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The Helvetic nappe system and landscape evolution of the Kander valley

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Summary of presentation and excursion guide given at the VSP/ASP annual convention, Interlaken, Switzerland, June 2009

1. Introduction

The steep flanks of the Kander valley and its tributary valleys offer a true three-dimensional view of the structure of the Helvetic nappe system. Recent geophysical investigations in the framework of NRP20 (Pfiffner et al., 1997) and the construction of the NEAT Lötschberg base tunnel (Frei & Pfiffner, 1990, Kellerhals & Isler, 1998) have expanded this view to the subsurface. Not only the thrust faults responsible for the nappe stack, but also the internal structure of the nappes are beautifully exposed in the valley flanks. Besides that, it is possible to study geomorphic features like the Kandersteg rockfall and the deeply incised Alpine valleys overdeepened by the Pleistocene glaciers, features that had a profound impact on settlement in the valley and construction of deep-seated tunnels.

2. Structure of the Helvetic nappe system

The Helvetic nappe system consist of far travelled thrust sheets, the Helvetic nappes, on one hand, and the Infrahelvetic complex, a highly deformed parautochthonous complex involving also crystalline basement rocks on the other hand.

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The Helvetic nappes comprise allochthonous sediments displaced along a basal thrust fault over distances of several tens of kilometers. The basal thrust changes in character and name along the strike of the nappe system. In the Kander valley (see Fig. 1) there is the Gellihorn thrust and the overlying Axen thrust on the eastern and the Wildhorn thrust on the western flank.

The Helvetic nappes are further subdivided into individual nappes by thrust faults with displacements of varying importance. One important thrust fault separates the mainly Cretaceous sediments from their Jurassic substratum. From the Kander valley to the east this is the Drusberg thrust and in eastern Switzerland the Säntis thrust. But west of the Kander valley, in the Wildhorn nappe, the separation between Cretaceous and Jurassic is less pronounced. Numerous thrust faults with small displacements may be recognized within the nappes and were used to define local thrust sheets and imbricates (Schuppen).

The Infrahelvetic complex encompasses all units beneath the basal thrust of the Helvetic nappes. It consists of pre-Triassic crystalline basement rocks and their autochthonous Mesozoic and Cenozoic sedimentary cover. The crystalline basement rocks form large-scale upwarps that are referred to as external massifs. In the Kander valley area (see Fig. 1) this includes the Aar massif with its Gastern submassif.

The cover rocks are highly deformed in

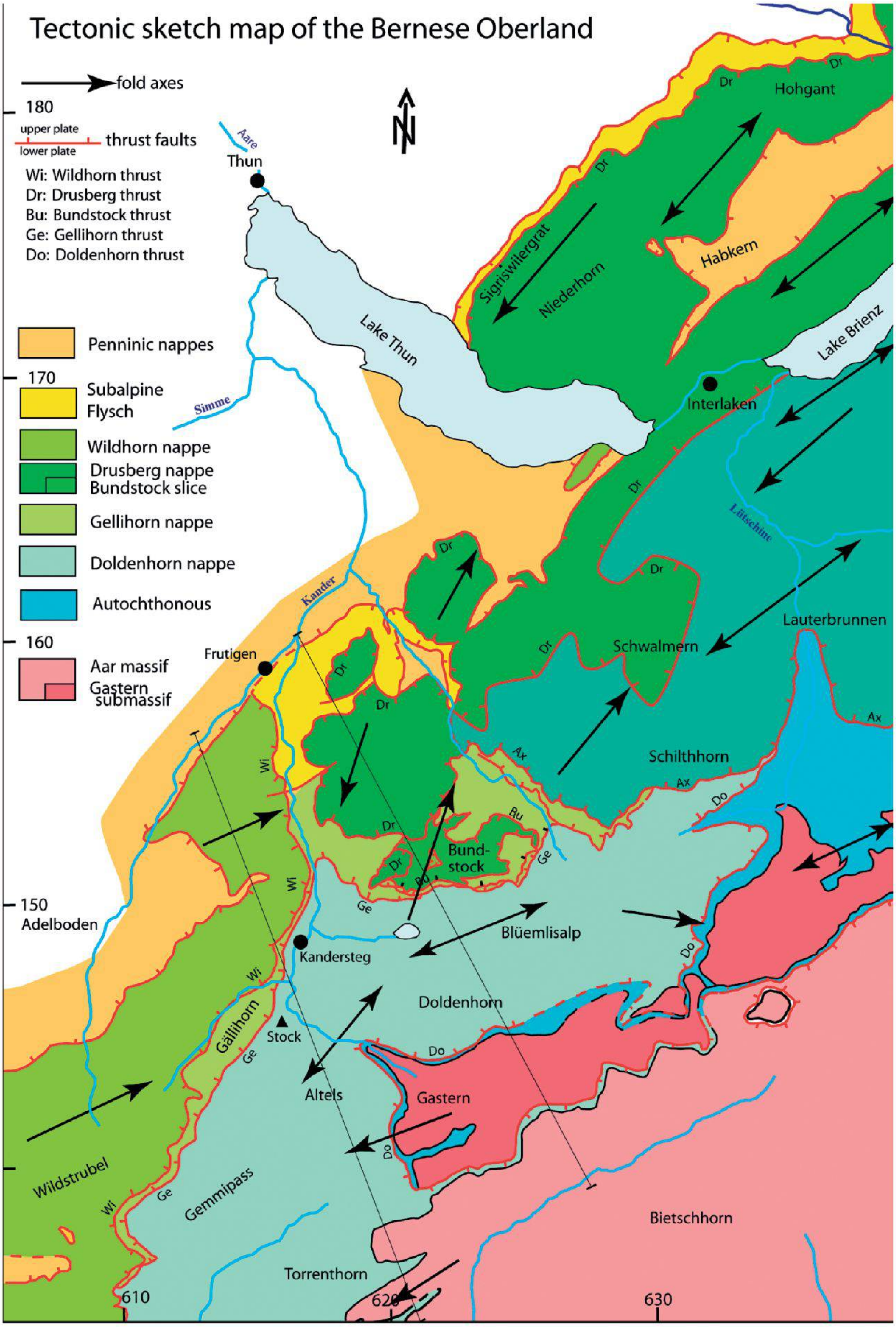

Fig. 1: Tectonic sketch map of the Bernese Oberland. Fold axes form an arc in the Doldenhorn nappe. In addition they show a discontinuity between the Axen-Drusberg and the Wildhorn nappe across the Kander valley between Kandersteg and Frutigen. Thin lines are traces of cross sections shown in Fig. 2.

many instances. Slices dislocated by thrust faults are referred to as parautochthonous. In the case of the Doldenhorn nappe (Fig. 1), displacement amounted to a few kilometers. Locally highly allochthonous units with displacements of tens of kilometers occur beneath the basal thrust of the Helvetic nappes. These units were initially deposited in the southernmost part of the Helvetic realm and are therefore referred to as South Helvetic and Ultrahelvetic units.

The map in Fig. 1 also shows the orientations of large-scale fold axes. In case of the Axen and Drusberg nappes the fold axes display an arcuate shape changing from a ENE-WSW to a NNE-SSW orientation. This fold arc is possibly due to an inverted basin. The Middle Jurassic sequences of the Axen nappe are approx. 2 km thick, whereas in the Wildhorn nappe this thickness amounts to only approx. 200 m. An abrupt lateral thickness change across a system of synsedimentary normal faults followed by inversion upon thrust faulting could explain the observed trend of the fold axes. Another fold arc is visible within the Doldenhorn nappe. This too, might be explained by inversion of the thick Early and Middle Jurassic strata deposited in a small basin at the SW end of the Aar massif.

The structural style in the various nappes is controlled by the mechanical properties of the Mesozoic strata. Of particular importance are the Cementstone beds and the Palfris Shale of Berriasian-Valanginian age that form a mechanically weak layer between the thick Late Jurassic and Early Cretaceous carbonates. In the Doldenhorn nappe, only relatively thin Cementstone beds are present such that the Late Jurassic and Early Cretaceous limestones are folded harmonically (Fig. 2). In contrast, the thick Palfris Shale in the Drusberg nappe allowed the detachment of the Cretaceous stockwerk and an inde-

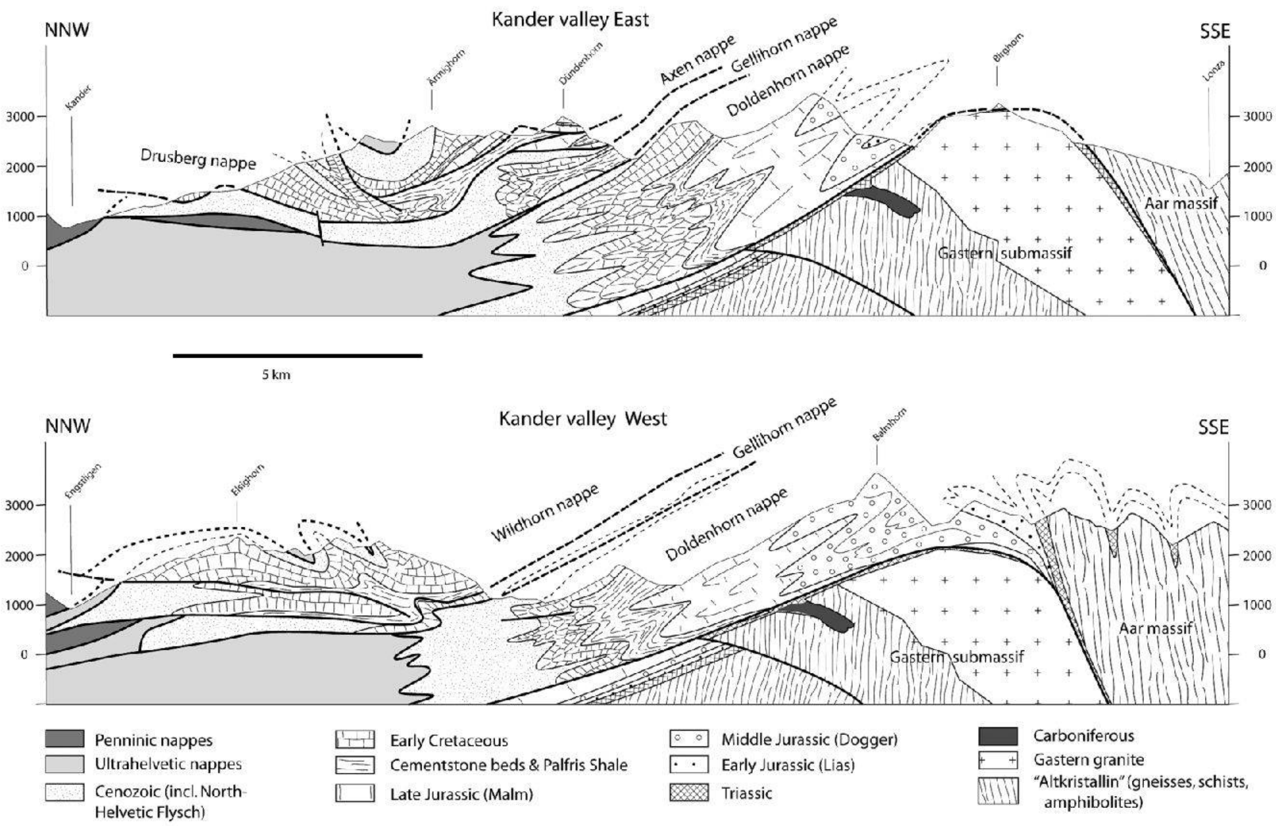

Fig. 2: Geological profiles across the Helvetic nappe system east and west of the Kander valley. Traces are given in Fig. 1. Whereas the Doldenhorn nappe and the underlying basement uplifts show a similar structure, the Doldenhorn nappe is much more voluminous on the eastern side and the structures within the Axen-Drusberg and the Wildhorn nappes are entirely different.

pendent internal deformation of the Jurassic and Cretaceous (Fig. 2). Fig. 3 is a photograph showing the style of folding within the Doldenhorn nappe. While the Jurassic and Cretacous limestones form relatively simple folds, the thin limestone beds within a marly succession of the Cementstone beds are intricately folded at a smaller scale.

Deposition of the Late Jurassic and Early Cretaceous carbonates occurred on a subsiding shelf. Abrupt thickness changes are observed within the Axen and Drusberg nappes (Hänni & Pfiffner 2001) and point to synsedimentary normal faults active from the Jurassic on into the Cretaceous. Within the Early Cretaceous of the Doldenhorn nappe, in situ brecciation and slumping occurred in the Helvetic Kieselkalk formation (Fig. 4). These features may tentatively be interpreted as being caused by extensional tectonics on this passive margin.

An important change in structural style occurs across the Kander valley. This change is best illustrated by two cross sections running parallel on either side of the valley (Fig. 2). In case of the Doldenhorn nappe, the internal structure is characterized by plunging anticlines and doesn't change across the valley. The Gellihorn nappe on the other hand is present as a thin

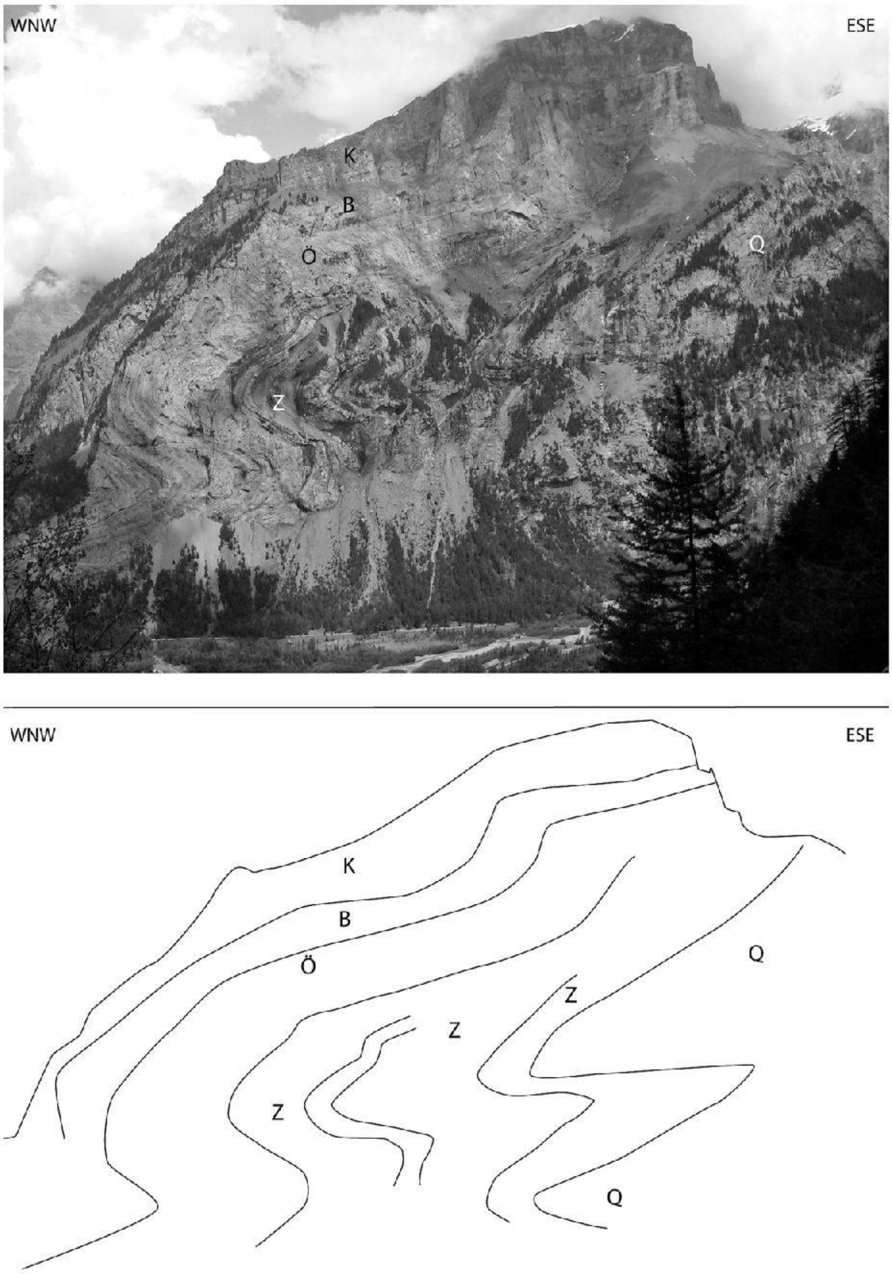

Fig. 3: Folds of the Doldenhorn nappe on the NNE flank of Gastern valley. Small scale folding in the Cementstone beds allow some disharmony between the folds in the Late Jurassic (Quinten Limestone) and Early Cretaceous carbonates. K: Helvetic Kieselkalk formation, B: Betlis Limestone, Ö: Öhrli Limestone, Z: Cementstone beds, Q: Quinten Limestone.

sheet of essentially Cretaceous limestones on the western side, whereas on the eastern side a plunging anticline (probably a fault bend fold) involving Cretaceous to Cenozoic strata is observed. The differences in structure are even more obvious when comparing the isoclinal folds in the Jurassic of the Axen nappe and the Drusberg nappes on one hand with the imbricate thrusting of the Cretaceous within the Wildhorn nappe on the other hand.

The cross sections in Fig. 2 also highlight the curved axial surfaces of the folds within the Doldenhorn nappe. The plunging anticlines in the north are wrapped around the rigid block of the Gastern submassif. They become recumbent folds on top of this basement block and then upright folds in the Aar massif. The crystalline basement rocks of the Aar massif there are tightly folded as indicated by the pinched in synclines of Triassic strata.

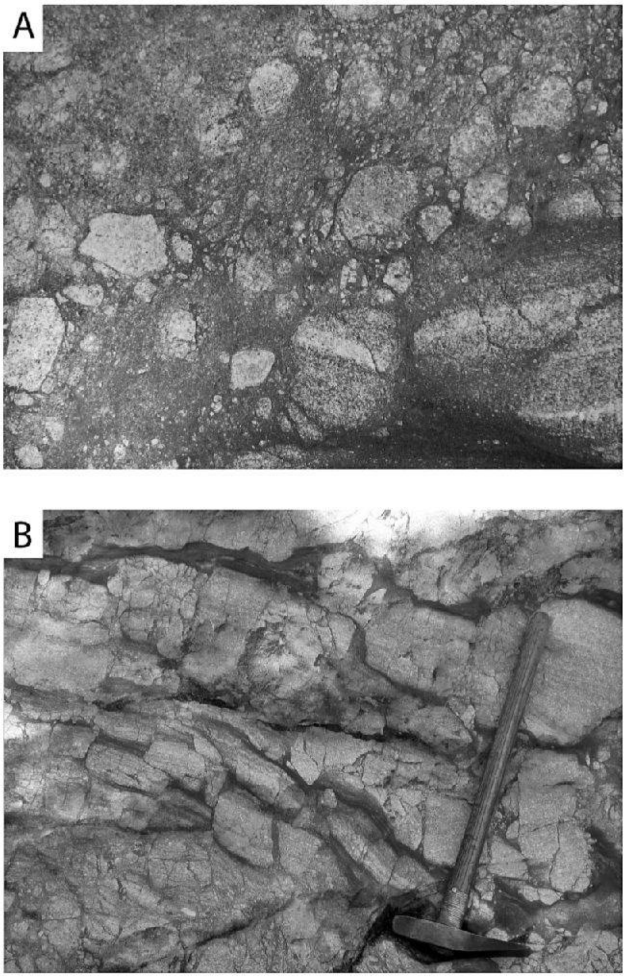

Fig. 4: Brecciation of siliceous limestones (Helvetic Kieselkalk formation) in the Doldenhorn nappe. A: Totally brecciated state with rounded components owing to abrasive wear. B: Incipient state of brecciation with high degree of fitting of components.

3. Structural evolution of the Helvetic nappe system

In Fig. 5, the evolution of the Helvetic nappe system in the Bernese Oberland is sketched in three time frames spanning the time interval from Early Oligocene to Pliocene. In the Helvetic nappe system, the sequence of deformational events may be determined by studying the geometric relationships between thrust faults and folds. Rather than numbering phases, phase names were established based on type localities and structural features such as done in lithostratigraphy. As shown in Fig. 2, the basal thrust of the Ultrahelvetic nappes is folded by the nappe-internal folds of the Doldenhorn and Wildhorn nappes. The same holds true for the Gellihorn and Wildhorn thrusts on the western flank of Kander valley. Thus one is forced to conclude that in a first step of the structural evolution the Ultrahelvetic nappes were emplaced onto the future Wildhorn and Doldenhorn nappes along a bedding parallel thrust fault. This deformation phase is referred to as the Plaine Morte phase (Burkhard 1988). Since the Wildhorn thrust is deformed by internal folds of the Gellihorn and Doldenhorn nappes, and the Gellihorn thrust is folded by internal Doldenhorn nappe folds, thrust propagation occurred in sequence, i. e. from top down, or from more internal to more external. The internal deformation and emplacement of the Wildhorn and Gellihorn nappes corresponds to the Prabé phase (Burkhard 1988). In the area considered here, the next following major deformation phase is the Kiental phase (Günzler-Seiffert 1943, Burkhard 1988), which relates to the deformation and emplacement of the Doldenhorn nappe. During the Grindelwald phase (Günzler-Seiffert

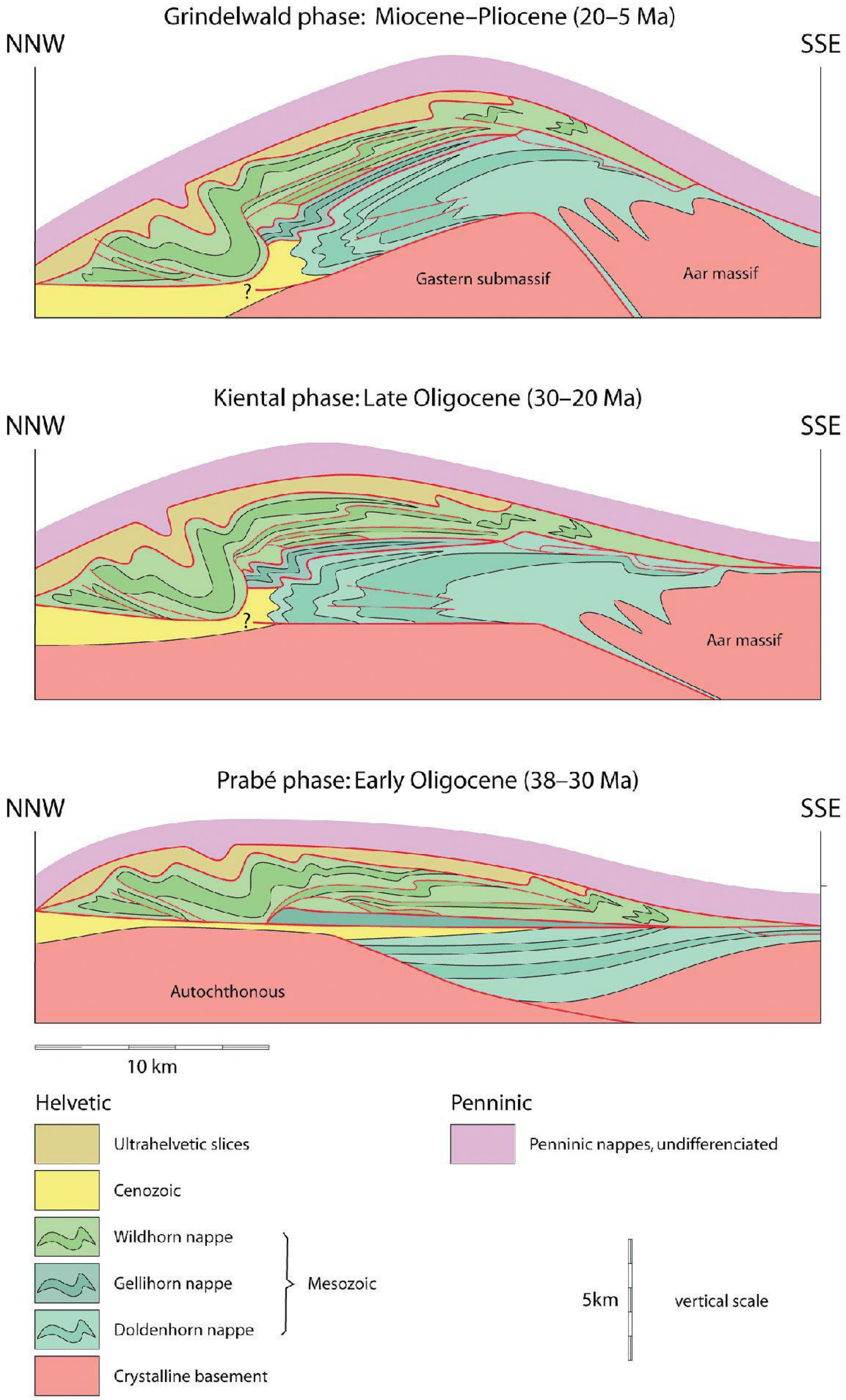

Fig. 5: Evolution of the Helvetic nappe system in the transect of Kander valley (based on Herwegh & Pfiffner 2005).

1943, Burkhard 1988), finally, upwarping of the Aar massif and its Doldenhorn submassif resulted in wrapping the Doldenhorn thrust and the axial surfaces of the internal folds of this nappe around the basement block.

4. Landscape evolution

The Kander valley and its headwaters, the Gastern valley, are deeply incised valleys with steep flanks. Although a structural change occurs within the Helvetic nappes across the Kander valley, the folds on either side of the Gastern valley correlate rather nicely. It is thus not conceivable to simply argue that fluvial incision followed a fault zone where shattered rocks facilitated river incision. It is more likely that the course of these valleys was determined by the paleo-landsurface located at a much higher level, within the Penninic and Austroalpine units now eroded. The fluvial valleys were however overprinted by the glaciers of the Pleistocene glaciations. The most profound effect of the glaciers was the overdeepening of the valleys. In the case of the Gastern valley, the question of how deep beneath the valley

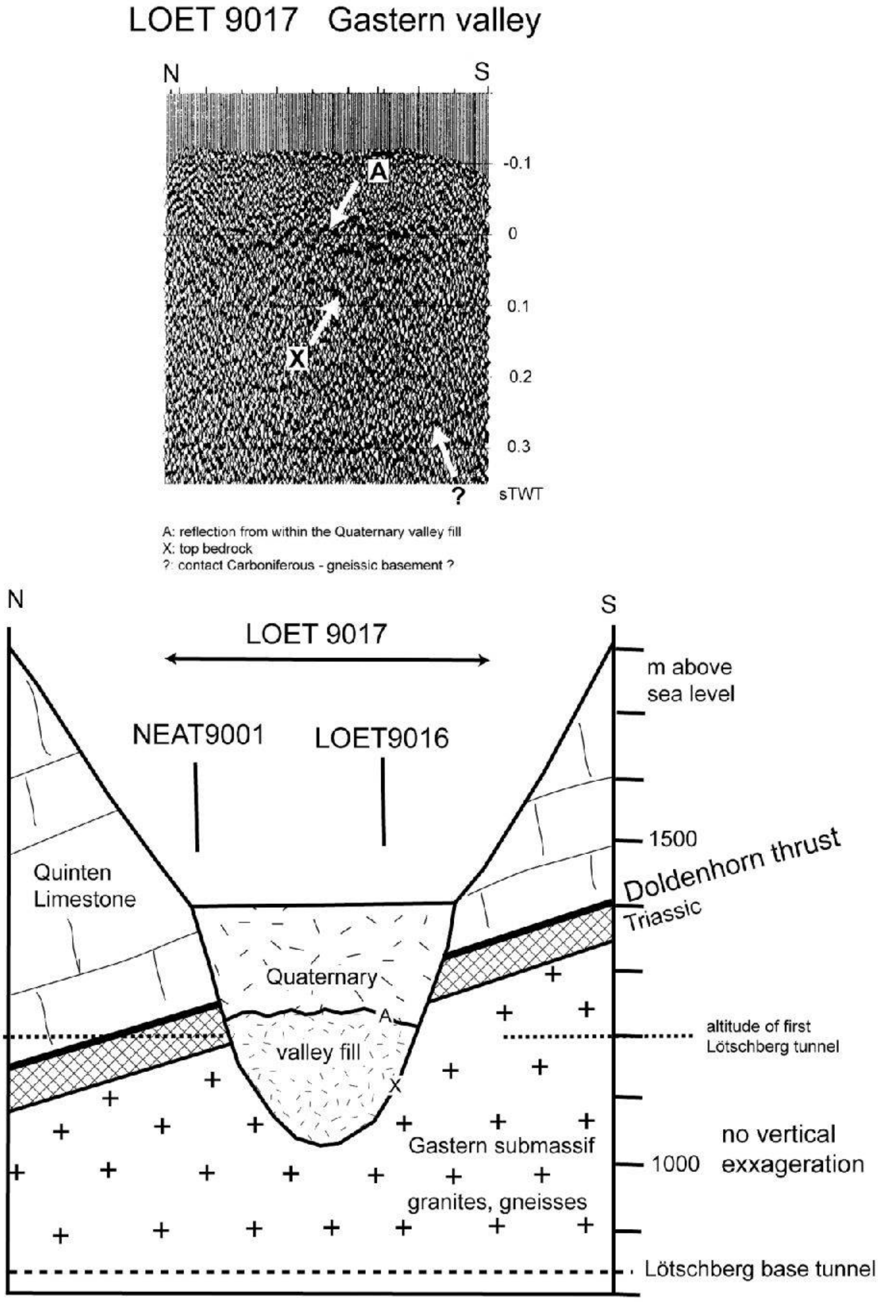

Fig. 6: Seismic section and geological profile across the Gastern valley. Seismic data are from Frei & Pfiffner 1990.

floor the bedrock is located arose to the construction of the old Lötschberg railroad tunnel. On the flat valley floor at 1360 meters above sea level, the Kander flows on unconsolidated Holocene sediments. To the northwest, a rocky barrier crosses the valley and the Kander is forced through a gorge cut into solid bedrock. An abrupt change in river gradient occurs at the entrance and exit of the gorge testifying to active backward river incision. Even if the walls of the gorge are cut into solid rock, the Kander itself flows on blocks of Early Cretaceous limestones. It thus must be assumed that the gorge was once even deeper and subsequently filled by rock fall. The valley floor of the Kander valley at Kandersteg (and the entrance of the old Lötschberg railroad tunnel) is at 1200 meters above sea level. The original plan was to cross the Gastern vally directly in order to minimize tunnel length. Despite warnings issued, the construction team proceeded according to this plan, underestimating (or ignoring) the effect of overdeepening by glaciers. The result was that the tunnel ran into unconsolidated glacial sediments causing flooding of the tunnel and the death of the miners on shift. With the construction of the new railroad Lötschberg base tunnel (NEAT) overdeepening of the Kander and Gastern valley was again an issue. The question was first addressed by a series of seismic lines (Frei & Pfiffner 1990) followed by a drilling campaign. Fig. 6 shows a seismic section and its geological interpretation that crosses the Gastern valley at the location of the collapse of the old railroad tunnel. Although the quality of the seismic data is relatively poor, the position of the bedrock surface shown in the geological interpretation was later confirmed to within 10 m by drilling. Surprisingly, the steep valley flanks observed at the surface become even steeper in the subsurface. The cross-sectional shape of the valley suggests that the glacier had not widened the lowermost part of the

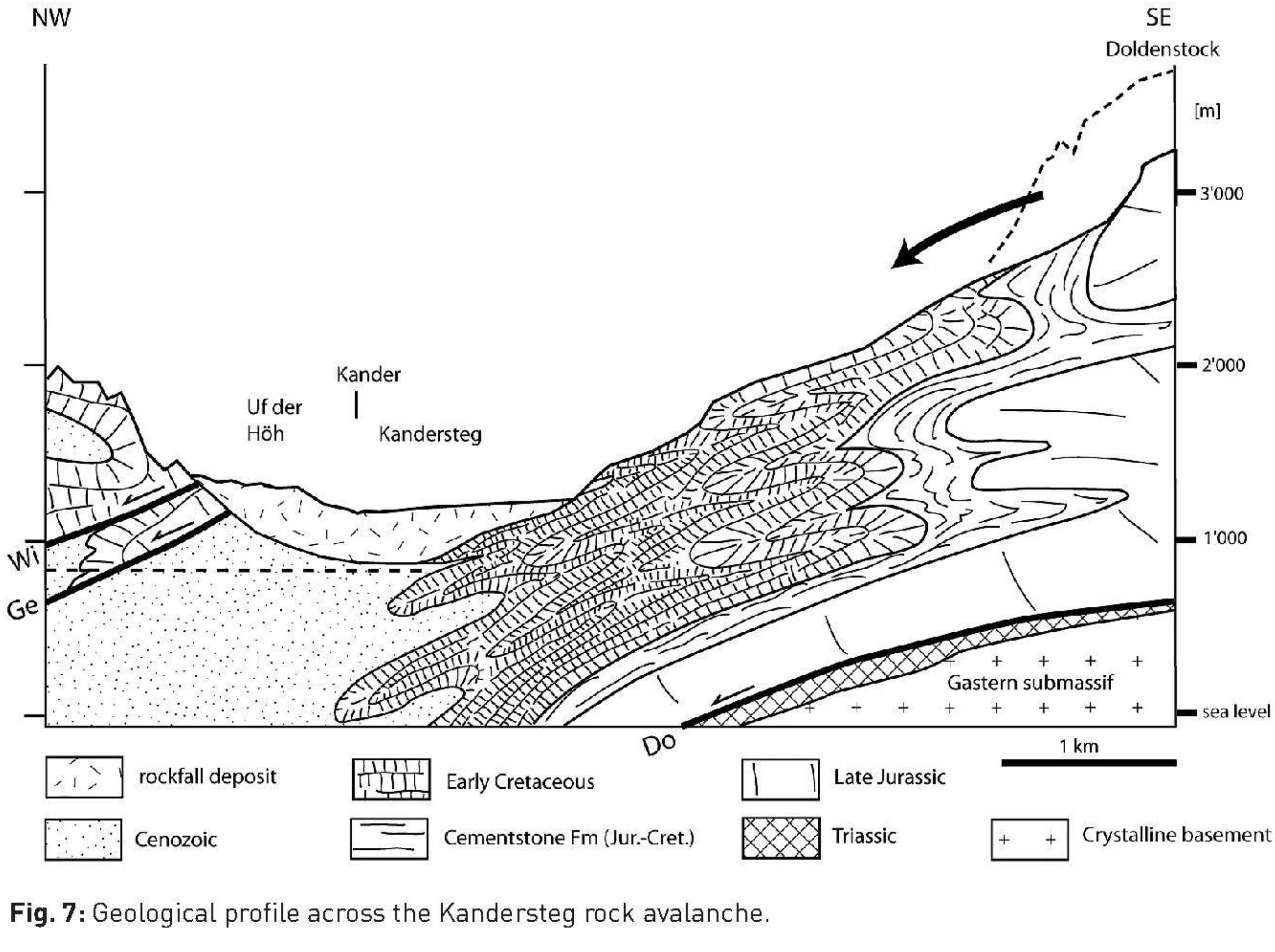

Fig. 7: Geological profile across the Kandersteg rock avalanche.

valley flanks, possibly because the actual overdeepening was caused by incision through overpressured water flowing at the base of the glacier.

Another seismic line was shot across the Kander valley at Kandersteg. The valley floor is at 1200 m, the bedrock surface at around 800 m above sea level. The overdeepened valley is filled mainly by sediments of the Kandersteg rock avalanche. This rock avalanche occurred between 9100 and 9600 B. P during an Early Holocene thermal and solar irradiational maximum (Tinner et al. 2005), i. e. well past the melt down of the glaciers of the Last Glacial Maximum (LGM or «Würm»). As evident from Fig. 7 and observation in the field, the basal sliding plane of the rock avalanche is parallel to bedding and schistosity in the Late Jurassic sediments of the Doldenhorn nappe. The rock avalanche masses can be studied in outcrops at Uf der Höh close to the railroad station of Kandersteg. But the rockfall itself spread out downward the valley over a distance of more than 10 km as far as Kandergrund. The volume of the rock avalanche mass is estimated to be around 2 km^3.

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