1661-8726/08/020311-12
DOI 10.1007/s00015-008-1258-0
Birkhäuser Verlag, Basel, 2008

Swiss J. Geosci. 101 (2008) 311–322

Tectonic evolution of the Engi Slates, Glarus Alps, Switzerland

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Key words: Engi Slates, Glarus Alps, infrahelvetic complex, North Helvetic Flysch

ABSTRACT

We present a geological map, profiles and the results of a detailed structural analysis of the Early Oligocene Engi Slates southwest of the village of Engi in the Sernft Valley in canton Glarus (Switzerland). In this area, the Engi Slates are folded on a deca- to hectometer scale into tight NW-vergent folds with sharp hinges. This took place during the Plattenberg F_1 folding phase. No axial plane foliation was formed. The F_1 folds are unconformably cut-off by a 16–25° NE dipping thrust, along which Eocene marls were emplaced onto the folded Engi Slates. We refer to this thrust as Riedboden Thrust and correlate it with the base of the upper, chaotic part of the Wildflysch Nappe of Oberholzer (1942). This is a (probably tectonic) mélange of rocks from the underlying Sardona, Blattengrat and North Helvetic Flysch Units. It lies as a 5 to 100 m thick, more or less continuous nappe below the Glarus Thrust. A younger, SE-dipping tectonic foliation (Plattenberg F_2 foliation) cuts both through the folded Engi Slates, the Riedboden Thrust and the Eocene marls. This foliation is the axial plane foliation to meter-scale open F_2 folds. It developed parallel to the overturned limbs of the F_1-folds.

1. Introduction

The Early Oligocene Engi Slates in the Glarus Alps are famous for their fossil record. Thousands of beautifully preserved fishes, turtles and birds were collected during centuries of mining in the Engi slate mine (the „Landesplattenberg“; Wettstein 1886, Furrer and Leu 1998). These fossils are show-pieces of renowned paleontological collections, such as in the Paleontological Museum in Zürich and the Museum of Natural History in Basel. The slate mine is abandoned, but can be visited. There are guided tours through the mine shafts and a small museum next to the mine is dedicated to the mining history and regional geology.

Remarkably enough, a detailed geological map and profile through the Engi Slates is lacking. We therefore decided to geologically map the area at a scale 1:5,000 and to carry out a detailed structural analysis (Gasser 2006). The results are presented in this paper.

2. Geological setting

The Engi Slates crop out in the northern Sernft Valley between the villages Engi and Matt (Fig. 1). They are part of the North Helvetic Flysch (NHF) Unit, which mainly consists of turbiditic sandstones and slates. Siegenthaler (1974) subdivided the NHF of the Sernft Valley into three formations. These are from bottom to top: (i) the Taveyannaz Formation, consisting of volcano-clastic, dark-greenish turbiditic sandstones, (ii) the Elm Formation, consisting of dark-grey turbiditic sandstones and slates, and (iii) the Matt Formation, consisting of (a) a lower member of light-grey turbiditic sandstones (the Matt Sandstones) and (b) an upper member of dark slates (the Engi Slates). Fossil fishes in the Engi Slates were dated Early Oligocene by Wettstein (1886). Andesitic hornblende from the Taveyannaz Formation has a K/Ar-radiometric age of 31.7 ± 1.6 and 32.4 ± 1.6 Ma, and a $^{40}Ar/^{39}Ar$-radiometric age of 31.96 ± 0.9 Ma (Fischer & Villa 1990), suggesting an Early Oligocene depositional age for these sediments as well.

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The NHF Unit is overthrust by the Blattengrat and Sardona Nappes. The Blattengrat Nappe consists of Late Cretaceous marls and Eocene limestones and marls (Bisig 1957, Trümpy 1969, Lihou 1995). The Sardona Nappe consists of Late Cretaceous limestones and marls, and an Eocene sequence of marine (mainly turbiditic) sandstones and marls (Leupold 1942, Trümpy 1969, Lihou 1996b). The NHF Unit, the Blattengrat Nappe and the Sardona Nappe were overthrust by Subhelvetic Units and by the Helvetic Nappes along the Glarus Thrust (Trümpy 1969, Schmid 1975), and are therefore commonly referred to as Infrahelvetic Complex (Milnes & Pfiffner 1977, Pfiffner 1978; Fig. 1).

According to Schmid (1975), deformation within the Infrahelvetic Complex occurred in three phases. He named them phase 1, 2 and 3, respectively. During phase 1 the Sardona and Blattengrat Nappes slid onto the NHF foreland (possibly by gravity sliding). During phase 2 the Infrahelvetic Complex was folded and a penetrative axial plane cleavage developed. During phase 3 the Glarus Thrust developed – out of sequence. A minimum displacement of 35 km took place, during which a steep crenulation cleavage developed just below the thrust.

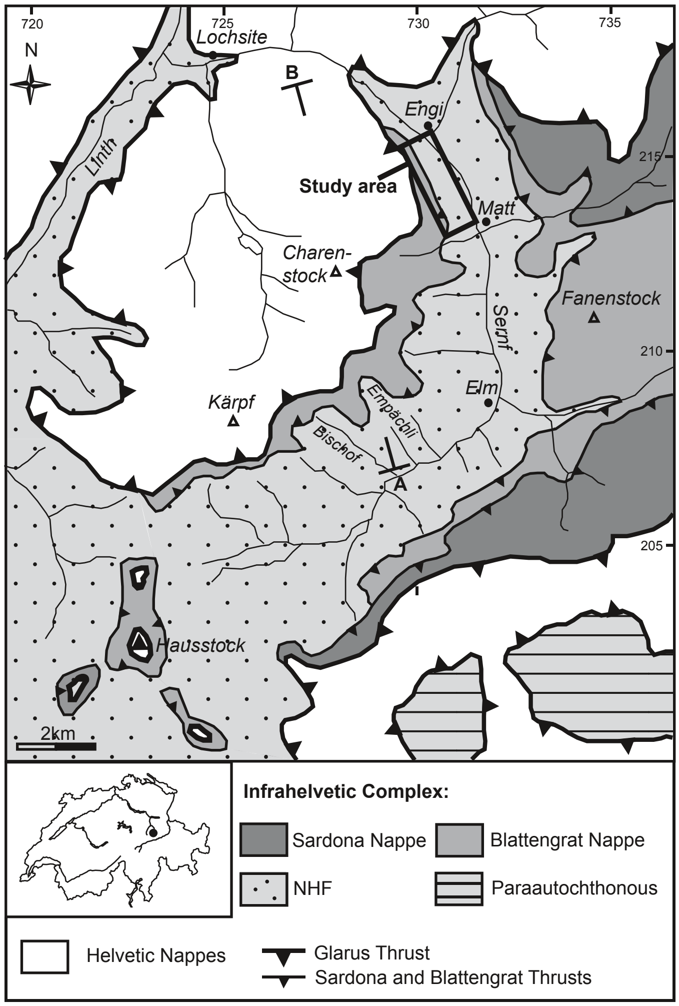

Fig. 1. Tectonic map of the Infrahelvetic Complex in the Sernft Valley (after Lihou 1996a). A-B: Profile trace of Figure 2. Coordinates in Swiss National Grid.

According to Milnes & Pfiffner (1977; see also Pfiffner 1978, 1986, Lihou 1996a), deformation of the Infrahelvetic Complex occurred in four phases: (i) the *Pizol* phase, (ii) the *Cavestrau* phase (of local importance and not included in the present discussion), (iii) the *Calanda* phase, and (iv) the *Ruchi* phase, respectively. During the Pizol phase, the Sardona and Blattengrat Nappes were thrust onto the NHF Unit, not by gravity, but by compressional tectonics. Much of the chaotic folding within the Blattengrat and Sardona Nappes, and some of the folding and thrusting in the NHF Unit may have been initiated at this time as well. During the subsequent Calanda phase the Glarus Thrust developed along which 25–30 km displacement took place. At the same time the Infrahelvetic Complex was folded, and a penetrative axial plane cleavage developed. During the Ruchi phase, the Infrahelvetic Complex was further overthrust by the Helvetic Nappes by 5–10 km and a steep crenulation cleavage developed below the Glarus Thrust.

3. Field results

We mapped the area around Landesplattenberg Engi at the scale 1:5,000 and conducted detailed microstructural work on thin sections (Gasser 2006). The study area covers the Engi Slates on the western side of the Sernft Valley between Schwarzkopfrus in the south and Badchopfrus in the north (Fig. 2). Our geological map and two profiles through the study area are presented in Figure 3.

The Engi Slates are well exposed. Outcrops exist around the entrances to the Landesplattenberg, around the Schwarzkopf mines, along the road to Chreuelalp, and in the numerous gullies cutting through the study area. Despite the steep mountainside and dense vegetation, all the outcrops indicated on the map are accessible and were visited. The Eocene marls on top of the Engi Slates are poorly exposed. Outcrops exist only at the head of the main gullies and in some isolated areas.

a) Lithology

The Engi Slates consist of an alternation of mm- to cm-thick silt and clay layers. In the lower part, several turbiditic sandstone layers of 10–50 cm thickness are intercalated with the silt and clay layers. These sandstone layers are graded and show load marks at their lower boundary, providing a good top-bottom criterium. The silt layers often show straight upper and undulated lower boundaries, providing a good top-bottom criterium as well. Bedding is the dominant structural feature in the Engi Slates and can be observed in almost every outcrop.

Microscopically, the sandstones consist of quartz grains and rock fragments (limestones, dolomites). The silt layers consist of quartz (~0.1 mm grain size), calcite, white mica and clay minerals. The clay layers consist of clay minerals, calcite, quartz

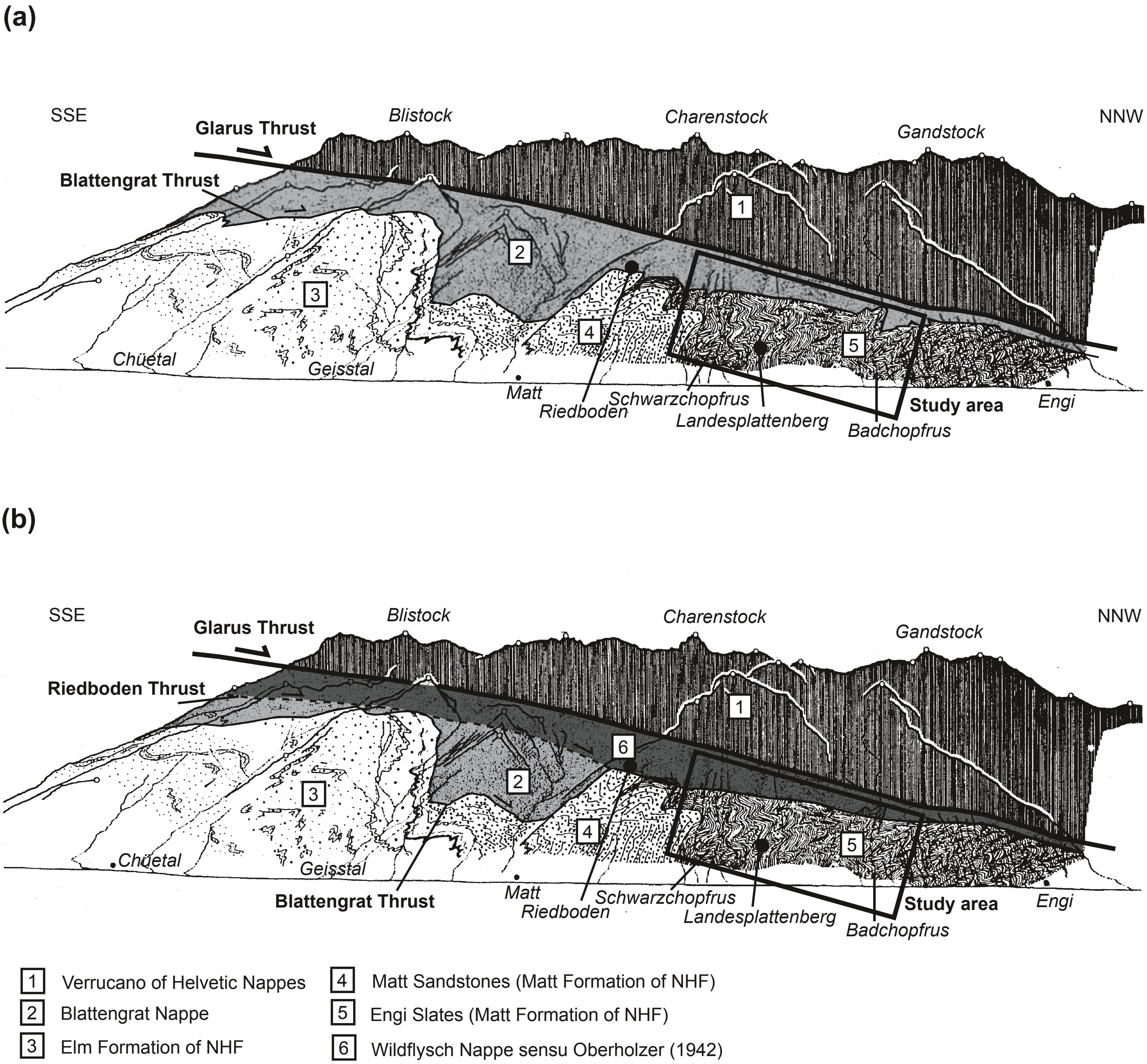

Fig. 2 (a) Siegenthaler's (1974) geological profile along the eastern side of the Sernft Valley. For location of the profile see Figure 1. Note the presence of the Blattengrat Nappe above the Engi Slates in our study area. (b) Re-interpretation in line with Oberholzer (1933, 1942) and our results.

(<0.05 mm grain size), white mica and organic material. The silt layers differ from the clay layers both in the larger grain size of quartz and in the higher calcite content.

b) Foliations

Two foliations were recognized: (i) a bedding-parallel slaty cleavage, and (ii) a tectonic, disjunctive, pressure solution cleavage, further referred to as Plattenberg foliation. The bedding-parallel slaty cleavage is defined by the alignment of detritic white mica in the clay layers parallel to the bedding. It is always oriented parallel to the bedding; no folds or other tectonic features related to this foliation have been found. The tectonic Plattenberg foliation is a disjunctive cleavage (Passchier & Trouw 2005) defined by dark seams of clay minerals and is particularly well developed in the clay layers. In the field it can only be observed with ease where it makes an angle with the bedding. It has a uniform orientation in the study area, dipping 15–40° towards SE (Fig. 4a). It is the only tectonic foliation in the study area. The bedding-parallel slaty cleavage is

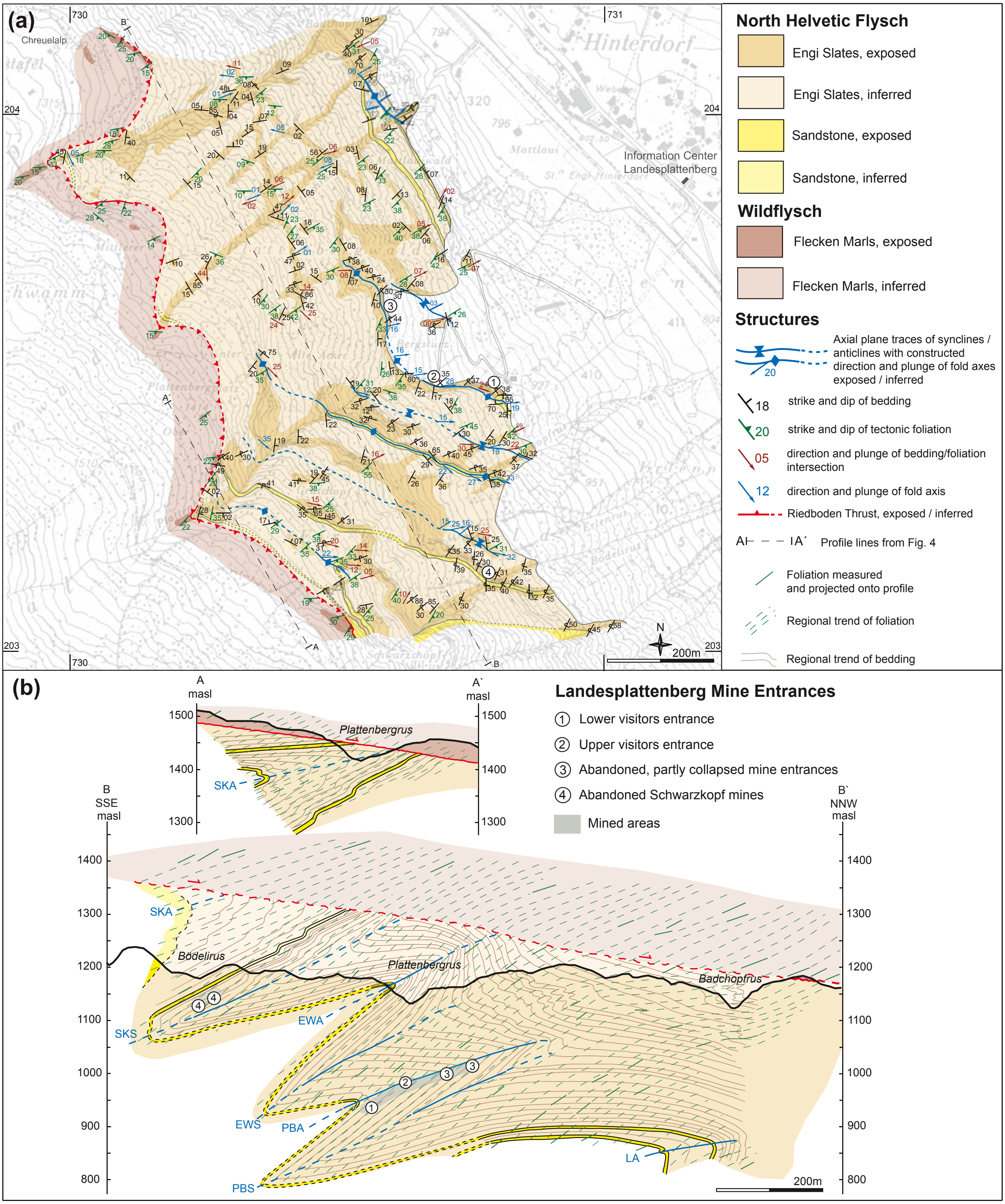

Fig. 3. (a) Geological map of the study area. The upper and lower visitors entrances of Landesplattenberg that are often visited on geological excursions are marked 1 and 2, respectively. Coordinates in Swiss National Grid. Map base: „Katasterplan der Gemeinde Engi", scale 1:10,000. (b) Tectonic profiles through the study area. Profile lines are indicated on Figure 3a. SKA: Schwarzkopf Anticline; SKS: Schwarzkopf Syncline; EWA: Erlenwald Anticline; EWS: Erlenwald Syncline; PBA: Plattenberg Anticline; PBS: Plattenberg Syncline; LA: Lochrus Anticline.

responsible for good fissility of the Engi Slates. Where both foliations are parallel, the quality of the Slates is good enough for mining.

c) Folds

Despite the uniform lithology of the Engi Slates we could determine the large-scale structure of the area with the help of the turbiditic sandstone layers. The Engi Slates appear to be tightly folded at deca- to hectometer scale into NW-vergent folds with straight limbs and sharp hinges. Four large-scale anticlines and three large-scale synclines could be mapped (Fig. 3b). We refer to these folds as Plattenberg F_1 folds. They are close to tight symmetrical folds, most of them of type 1C, i.e. the limbs are thinner than the hinges (classification of Ramsay 1967). The normal and inverted limbs are equally thick. An example of such a type 1C fold is exposed just right of the upper visitors entrance of Landesplattenberg mine (Fig. 5a). Other examples can be found along the partly collapsed mine entrances *above* the upper visitors entrance (Fig. 5b) and in the Badchopfrus gully (Fig. 5c).

The fold axes of the F_1 folds were constructed by plotting bedding in a stereonet, whereas the fold axes of smaller F_1 folds could be measured directly in the field. The fold axes appeared to vary significantly in orientation, but they all plot on one single great circle that corresponds to the axial plane of the folds (135/20, Azimuth/Dip; Fig. 4b). The fact that the fold axes scatter on a great circle, but that the orientation of the axial planes is constant, was also observed by Siegenthaler (1974) and Schmid (1975) further south in the Sernft Valley. It suggests that the Engi Slates were already folded when the large-scale F_1 folds developed (e.g. Speksnijder 1987). We refer to these hypothetical older folds as pre-F_1 folds.

The Plattenberg foliation is oriented sub-parallel to the overturned limbs of the F_1 folds (at all scales) and cuts through their axial planes. There is always a significant angle between the axial plane (i.e. the plane connecting the hinge lines of the folds) and the foliation (Fig. 5a–d). Hence, the Plattenberg foliation is not the axial plane foliation to the F_1 folds. In the case of the F_1 Schwarzkopf Syncline (Fig. 3, 5d), it even appeared to cut through the overturned limb in the wrong way, i.e. the foliation is steeper than the bedding, whereas it should have been the other way round if it would have been an axial plane foliation. These observations indicate that the F_1 folds are older than the Plattenberg foliation.

Intersection lineations between bedding and Plattenberg foliation were also determined. They spread along the same great circle as the F_1 fold axes (Fig. 4b). This is not a surprise, because the Plattenberg foliation is parallel to the overturned limbs of the F_1 folds.

Locally, open folds with the Plattenberg foliation as an axial plane foliation were observed. These folds most likely developed simultaneously with the Plattenberg foliation. They will therefore be referred to as Plattenberg F_2 folds. A good example of an F_2 fold is exposed just above the lower visitors entry of Landesplattenberg mine (Fig. 5e).

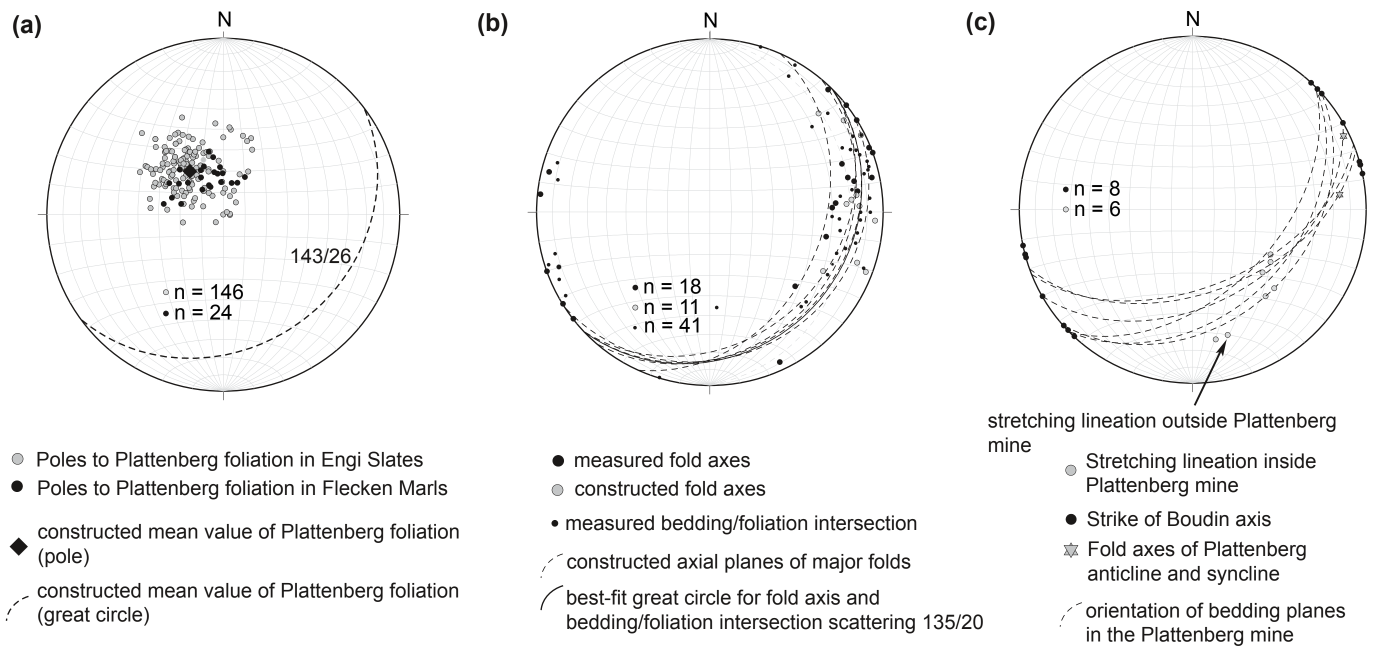

Fig. 4. (a) Orientation of Plattenberg foliation in the Engi Slates (grey dots) and the Flecken Marls (black dots). (b) Orientation of measured and constructed fold axes (big black and grey dots respectively), bedding/foliation intersections (small black dots), as well as constructed axial planes (great circles) of Plattenberg F_1 folds in the Engi Slates. Note that fold axes scatter on a great circle (the dashed great circle) approximately corresponding to the axial plane of the folds. (c) Stretching lineations measured inside and outside the Landesplattenberg mine, bedding measured inside the Landesplattenberg mine, and fold axes of Plattenberg Anticline and Syncline. Lower hemisphere equal area projections.

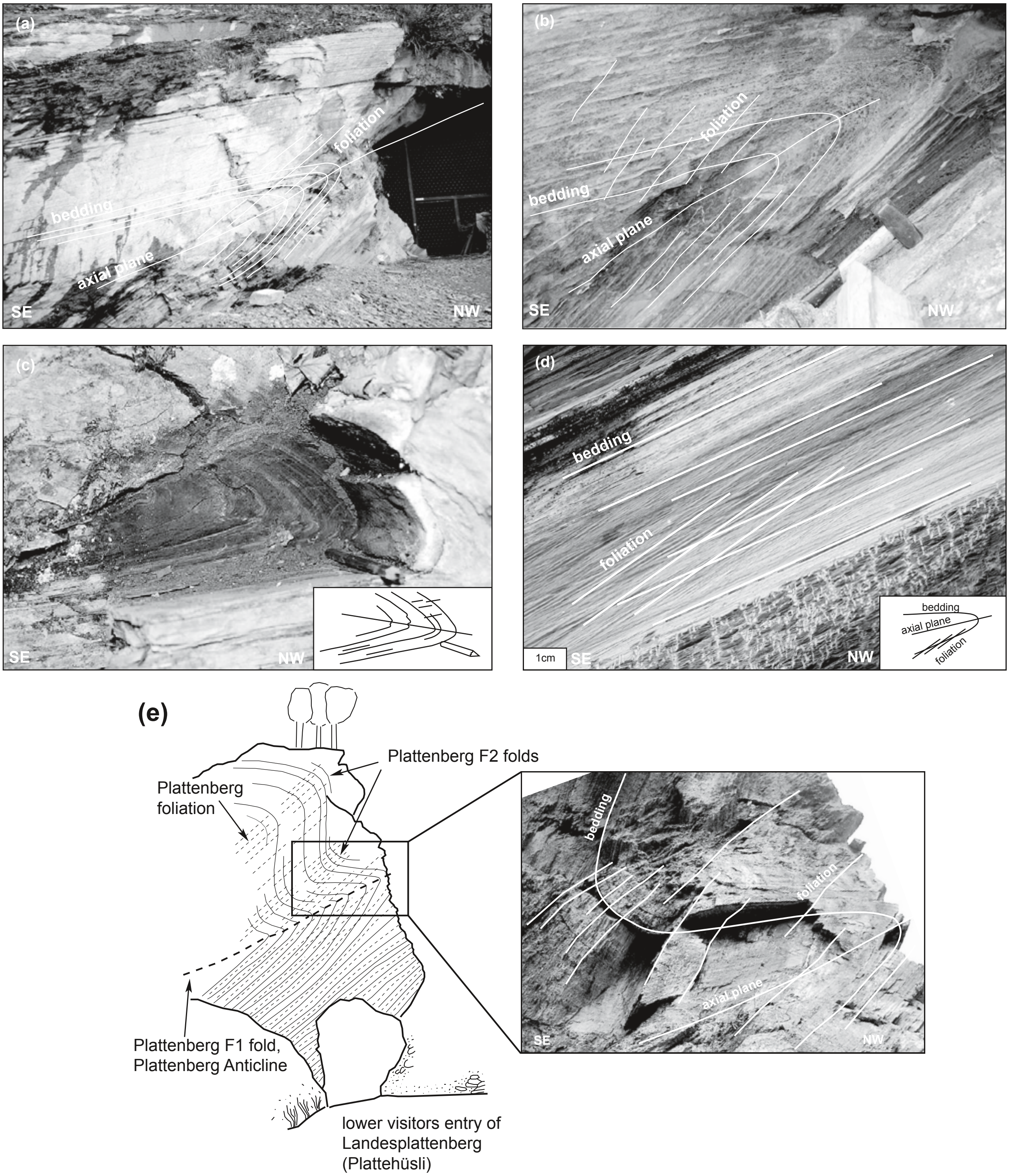

Fig. 5. (a) Photograph of upper visitors entry of the Landesplattenberg mine showing an example of a Plattenberg F_1 fold (the hinge of the Plattenberg Anticline). The Plattenberg foliation is oriented parallel to the overturned limb and cuts through the axial plane of the fold. The entrance to the mine is ~5 m high. (b) Photograph of an example of a Plattenberg F_1 fold between the upper visitors entrance of Landesplattenberg and the abandoned mine entrances (Fig. 3). Normal and inverted limb are almost equally thick; the foliation is parallel to the overturned limb and cuts through the axial plane of the fold. (c) Photograph of a Plattenberg F_1 fold in the Badchopfrus (Fig. 3). Normal and inverted limb are almost equally thick. (d) Photograph illustrating relationship between sedimentary bedding and Plattenberg foliation near the Schwarzkopf mines. The bedding is overturned, the foliation cuts through the bedding with the wrong orientation for an axial plane foliation. (e) Sketch and photograph of the lower visitors entrance of Landesplattenberg mine. Just above the entrance, the hinge of the F_1 Plattenberg Anticline is exposed. The inverted limb is oriented parallel to the Plattenberg foliation. Above this anticline, open Plattenberg F_2 folds with the foliation as axial plane foliation are exposed.

d) Stretching lineation and boudinage

According to Wettstein (1886) the slates from the Landesplattenberg mine show a pronounced stretching lineation. The fish fossils found in these slates are stretched by amounts of up to 2.4 parallel to this lineation. Unfortunately the lineation is extremely difficult to recognize in the field. We were able to determine its orientation at very few localities only, notably inside the Landesplattenberg mine and at one locality outside the mine (Fig. 4c). More commonly we observed boudinaged silt layers, both in the normal as well as in the inverted limbs of the Plattenberg F_1 folds. The boudin axes are oriented parallel to the fold axes of the F_1 folds. The stretching lineations that we were able to measure made an angle of about 70° with the boudin axes and the F_1 fold axes (Fig. 4c). The data are too sparse to judge whether boudinage and stretching took place before, or after the development of the F_1 folds.

e) Upper tectonic boundary of the Engi Slates

The Engi Slates are bounded upwards by a thrust, which we refer to as Riedboden Thrust (not to be confused with the Glarus Thrust). This thrust corresponds to a major change in local geomorphology. The steep and rugged slope below the thrust, with many outcrops of Engi Slates, gives way to a much flatter and smoother slope above the thrust, where light-grey marls are exposed in the main gullies and along the path to Chreuelalp. These marls show characteristic dark stains (believed to be due to bioturbation) and belong to the Eocene Flecken Marl Formation (Siegenthaler 1974, Lihou 1995).

The relationship between the Riedboden Thrust and the structures in the Engi Slates is well exposed near the upper part of the Plattenbergrus gully (Fig. 3). The overturned sandstone beds, which run from the Schwarzkopf mines in the south-east to the Plattenbergrus gully in the north-west, are unconformably overlain by the Flecken Marl Formation just below Oberer Plattenbergplatz. The thrust contact itself is not exposed. The same sandstones reappear higher up in the Plattenbergrus gully in normal position, representing the normal limb of the Schwarzkopf Anticline. They are also unconformably overlain by the Flecken Marl Formation. So it appears that the hinge of the Schwarzkopf Anticline, which is exposed north of Schwarzchöpf, is unconformably cut-off by the Riedboden Thrust just north of the Plattenbergrus gully.

The thrust zone is well exposed in the upper Plattenbergrus gully, but the thrust contact itself could not be identified. Between the uppermost clearly identifiable Engi Slates (characteristic alternation of silt-and clay layers) and the lowermost clearly identifiable Flecken Marls (characteristic dark stains, i.e. bioturbation) there is a 4 to 5 m wide zone of marls that we were unable to attribute to either Engi Slates or Flecken Marls. A thrust as tectonic feature (e.g. shear zone) was not observed. The only structural feature recognized was the south-east dipping Plattenberg foliation cutting through the contact zone. No other (older or younger) foliations were observed. The Riedboden Thrust may be folded at meter-scale by open Plattenberg F_2 folds, but we were unable to verify this, since the outcrop is only a few meters wide. At large scale the thrust is a straight surface, dipping 16–25° towards NE, at least in the area we mapped (Fig. 6).

The fact that the Plattenberg F_1 folds are unconformably cut-off by the Riedboden Thrust, whereas the Plattenberg foliation cuts through the Rietboden Thrust, corroborates our earlier mentioned argument that the Plattenberg F_1 folds must be older than the Plattenberg foliation.

4. Model for the tectonic evolution of the Engi Slates

Our model for the tectonic evolution of the Engi Slates is illustrated in Figure 7. After deposition and compaction of the

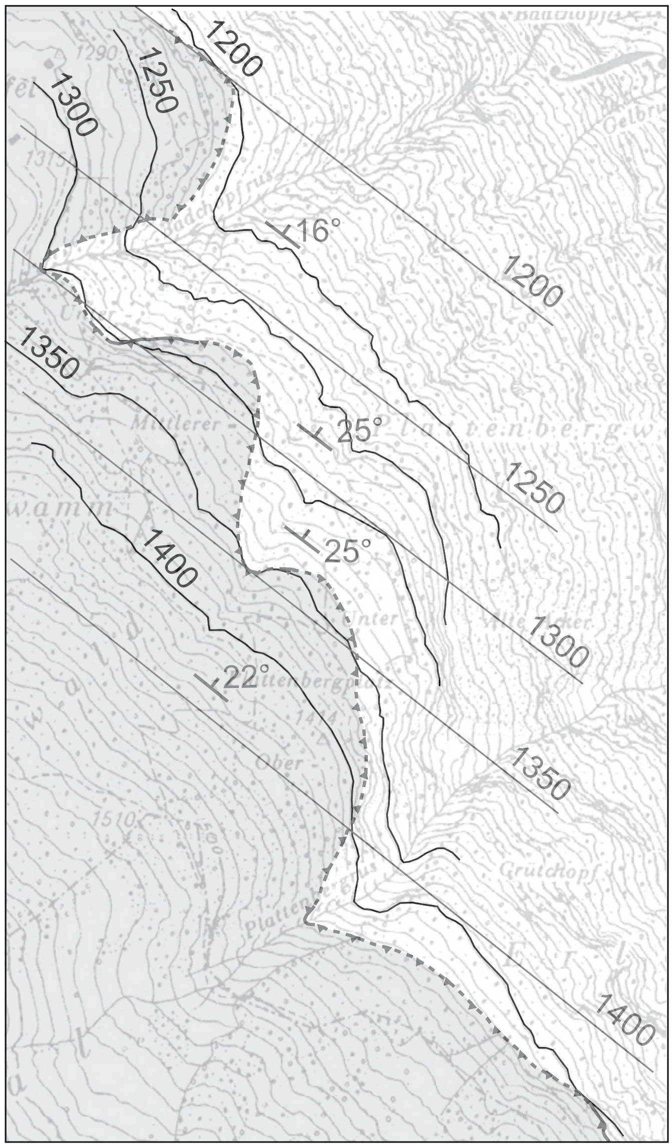

Fig. 6. Detail of geological map with contour lines of the Riedboden Thrust suggesting that the thrust corresponds to a straight, 16–25° NE-dipping plane.

Engi Slates (Figs. 7a–b), an early, pre-Plattenberg F_1 folding phase must have taken place, as was inferred from the scatter of Plattenberg F_1 fold axes along the F_1 axial planes (Fig. 7c). Then the Engi Slates were folded on a regional scale during the Plattenberg F_1 phase, but *no* axial plane cleavage developed (Fig. 7d). The F_1 folds were subsequently unconformably cut-off by the Riedboden Thrust, along which Eocene Flecken Marls were placed on top of the lower Oligocene Engi Slates (Fig. 7e). Thereafter, the Plattenberg foliation developed, both in the Engi Slates and the Flecken Marls as an axial plane foliation to open Plattenberg F_2 folds (Fig. 7f).

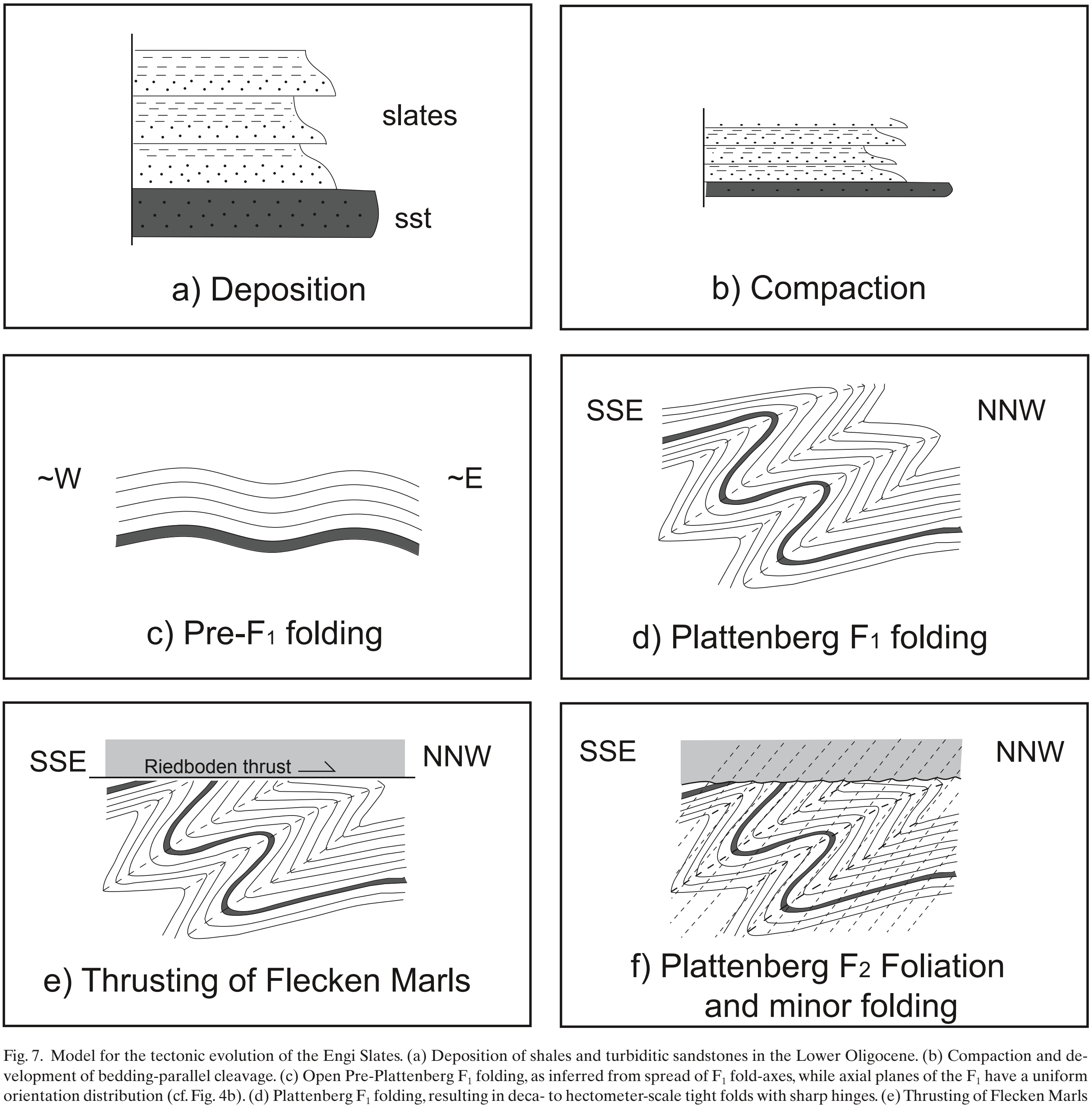

Fig. 7. Model for the tectonic evolution of the Engi Slates. (a) Deposition of shales and turbiditic sandstones in the Lower Oligocene. (b) Compaction and development of bedding-parallel cleavage. (c) Open Pre-Plattenberg F_1 folding, as inferred from spread of F_1 fold-axes, while axial planes of the F_1 have a uniform orientation distribution (cf. Fig. 4b). (d) Plattenberg F_1 folding, resulting in deca- to hectometer-scale tight folds with sharp hinges. (e) Thrusting of Flecken Marls onto the Engi Slates, which were already folded during F_1. The thrust cuts unconformably through the F_1 folds in the Engi Slates. The Flecken Marls are assumed to belong to the Wildflysch Nappe, such as on Oberholzer's (1942) geological map. (f) Development of SE-dipping Plattenberg foliation plus open F_2 folding.

5. Comparison with previous work

a) Phase correlations

Our Plattenberg F_1 folds correspond to phase 2 folds of Schmid (1975) and to Calanda phase folds of Milnes & Pfiffner (1977). Our Plattenberg *foliation* corresponds to phase 2 foliation of Schmid (1975) and to Calanda phase foliation of Milnes & Pfiffner (1977). The relationships are depicted in Figure 8. In the following, we will refer to Schmid's (1975) phase 2 as Calanda phase as well. According to Schmid (1975) and Milnes & Pfiffner (1977) the Calanda phase foliation is the axial plane foliation to the Calanda phase folds and developed simultaneously with the folds. According to us these folds and foliation developed during two separate phases: the foliation cuts through the axial plane of the folds and therefore developed *after* the folding. Moreover, the folds are cut-off by the Riedboden Thrust, whereas the foliation cuts through the Riedboden Trust.

b) Fold geometries and their relationship to the foliation

Schmid (1975) and Pfiffner (1977, 1978, 1980) report geometries from folds they observed in the Infrahelvetic Complex. Schmid (1975) describes Calanda phase folds that developed in the NHF Unit in the Sernft Valley, including examples from the Engi Slates near the Landesplattenberg. He describes them as tight folds with the Calanda phase foliation oriented sub-parallel to the inverted limbs. Similarly, Pfiffner (1977, 1978, 1980), who studied the fold geometry of Calanda phase folds in the Infrahelvetic Complex in the area around Kistenpass (~15 km SW of our study area) and Kunkelspass (NW of Chur), likewise describes tight folds with Calanda phase foliation oriented parallel to the overturned limb. Both authors report that the foliation is not only sub-parallel to the inverted limb, but also parallel to the fold axial plane. This requires extreme thinning of the inverted limb compared to the normal limb, such as schematically depicted by Milnes (1981, in Furrer & Leu 1998; Fig. 9a) as a representative example of such folds in the Engi Slates at the Landesplattenberg.

Our observations are different. First, we observed that the Plattenberg foliation is indeed oriented parallel to the overturned limbs, but not parallel to the axial planes of the F_1 folds. It cuts through them with a significant angle. Second, we observed that the inverted limbs are generally not much thinner than the normal limbs (Fig. 5). The fold geometry such

<table>
<tr><td>Authors</td><td>Schmid (1975)</td><td>Milnes & Pfiffner (1977)</td><td colspan="2">this study</td></tr>
<tr><td>Study area</td><td>Infrahelvetic Complex
Sernft Valley</td><td>Infrahelvetic Complex
Kunkels- and Kistenpass</td><td colspan="2">Infrahelvetic Complex
Landesplattenberg</td></tr>
<tr><td rowspan="8">Phase correlations</td><td rowspan="2">Phase 3
Development of Glarus Thrust and crenulation cleavage below Glarus Thrust</td><td rowspan="2">Ruchi phase
Development of crenulation cleavage below Glarus Thrust and further movement along Glarus Thrust</td><td colspan="2">Thrusting along Glarus Thrust</td></tr>
<tr><td colspan="2">Ruchi phase
foliation and folding</td></tr>
<tr><td>Thrusting of Subhelvetic Units</td><td></td><td colspan="2">Thrusting of Subhelvetic Units</td></tr>
<tr><td rowspan="3">Phase 2
Ductile penetrative phase of folding with axial plane foliation</td><td rowspan="3">Calanda phase
Ductile penetrative deformation (folding and foliation development) movement along Glarus Thrust</td><td colspan="2">Plattenberg F2 phase
Penetrative tectonic foliation and meter- to decameter scale folding</td></tr>
<tr><td colspan="2">Thrusting of
Wildflysch Nappe</td></tr>
<tr><td colspan="2">Plattenberg F1 phase
Folding up to hectometer-scale</td></tr>
<tr><td></td><td>Cavestrau phase
Thrusting of Subhelvetic Units</td><td colspan="2"></td></tr>
<tr><td>Phase 1
Diverticulation, gravity sliding? of Blattengrat and Sardona Nappes</td><td>Pizol phase
Emplacement of Blattengrat and Sardona Nappes</td><td>Emplacement of Blattengrat and Sardona Nappes</td><td>Pre F1 folding</td></tr>
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Fig. 8. Table showing the relationships between the deformational phases defined in the Infrahelvetic Complex by Schmid (1975), Milnes & Pfiffner (1977) and the present study.

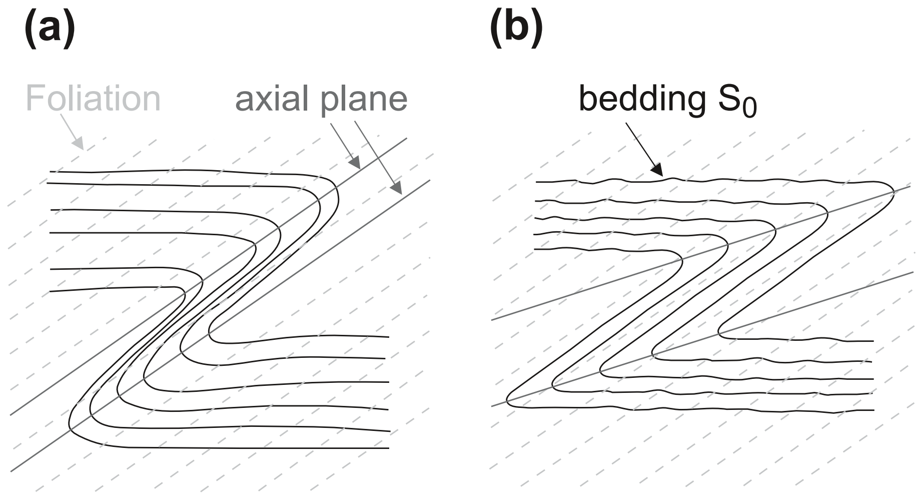

Fig. 9. (a) Fold geometry such as observed by Schmid (1975) and Pfiffner (1977, 1978). The foliation is oriented parallel to the axial plane and to the inverted limbs of the folds. The folds and foliation is assumed to have developed simultaneously. (b) Geometry of folds and foliation such as observed in the present study (cf. Fig. 5). The foliation is oriented parallel to the inverted limb, but cuts through the axial plane of the folds. It developed *after* the folding.

as we observed in the Engi Slates of the Landesplattenberg area is schematically depicted in Figure 9b. In fact, the Calanda phase fold and foliation drawn by Pfiffner (1978, fig. 2b) is almost identical to the folds observed by us, also showing foliation oriented parallel to the inverted limb, with both the inverted and the normal limb being almost equally thick. We cannot imagine how this geometry can be interpreted else than by a first phase of folding (F_1) without development of an axial plane foliation, followed by a second phase of further coaxial folding (F_2) with foliation development parallel to the overturned limb of the F_1 folds. The Y-axis of incremental strain during F_2 must have been approximately parallel to the Y-axis of finite strain of the F_1 folds, whereas the XY-plane of incremental strain during F_2 must have been ~20° steeper than the XY-plane of finite strain of the F_1 folds and approximately parallel to the overturned limbs of the F_1 folds. The limbs may have rotated further towards parallelism with the foliation during F_2.

Note that Schmid's (1975) phase 3 folds and crenulation foliation, corresponding to Milnes & Pfiffner's (1977) Ruchi phase folds and crenulation foliation, did not develop in our study area. As mentioned by these authors, Ruchi phase structures exclusively developed in a zone just below the Glarus Thrust. Ruchi phase crenulation foliation is well exposed in the upper Chüetal, directly south of our study area, where it crenulates the Calanda phase foliation (Plattenberg foliation in our terminology).

c) Truncated folds and the Riedboden Thrust

The Flecken Marls above the Engi Slates are commonly attributed to the Blattengrat Nappe. The Riedboden Thrust is consequently assumed to correspond to the thrust at the base of the Blattengrat Nappe, further referred to as Blattengrat Thrust (Bisig 1957, Siegenthaler 1974, Schmid 1975, Lihou 1995; Fig. 2a). We prefer another interpretation.

Thrusting of the Blattengrat Nappe onto the NHF Unit took place during phase 1 of Schmid (1975), corresponding to the Pizol phase of Milnes & Pfiffner (1977). The Blattengrat Nappe was subsequently folded together with the underlying NHF Unit (including the Engi Slates) during the Calanda phase (Schmid 1975, Milnes & Pfiffner 1977). A good example of a large-scale Calanda phase fold folding the Blattengrat Thrust is exposed near the village of Matt, a few kilometers south of our study area (Fig. 2a). The Calanda phase foliation cuts through the folded Blattengrat Thrust (see e.g. Schmid 1975, fig. 2).

The Riedboden Thrust, however, is *not* folded by the Calanda phase folds (Plattenberg F_1 folds in our terminology). The thrust cuts straightly *through* the Calanda folds. In Siegenthaler's (1974) profile through our study area (Fig. 2a) the Blattengrat Thrust, corresponding to our Riedboden Thrust, is also drawn straight. It only shows one single remarkable tight fold just north of Badchopfrus. This outcrop pattern at Badchopfrus may indeed suggest the existence of this fold, but we could not discover a corresponding fold in the underlying Engi Slates. According to us, the outcrop pattern is better explained by intersection between the rugged topography and a straight, 16–25° NE-dipping thrust plane (see Fig. 6).

So it appears that the Blattengrat Thrust is folded by Calanda phase folds, whereas the Riedboden Thrust cuts through these folds. These cannot be the same thrusts. We therefore correlate the Riedboden Thrust with another thrust. On the geological map of the Glarus Alps drawn by Oberholzer (1942) the Flecken Marls above the Engi Slates are not attributed to the Blattengrat Nappe, but to the so-called "Wildflysch" (w_f on his map; Wildflysch Nappe in Oberholzer 1933; Fig. 2b). The Riedboden Thrust would in this case correspond to the base of the Wildflysch Nappe, which cuts unconformably through Calanda phase folds (Plattenberg F_1 folds in our terminology) just south of our study area. For example, on Oberholzer's (1942) map, the base of the Wildflysch Nappe unconformably cuts through

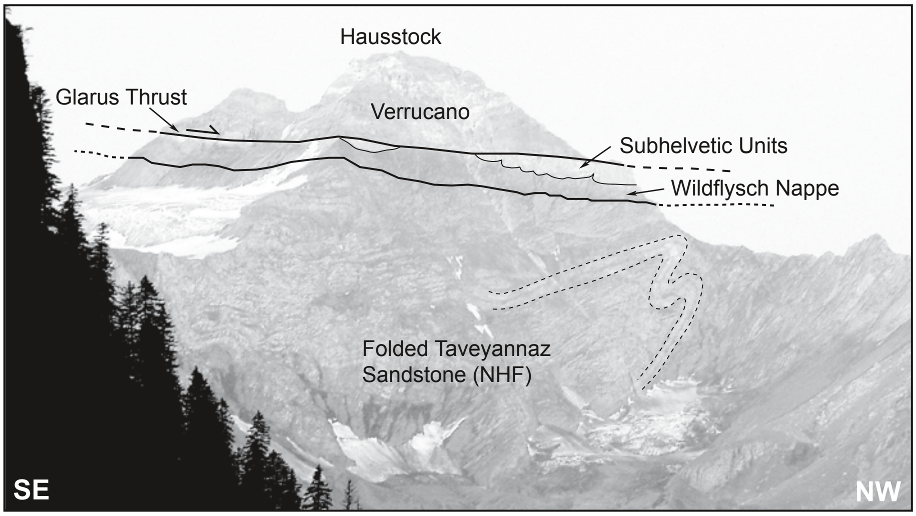

Fig. 10. Photograph of north-east face of Hausstock in the southern Sernft Valley. The dark slates below the Glarus thrust belong to Oberholzer's (1933, 1942) Wildflysch nappe, the base of which unconformably cuts through Calanda phase folds in the underlying Taveyannaz Sandstone Formation of the NHF.

the aforementioned Calanda phase syncline in the Blattengrat Nappe near the village of Matt (Fig. 2b). The folded Blattengrat Thrust is cut-off by the base of the Wildflysch Nappe just east of Riedboden Alp. Other synclines in the Blattengrat Nappe west of Elm, notably at Empächli Alp and Bischof Alp seem to be cut-off by the base of the Wildflysch Nappe on Oberholzer's (1942) map as well. In the north-east face of Hausstock, another large-scale Calanda phase fold in the Taveyannaz Sandstone Formation of the NHF Unit seems to be unconformably cut-off by the base of the Wildflysch Nappe (Fig. 10).

Oberholzer (1942) drew Wildflysch (w_f) almost everywhere below the Glarus Thrust in the Sernft Valley. Geological mapping carried out in the whole Sernft Valley by one of the authors (BdB, geological mapping of map sheet Elm 1:25,000 for the Swiss Geological Survey, work in progress) revealed, that this Wildflysch Nappe consists of (i) a lower part that was renamed Sardona Flysch by Leupold (1942) (later referred to as Sardona *Nappe*: see e.g. Lihou 1996a, 1996b), and (ii) an upper chaotic part (Schmid 1975), which is a (probably tectonic) mélange of rocks from the Sardona Nappe, Blattengrat Nappe and NHF Unit. In the western Sernft Valley Oberholzer's (1942) Wildflysch (w_f) entirely seems to correspond to this mélange, which lies as a roughly 5 to 100 m thick, more or less continuous sheet or nappe below the Glarus Thrust. Single components of the mélange may locally be up to several hundreds of meters in size. For example, hectometer-size olistholith-like exotic bodies of Nummulitic limestone from the Blattengrat Nappe occur in this Wildflysch mélange west of Matt and Elm in the upper Geisstal Alp and the upper Chüeboden Alp (Oberholzer 1942).

According to our interpretation, the Flecken Marls on top of the Engi Slates are part of a large olistolith or fragment within the Wildflysch Nappe, much like the Nummulitic limestone fragments in the Wildflysch Nappe in the upper Geisstal Alp and the upper Chüeboden Alp further south. The emplacement of the Wildflysch Nappe should accordingly have taken place after Plattenberg F_1 folding and before Plattenberg F_2 folding and foliation development.

On the profiles through the Glarus Alps made by Schmid (1975) and Lihou (1996a) the Calanda phase folds in the Infrahelvetic Complex are also clearly cut-off unconformably, but by the Glarus Thrust itself. Our observations suggest that this unconformity should not be located at the Glarus Thrust itself, but at the base of the underlying mélange of the Wildflysch Nappe.

d) Relationship between our observations and the Glarus Thrust

The Plattenberg foliation cuts through the Riedboden Thrust, passes upwards through the mélange of the Wildflysch Nappe, and bends northwards into parallelism with the base of the Subhelvetic Units below the Glarus Thrust. These units were therefore emplaced onto the mélange of the Wildflysch Nappe *after* the development of the Plattenberg foliation, i.e. after our Plattenberg F_2 folding phase (Fig. 8). The steeply South-dipping Ruchi phase crenulation foliation, which crenulates the Plattenberg foliation, is the axial plane foliation of centimeter- to decameter-scale cuspate-lobate folds in the lower boundary of the Subhelvetic Units. The Ruchi phase therefore must have taken place *after* the emplacement of the Subhelvetic Units onto the mélange of the Wildflysch Nappe. The Ruchi phase foliation bends northwards into parallelism with the Lochseiten tectonite of the Glarus Thrust, just ~10 cm below the thrust. The Glarus Thrust consequently developed *after* the Ruchi phase.

6. Conclusion

Our study shows that the Engi Slates were folded on a deca- to hectometer scale during the Plattenberg F_1 phase, corresponding to phase 2 folding of Schmid (1975) and to Calanda phase folding of Milnes & Pfiffner (1977). These folds are unconformably cut-off by the Riedboden Thrust at the base of a (tectonic?) mélange mapped by Oberholzer (1942) as Wildflysch (w_f). A tectonic foliation subsequently developed during the Plattenberg F_2 folding phase. This Plattenberg foliation corresponds to phase 2 foliation of Schmid (1975) and Calanda phase foliation of Milnes & Pfiffner (1977). It cuts through the Riedboden Thrust and developed both in the Engi Slates and in the overlying Eocene Flecken Marls of the Wildflysch Nappe. Open Plattenberg F_2 folds probably folded the Riedboden Thrust on a meter- to decameter scale.

Our results differ from previous studies in the Infrahelvetic Complex in three ways: (i) the main tectonic foliation in the area around the Landesplattenberg (Plattenberg foliation in our terminology) is *not* the axial plane foliation to the major folds (Plattenberg F_1 folds in our terminology). In most cases the Plattenberg foliation is oriented parallel to the overturned limb of the F_1 folds and cuts through the axial plane of the F_1 folds. The Plattenberg foliation is therefore *younger* than the F_1 folds. It developed during the Plattenberg F_2 phase. (ii) The overlying Riedboden Thrust was not folded together with the underlying Engi Slates during the Plattenberg F_1 phase. The F_1 folds are cut-off unconformably by the Riedboden thrust, but the Plattenberg foliation cuts *through* the thrust. (ii) The Eocene Flecken Marls above the Engi Slates do not belong to the Blattengrat Nappe, but to the Wildflysch Nappe, such as already proposed by Oberholzer (1933, 1942).

Acknowledgements

This contribution is dedicated to Martin Burkhard, who encouraged the first author to present the results of her diploma thesis to a wider audience. We thank Neil Mancktelow and Heinz Furrer for fruitful discussions and Geoff Milnes and Adrian Pfiffner for critical and very useful reviews.

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Manuscript received October 15, 2007
Revision accepted February 19, 2008
Published Online first July 25, 2008
Editorial Handling: S. Schmid & S. Bucher