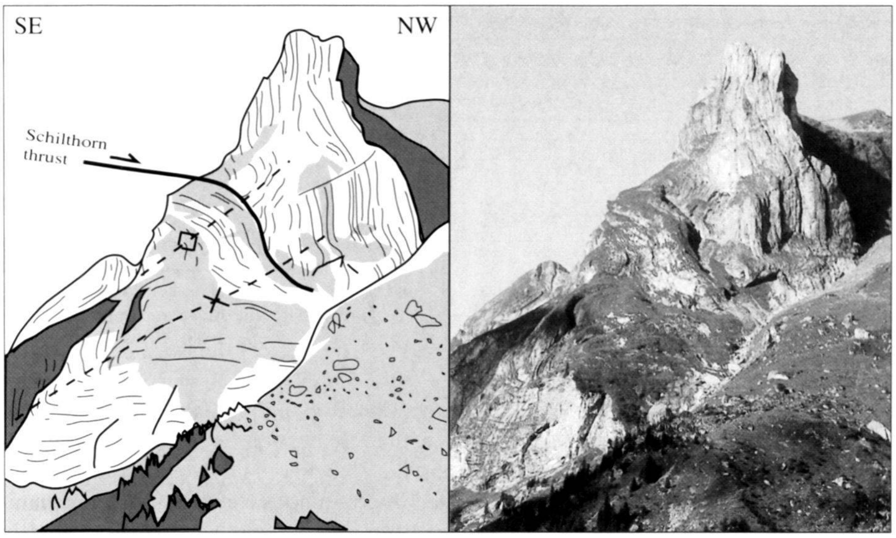


Fig. 6. At the Spaltenhorn (Saustal) the Quinten limestone is repeated by the Schilthorn fault, a fault cutting across earlier formed folds. The later folding of this thrust fault in the Saustal illustrates the multi-phase deformation of the Axen nappe.

**8. The deformation sequence**

The deformation sequence in the Helvetic nappes and the Aar massif can be compared with a foreland propagating fold and thrust system, where new thrust faults form more externally than the preceding ones. Superposing of individual deformation events led to features like foliations, folds and folded thrust faults, which have been used for definition and relative dating of several defomation phases.

(1) The Plaine Morte phase (Burkhard 1988) describes the emplacement of highly allochthonous thin sheets of sediments from the more internal and southerly, Ultrahelvetic domain onto the future Helvetic nappes.

(2) The Prabé phase (Burkhard 1988) designates the shortening and main transport phase of the Wildhorn nappe. During this event, the basal (Plaine Morte phase) thrust of the Ultrahelvetic units was folded.

(3) The basal thrusts of the Axen/Wildhorn and Gellihorn nappes were overprinted by later events. Depending on the locality, these events can be subdivided in up to three individual deformation phases.

(i) The Trubelstock phase (Burkhard 1988) is the earliest, but it is restricted to the western Aar massif and seems to be of rather local character. The out-of-sequence Schilthorn thrust, which was folded by subsequent Kiental phase folding, must have formed in a deformation phase similar to the Trubelstock phase, although there is no direct structural link to the locality where the Trubelstock phase is defined.

(ii) The Kiental phase (Günzler-Seiffert 1941b) is defined by the emplacement of the Doldenhorn nappe, overprinting the earlier thrust faults. In section I, which runs through the locality where the Kiental phase is defined, continuous axial planes indicate that the basal thrust of the Gellihorn nappe was folded during the Kiental phase shortening of the Doldenhorn nappe.

(iii) The Grindelwald phase (Günzler-Seiffert 1941b) is defined by tilting of the basal thrust of the Axen nappe into a subvertical position, best visible in sections II and III. In section I and to the west of it, large scale bending of the Kiental phase axial surfaces in the Doldenhorn nappe is ascribed to the Grindelwald phase (Burkhard 1988).

One major problem when trying to correlate deformation phases from different regions is their regionally limited validity. As discussed by Pfiffner et al. (1997), the Plaine Morte phase can be correlated to the Pizol phase in eastern Switzerland, and the Prabé phase to the Calanda phase, but the Kiental phase, for instance, is by definition bound to the Doldenhorn nappe. To the east of the Lauterbrunnen valley, where the Doldenhorn nappe no longer exists, Kiental phase structures cannot be identified. In a similar way, the Grindelwald phase cannot easily be correlated into eastern Switzerland (Pfiffner et al. 1997).

We try to defuse this situation by relating the locally defined deformation phases to three superordinate, orogen-scale deformation events (Table 1). These are:

1. Emplacement of southern tectonic units on top of the future Helvetic nappes. In the Bernese Oberland this event is described by the Plaine Morte phase, in eastern Switzerland it is defined as the Pizol phase (Pfiffner 1977, 1978, Milnes & Pfiffner 1977).
2. Shortening of the Helvetic nappes and their transport onto the region of the future Aar massif. This event is described by the Prabé phase for the Bernese Oberland and by the Cavistrau and a part of the Calanda phase for eastern Switzerland (Pfiffner et al. 1997).
3. Shortening and uplift of the Aar massif. For the Bernese Oberland, the Grindelwald and the Kiental phases are attributed to this event. In fact, the Doldenhorn nappe pos-

| Deformation events / Region | Emplacement of southern units | Shortening and transport of the Helvetic nappes onto the future Aar massif | Continued transport of the Helvetic nappes and shortening of the Aar massif |
|---|---|---|---|
| | → relative sequence of events | | |
| Eastern end of the Aar massif | Pizol | Cavistrau, Calanda | Calanda, Ruchi |
| Haslital-Lauterbrunnen | Plaine Morte | Prabé | Grindelwald |
| Western end of the Aar massif | Plaine Morte | Prabé | Trubelstock, Kiental, Grindelwald |

Table 1. Local deformation phases can not easily be correlated over large distances along strike of the orogen, although the orogenic processes related to these phases are well comparable.

sesses a crystalline core (the southern Aar massif) from which the sediments are more or less detached. The formation of the recumbent folds and thrust faults within the Doldenhorn nappe are Kiental phase structures. The deformation resistant Gastern granite, situated to the north of the Doldenhorn nappe's crystalline core, was overridden by the Doldenhorn nappe. Its late upwarp bent the overlying structures and tilted the basal thrusts of the Helvetic nappes, which is attributed to the Grindelwald phase. In eastern Switzerland, deformation of the Aar massif is attributed to the Calanda phase, which – in absolute time - was later in the Infrahelvetic complex compared to the overlying Helvetic nappes. Transport of the Helvetic nappes continued during shortening of the Aar massif as is evident from the relation between penetrative foliations above and beneath the basal thrust of the Helvetic nappes. The last phase of transport of the Helvetic nappes is correlated to the Ruchi phase.

In contrast to eastern Switzerland, where transport along the basal thrust of the Helvetic nappes continued during the shortening of the Aar massif, the Grindelwald phase shortening of the western Aar massif led to enhanced rotation of the basal Helvetic thrust, making any further transport along this thrust impossible (Pfiffner et al. 1997). This continued shortening of the Aar massif during the Grindelwald phase points to a late phase of deformation restricted to the western Aar massif, which might be linked to shortening and folding of the Jura Mountains.

## 9. Conclusions

Respecting the rules for retrodeformable cross sections greatly reduces the interpretational leeway. It permits the construction of a plausible structure for the Drusberg and the Axen nappe. Although there is still some interpretation required, the cross sections unveil new connections by putting old problems into a larger scale context.

Synsedimentary normal faults that were active during the Cretaceous and Tertiary leave their mark also in the older sediments and can therefore be used to determine the initial position of the Drusberg nappe relative to the Axen nappe. The retrodeformed sections show that the Bürgle fault must be considered as the continuation of the Bachli-Giesenen fault. It turned out that a similar connection between the Hohgant-Sundlauenen fault and the Aabeberg fault is plausible. Synsedimentary faults caused discontinuous changes in the mechanical stratigraphy within the nappes. In places, this resulted in unusual structures, such as the Bürgle and Sylere faults. In general, synsedimentary normal faults were passively folded rather than reactivated as reverse faults during nappe compression.

The Schilthorn thrust offsets the base of the Axen nappe by some 2.5 km as an important out-of-sequence thrust. It probably extends beyond the Haslital valley to the east. The Schilthorn thrust crosscuts the deformed Axen nappe and is itself folded. The deformation of the Axen nappe is therefore the result of several superimposed deformation events. Deformation phases defined by local overprinting relationships have the disadvantage that they can not be traced over great distances. This problem can partly be overcome by relating local deformation phases to larger scale deformation events such as, for example, the formation of the Aar massif dome.

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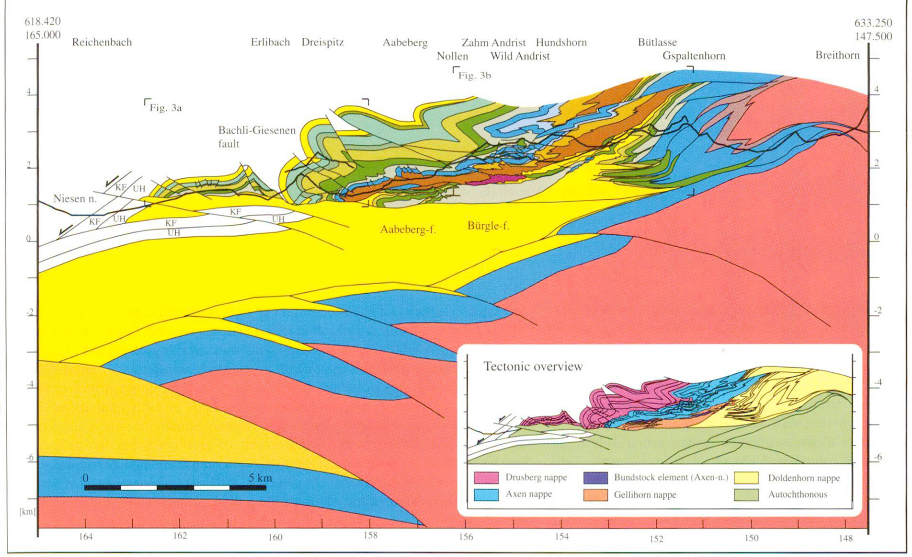
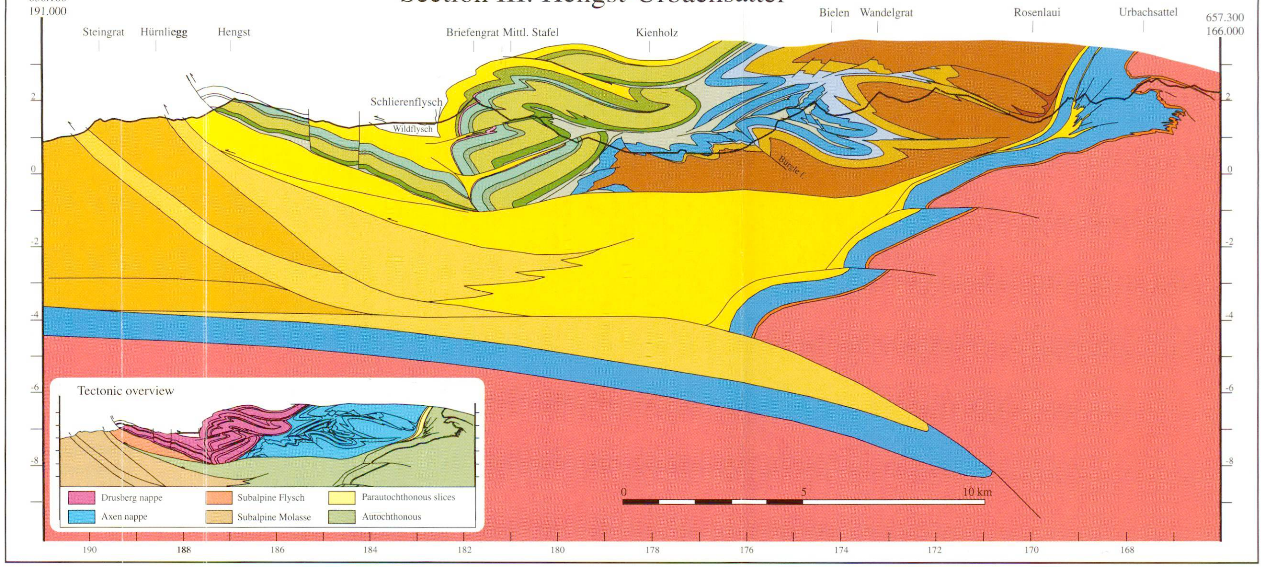
## Section I: Reichenbach-Breithorn




## Section III: Hengst-Urbachsattel




## Section II Linden-Jungfraujoch