The deep structure of the Engadine window : evidence from deep seismic data

Autor(en): **Hitz, Luzi**

Objekttyp: **Article**

Zeitschrift: **Eclogae Geologicae Helvetiae**

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

Heft 2

PDF erstellt am: **25.09.2024**

Persistenter Link: https://doi.org/10.5169/seals-167919

Eclogae geol. Helv. 89/2: 657–675 (1996)

0012-9402/96/020657-19 $1.50 + 0.20/0
Birkhäuser Verlag, Basel

The deep structure of the Engadine Window: Evidence from deep seismic data

LUZI HITZ[1]

Key words: Seismic reflection, deep structure, Engadine Window

ABSTRACT

A deep seismic reflection profile through the Engadine Window provides a first detailed image of the Window's deep crustal structure. The profile, termed E3, is located in the western half of the Window in eastern Switzerland and consists of the two lines E3-South and E3-North. For the geologic interpretation, the seismic reflection data are transformed into computer-generated line drawings and are ray-theoretically depth-migrated. The depth-migrated reflections are then projected onto the common trace of the E3-transect. The geologic interpretation, using surface correlation and the results of existing seismic profiles, points towards an up to 10 km thick pile of N-Penninic Bündnerschiefer building the inner core of the Window. The Bündnerschiefer form a large-scale detachment fold. They are underlain by an ENE-striking basement nappe-stack consisting of N-Penninic and Helvetic basement units. The lowermost crust is only reflective in the northern, external part of the E3-transect. It indicates a crustal thickness of more than 50 km with the European Moho dipping towards the SSE. The geologic interpretation suggests that the Engadine Window was formed by the indentation of an upper crustal basement-wedge leading to large-scale detachment folding, local uplift and extension in Late Tertiary times.

ZUSAMMENFASSUNG

Diese Arbeit präsentiert ein tiefenseismisches Profil durch das Engadiner Fenster und zeigt zum ersten Mal ein detailliertes Bild der Krustenstruktur im Fensterbereich. Das Profil wurde im westlichen Teil des Engadiner Fensters aufgezeichnet. Es besteht aus den zwei Teilprofilen E3-Süd und E3-Nord. Für die geologische Interpretation wurden die seismischen Reflexions-Daten in computer-generierte Strichzeichnungen umgewandelt und strahlen-theoretisch migriert. Die tiefen-migrierten Reflexionen wurden in der Folge auf die gemeinsame E3-Profilspur projiziert und mit der Oberflächengeologie und Resultaten von bestehenden seismischen Profilen korreliert. Die so entstandene geologische Interpretation des E3-Profils zeigt, dass die N-Penninischen Bündnerschiefer den inneren Kern des Fensters bilden. Die bis zu 10 km mächtigen Bündnerschiefer bilden dabei eine grossmassstäbliche Falte, welche von den darunterliegenden, ENE-streichenden N-Penninischen und Helvetischen kristallinen Decken entkoppelt ist. Die Unterkruste im Bereich des Engadiner Fensters ist nur im nördlichen, extern-alpinen Teil des E3-Profils reflektiv. Die Interpretation deutet dort auf eine nach SSE einfallende Europäische Moho und Krustenmächtigkeiten von über 50 km hin. Im weiteren erlaubt die geologische Interpretation die Formulierung eines tektonischen Modells, welches die Bildung des Engadiner Fensters mit dem spättertiären Eindringen eines kristallinen Keils in der Oberkruste erklärt. Letzteres führt zur Entkoppplung und Deformation der darüberliegenden Bündnerschiefer sowie zu einer beträchtlichen Hebung und Extension im Fensterbereich.

[1] Geologisches Institut der Universität Bern, Baltzerstrasse 1, CH–3012 Bern, Present Address: Froschaugasse 12, CH–8001 Zürich

1. Introduction

For the understanding of the structure and the development of an orogen, tectonic windows – eroded areas of one or several thrust sheets exposing the rocks underneath – are of particular interest. In the Alps, the tectonic windows in the Tauern area and in the area of the Lower Engadine valley represent the most prominent examples. The latter, here called the Engadine Window, is situated in eastern Switzerland and western Austria. It exposes a Penninic nappe stack framed by Austroalpine tectonic units. With its eye-shape geometry in map-view and the overlookable dimensions of 55 km × 17 km it often serves as a school-book example of tectonic windows (cf. Boyer & Elliot 1982, Twiss & Moores 1992) and has attracted the interest of geologists for over 150 years (Escher & Studer 1839).

The French geologist Termier (1903) recognized for the first time the tectonic nature of the Engadine Window. Since then over 280 articles have been published dealing mainly with surface geologic aspects. The first attempts to enlighten the deep structure of the Engadine Window date back to the early 1970ies (Scheliga 1971, Giese & Prodehl 1976). The refraction seismic measurements undertaken in that period produced consistent estimates of the overall crustal thickness but contrasting interpretations of the internal crustal structure (cf. Miller et al. 1978, Noack 1984, Yan & Mechie 1989). In the early 1990ies, the Swiss National Science Foundation Program 20 (NFP20), therefore, decided to launch a deep reflection seismic survey crossing the Engadine Window. The survey is situated in the western half of the Window and is termed E3 (Fig. 1).

In this contribution, I present the reflection seismic data of the E3-transect and discuss a possible geologic interpretation. The results are summarized in a crustal cross-section through the Engadine Window which serves to develop a new model concerning the formation of the window.

2. Geologic setting

The Engadine Tectonic Window is formed by two major Alpine nappe systems (Fig. 1). The *Penninic nappes* represent the lower system and build the core of the Window. They are surrounded and overlain by *Austroalpine nappes*. The latter are derived from the NW margin of the Adriatic microplate and consist of the thick-skinned Silvretta-, Ötztal-, Sesvenna- and Scarl-nappes (cf. Trümpy 1980, Laubscher 1983, Thöni 1988). In the Window's core, the Arosa mélange zone forms the highest Penninic nappe. This mélange of predominantly pelagic sediments and ophiolitic material is interpreted as the Mesozoic remnants of the South-Penninic Piemont-Liguria ocean floor (Bernoulli & Weissert 1985). The Tasna nappe forms the next lower Penninic unit. It consists of continental and subcontinental basement and a Mesozoic sedimentary succession. During the Early Cretaceous, it formed the northern transition between the Middle-Penninic Briançonnais Swell and the North-Penninic Valais basin (Stampfli 1993, Florineth & Froitzheim 1994). The sediments and "ophiolites" of the Valais basin build up the inner core of the Engadine Window. They consist of the thin zone of Ramosch with prominent ophiolitic inclusions, the Roz-Champatsch Flysch, and the North-Penninic Bündnerschiefer sediments (Cadisch et al. 1968, Trümpy 1972).

The occurrence of Early Eocene foraminifera in the Tasna Flysch (Rudolph 1982, Oberhauser 1983) demonstrates that the Austroalpine nappes were transported onto the

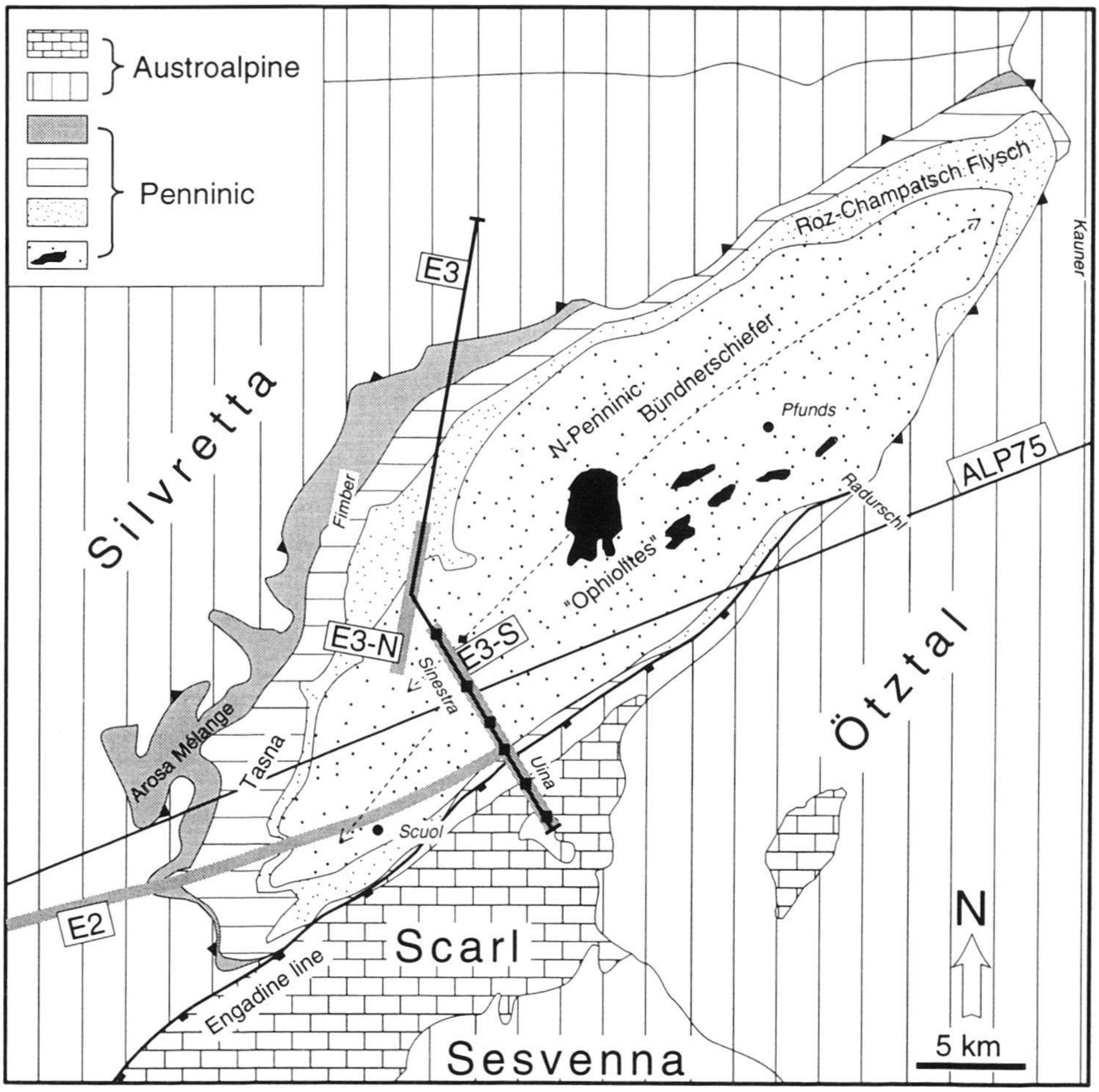


Fig. 1. Simplified tectonic map of the Engadine Window showing the location of the E3-transect consisting of the seismic reflection profiles E3-North (E3-N) and E3-South (E3-S). Also shown are the positions of the intersecting seismic reflection profile E2 (Pfiffner & Hitz 1996, Hitz 1994) and of the seismic refraction profile ALP75 (Yan & Mechie 1989). Profile coordinates are given in figures 3 and 6.
Grey lines = CDP-lines, black squares = shot points, black straight line = trace of cross-section in Fig. 6, dashed lines = crest-lines of the Engadine antiform (Cadisch et al. 1963). The E3-S receiver spread went along the Uina and Sinestra valleys. The E3-N receiver spread was located in the Fimber (= Fenga) valley.

Penninic units after the Early Eocene. Collision was accompanied by the exhumation of high-pressure/low-temperature rocks found in the inner core of the Window (Bousquet et al. 1995). The Early Tertiary northward thrusting was followed by post-stack E-W extension and large-scale open folding in late Oligocene times (Foitzheim et al. 1994). Contemporaneous or successive local uplift together with faulting along the Engadine Line (Schmid & Froitzheim 1993) and erosion engendered the Engadine Window's present shape.

3. The seismic data of the E3-transect

The deep seismic E3-transect was recorded in the fall of 1991 in a joint operation of the geophysical Institutes of the Universities of Clausthal (FRG), Munich (FRG), Münster (FRG), Leoben (A), the ETH Zürich (CH) and the Swiss company GeoExpert (CH). A total of six dynamite shots were fired, each with a 30 kg charge. They were recorded by a 14.3 km long receiver spread comprising five separate registration units in the Uina and Sinestra valleys (Clausthal: 48 channels, Munich: 48 channels, Münster: 96 channels, Zürich: 48 channels, GeoExpert: 48 channels), and by a separate 4.8 km long receiver spread in the Fimber valley (Leoben: 96 channels). This configuration resulted in two CDP-processing lines (grey lines in Fig. 1), one oriented SSE-NNW (E3-South), and one oriented SSW-NNE (E3-North). Note that E3-North was oriented obliquely to the line of shotpoints.

Seismic data processing of the E3 data was carried out at the processing center of the Institute of Geophysics at the ETH Zürich. The variable quality of the shot-gathers and the low CDP-coverage demanded a special processing approach, which is outlined in detail by De Haas (1992). In the following, the reflectivity of lines E3-North and E3-South is described briefly.

The northern half of the E3-transect, line E3-North (Fig. 2a, see also Fig. 3a), shows a strongly reflective upper crust starting with an approximately 1 s "thick" reflective zone from 2 s in the NNE to 3 s in the SSW. This is followed by a reflection group between 3 to 4 s two-way traveltime (TWT) with a marked change in reflection geometry: in the SSW, reflections are subhorizontal to NNE-dipping whereas towards the NNE, they are SSW-dipping. Below the latter, a 2 s "thick" zone with constantly SSW-dipping reflection packages can be observed marking the base of the reflective upper crust. The lowermost crust is characterized by strong, SSW-dipping reflections between 15 and 17 s.

Similar to E3-North, the southern half of the E3-transect, line E3-South (Fig. 2b, see also Fig. 3d) shows strong reflections in the upper 8 s dipping predominantly to the SSE. Below 8 s, reflectivity is poor. The most prominent reflection group is characterized by two-cyclic, high-amplitude reflections dipping from 2.0 s in the NNW to 3.5 s in the SSE. Below this group, a subhorizontal to slightly NNW-dipping reflective zone can be observed. The latter is followed by two SSE-dipping reflection groups, one from 4 to 5.5 s in the SSE, the other from 5 to 6.5 s in the SSE. Upper crustal reflectivity ends with a strongly SSE-dipping reflection group at 6 s in the NNW. Reflectivity in the first 1.5 s of the E3-transect is erratic. Note, however, a change in reflection orientation from subhorizontal/NNW-dipping in the central part to SSE-dipping in the southern part of the line.

For the purpose of depth-conversion, the seismic data (Fig. 2) were transformed into computer-generated line drawings (Fig. 3a and d) using a program developed by Valasek (1992). Ray-theoretical depth-migration of the automatic line drawings (cf. Holliger & Kissling 1991) was done with a velocity structure derived from the ALP75 refraction line by Yan & Mechie (1989). The resulting depth-migrated line drawings are shown in figures 3b and e. Note that up-dip migration of dipping line elements increased the profile length considerably and that the identification of the above described reflection groups, which is easy in figures 3a and d, is less evident in the depth-migrated line drawings of figures 3b and e.

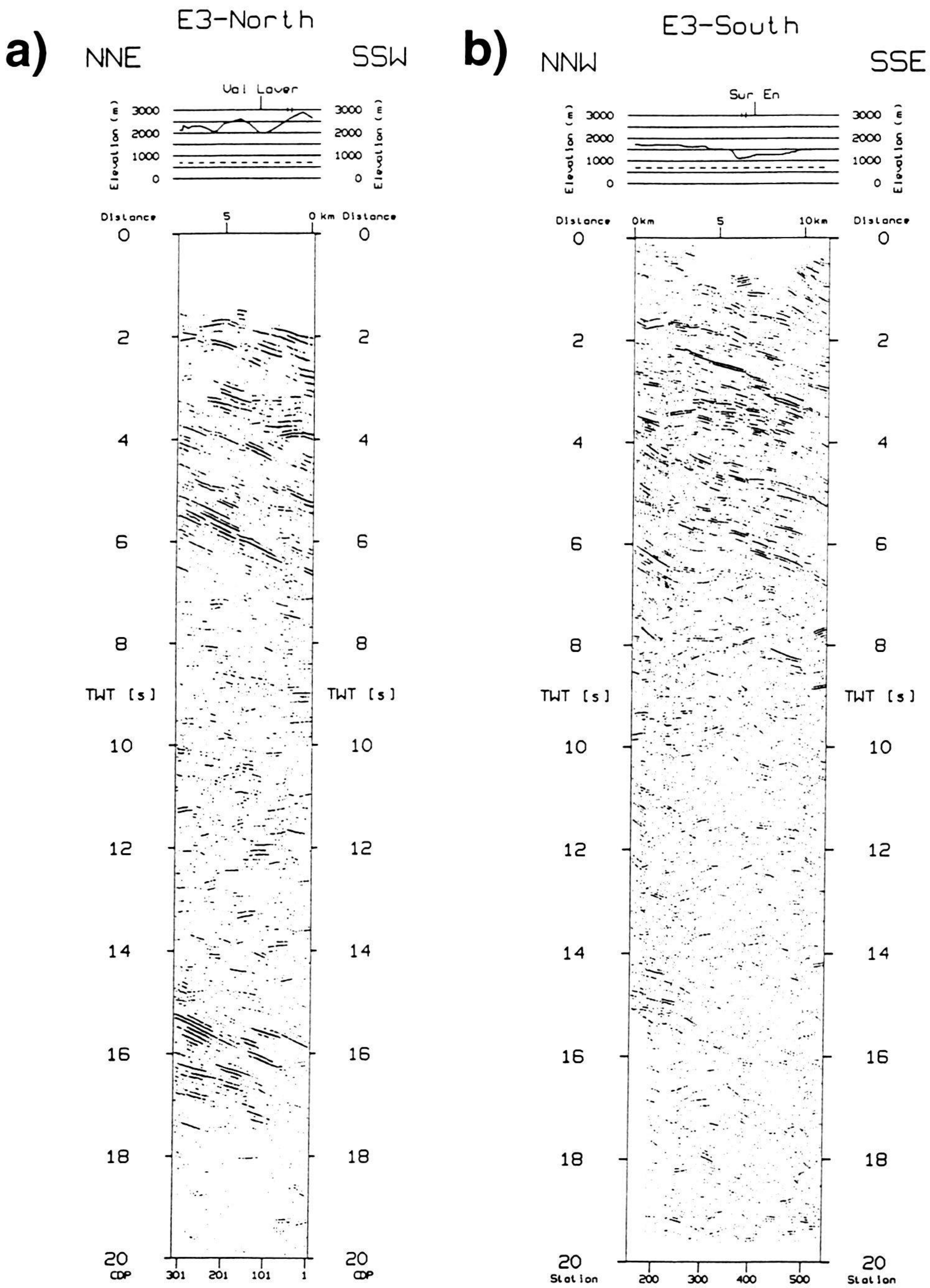


Fig. 2. Unmigrated seismic reflection data shown in an apparent line drawing format (= strongly coherency filtered). Both sections have a single-fold coverage and consist of six shot-recordings each. (a) E3-North. (b) E3-South.

Horizontal to vertical scale = 1 : 1 at an average crustal velocity of 6.0 km/s (1 s TWT ≈ 3 km). Datum = 700 m a.s.l.

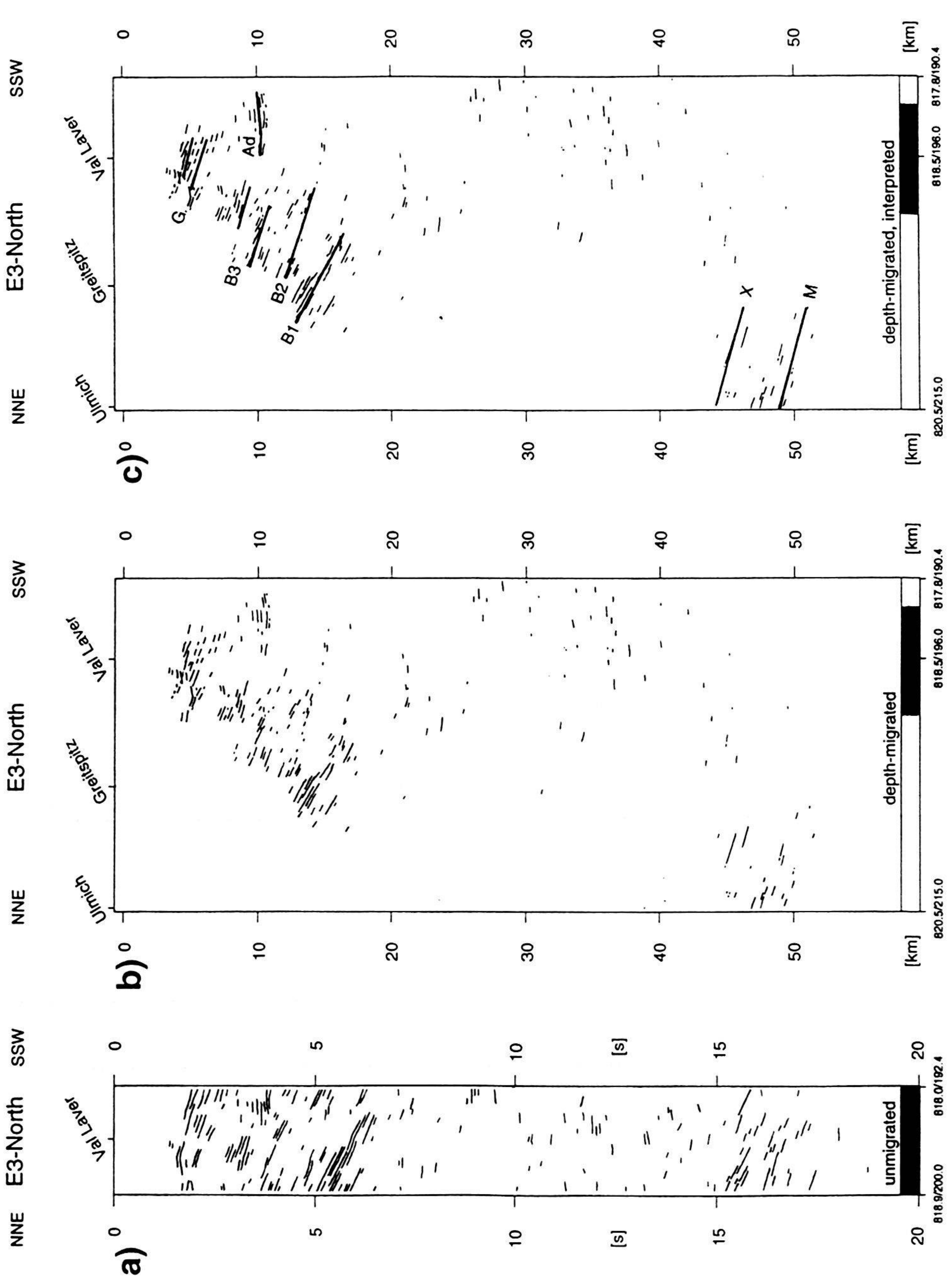
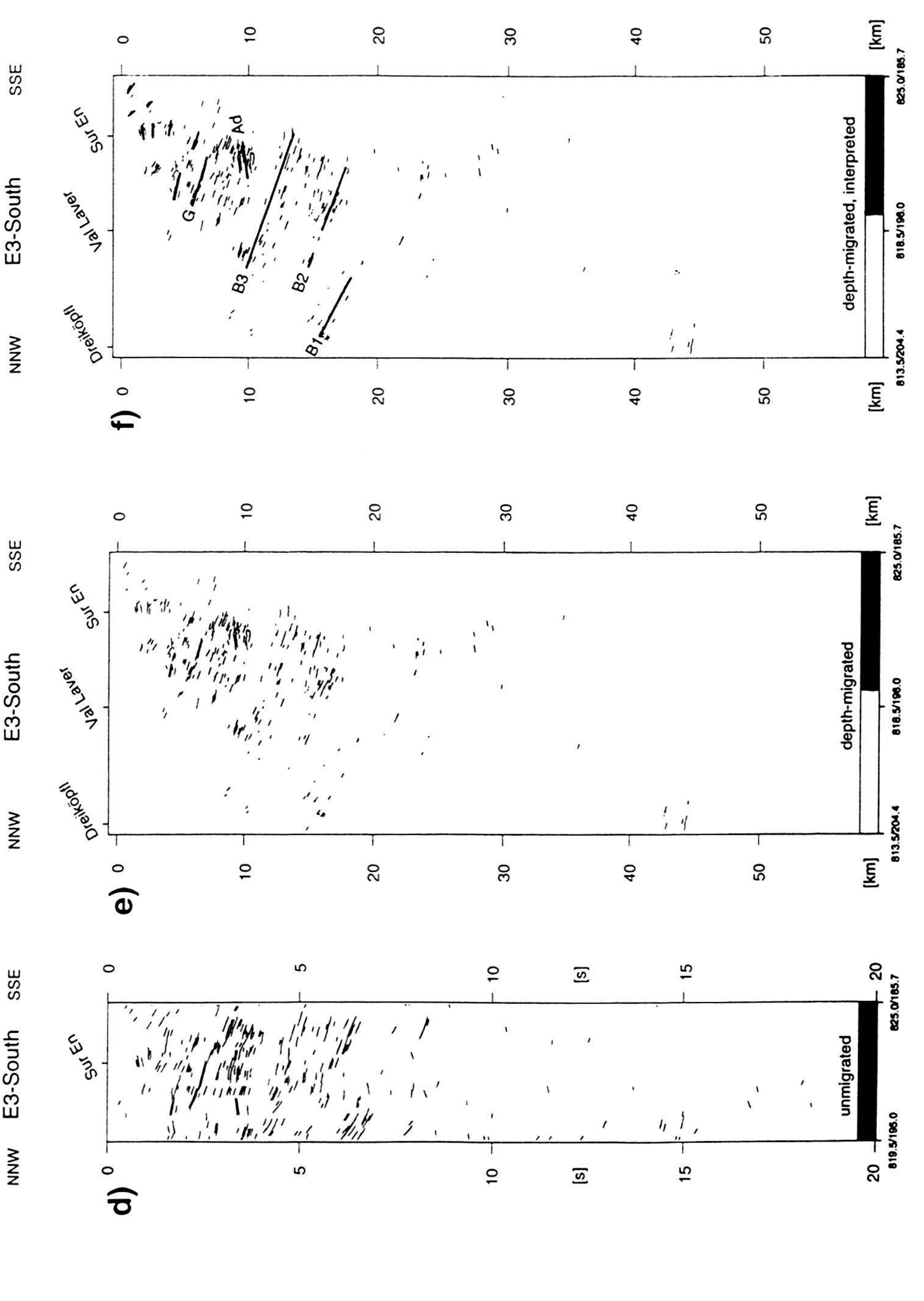


Fig. 3. Computer-generated line drawings of the E3 seismic reflection data. Data are shown in unmigrated (a and d), depth-migrated (b and e) and interpreted form (c and f). Lettered reflection groups are discussed in the text. Note the increase in profile length due to up-dip migration of dipping line elements. Horizontal to vertical scale = 1 : 1. Coordinates correspond to the Swiss National km-Grid. Datum = 700 m a.s.l.


d)
E3-South
NNW
SSE
Sur En
unmigrated
[s]
e)
E3-South
Dreiköpfl
Val Laver
depth-migrated
[km]
f)
E3-South
depth-migrated, interpreted
G
Ad
B3
B2
B1

4. Geologic interpretation of the E3-transect

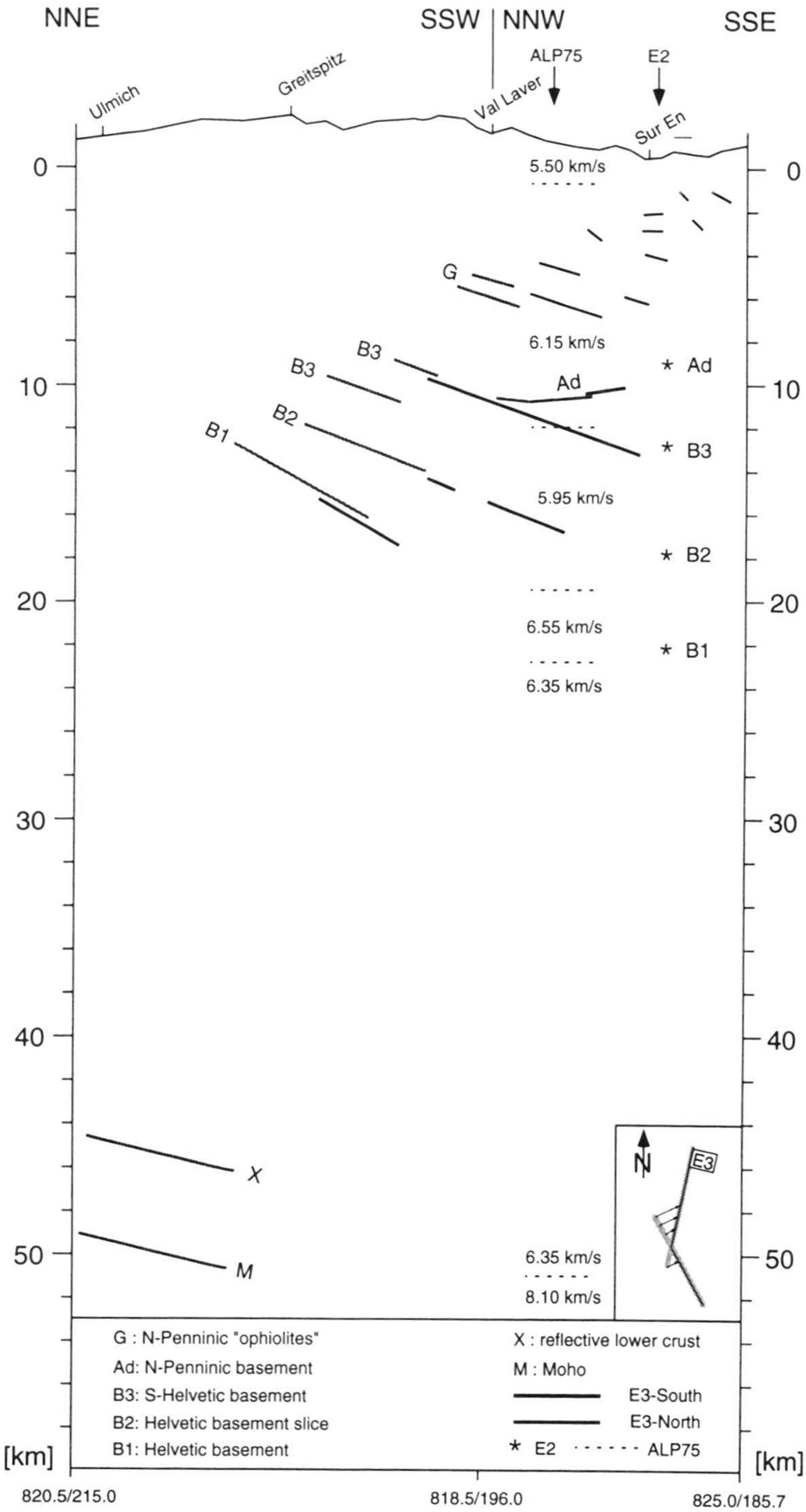
In a first interpretative step, depth-migrated coherent reflections were laterally correlated into groups (labeled in Fig. 3c and f). In a second step, the reflection groups were projected parallel to the WSW-ENE regional structural trend (see inset in Fig. 4) onto the common E3-transect (Fig. 1). This procedure resulted in the simplified line drawing of figure 4. Note that the projected reflections of E3-North and E3-South line up smoothly in the composite transect, indicating that distortions due to projection are moderate. The next interpretation step involved the correlation of the simplified line drawing with the existing geophysical and geological database of the study area. The geophysical data consist of the intersecting E2 seismic reflection profile (Pfiffner & Hitz 1996, Hitz 1994, 1995), the intersecting ALP75 seismic refraction profile (Yan & Mechie 1989, Noack 1984) and two seismic experiments in the area E of Pfunds (Scheliga 1971, Giese & Prodehl 1976). The geologic data used include geologic and tectonic maps (Kläy 1957, Cadisch et al. 1963, Trümpy 1972, Oberhauser 1980), structure contour maps (Stutz & Walter 1983) and various studies regarding the geology of the Lower Engadine valley (cf. Cadisch 1953, Trümpy 1972, Trümpy 1980, Schmid & Haas 1989, Mattmüller 1991, Schmid & Froitzheim 1993, Froitzheim et al. 1994, Florineth & Froitzheim 1994).

Regarding the interpretation of the E3-transect, it should be noted that the domal structure of the Engadine Window generally prohibits reflection correlation with geologic outcrops by means of projections. This stands in contrast to the deep-seismic lines in the Central Alps (for example line E1) where down-plunge projections are feasible due to pronounced axial dips (Litak et al. 1991). The identification of individual reflections in the E3-transect must thus be mainly based on the correlation with the intersecting seismic lines E2 and ALP75, respectively. In the following, the results of the geologic interpretation are presented. They are summarized in the crustal cross-section of figure 6.

Shallow crust: Due to large offset recordings and low CDP-coverage, reflections from the shallowmost crust are sparse. Only in the southernmost part of the E3-transect where offsets are smallest can shallow reflectivity be observed (Fig. 2b, Fig. 3d). There, line E3-South shows some strongly SSE-dipping reflections at 1 to 1.5 s at the line's southern end (Fig. 5). By up-dip projection, they match with the Engadine line, a scissor fault with an estimated vertical throw of 4 km in the area of Scuol (Schmid & Haas 1989, Schmid & Froitzheim 1993). Reflectivity might stem from the juxtaposition of contrasting lithologies as downfaulting along this part of the Engadine line places Austroalpine basement (Sesvenna) next to Penninic sediments (Bündnerschiefer).

The structure of the Austroalpine units, the Arosa mélange zone and the Middle-Penninic Tasna nappe as shown in figure 6 is based on surface data by Kläy (1957) and Oberhauser (1980) in the northern part, and Cadisch et al. (1963), Stutz & Walter (1983),

Fig. 4. Depth-migrated line drawing resulting from the projection (see inset) of coherent reflection groups of lines E3-North and E3-South (Figs. 3c and f) onto the common E3 trace (Fig. 1). Note that the migrated reflection groups of the two lines line up smoothly indicating that distortions due to the projection are moderate. Stars = intersecting reflection groups of line E2 (Pfiffner & Hitz 1996, Hitz 1994), dashed lines = intersecting discontinuities from the ALP75 velocity-depth model (Yan & Mechie 1989). Coordinates correspond to the Swiss National km-Grid. Horizontal to vertical scale = 1 : 1.


NNE
SSW
NNW
SSE
ALP75
E2
Ulmich
Greitspitz
Val Laver
Sur En
5.50 km/s
6.15 km/s
5.95 km/s
6.55 km/s
6.35 km/s
6.35 km/s
8.10 km/s
G
B3
B3
B2
B1
Ad
X
M
* Ad
* B3
* B2
* B1
E3
N
G : N-Penninic "ophiolites"
Ad: N-Penninic basement
B3: S-Helvetic basement
B2: Helvetic basement slice
B1: Helvetic basement
X : reflective lower crust
M : Moho
E3-South
E3-North
* E2
ALP75
[km]
820.5/215.0
818.5/196.0
825.0/185.7

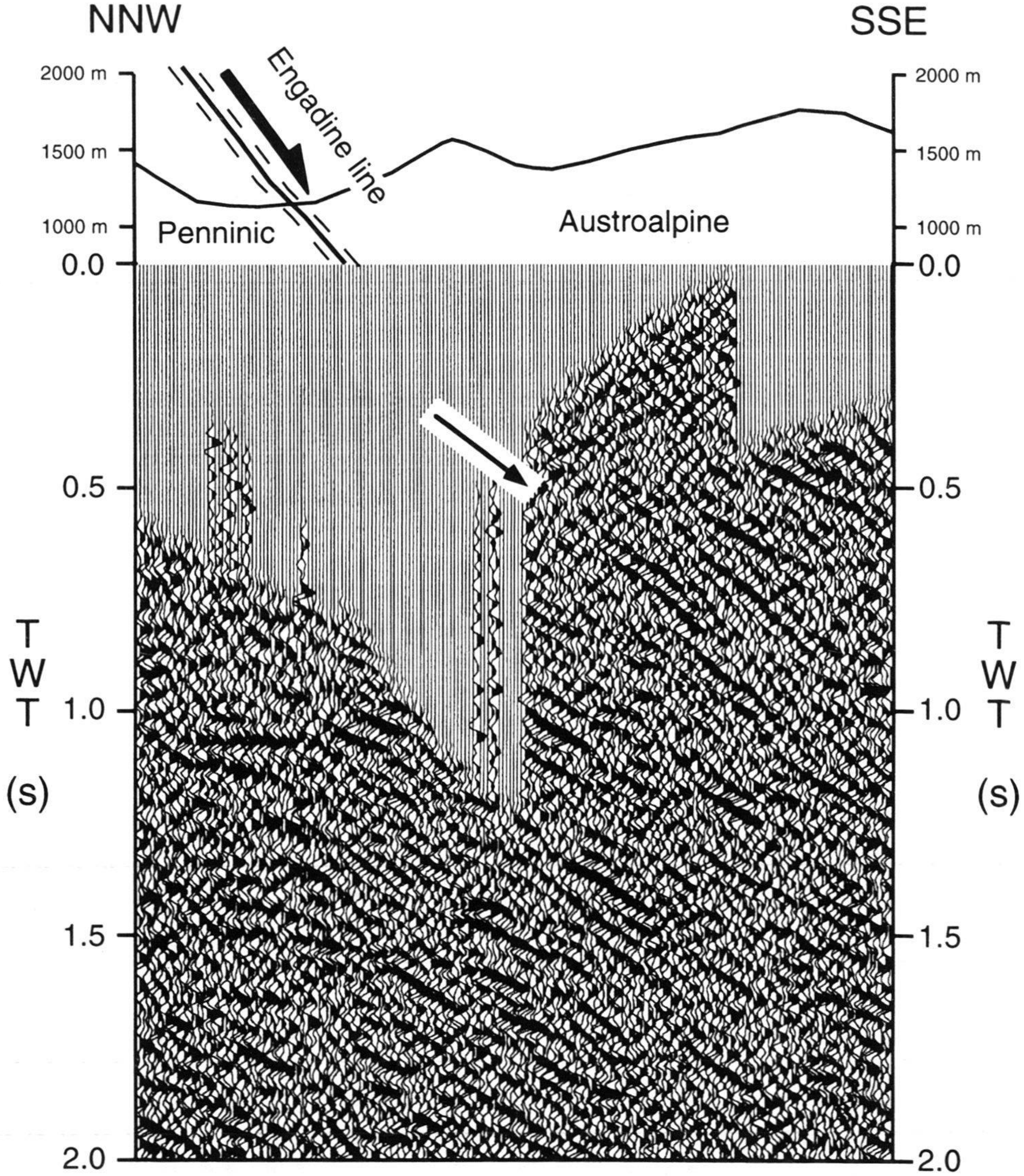


Fig. 5. Unmigrated extract of the southernmost part of line E3-South. SSE-dipping reflections (arrow) can be correlated with the surface position of the Engadine line, which essentially acts as a normal fault in the area. Note the change from subhorizontal reflections in the NNW to SSE-dipping reflections in the SSE. This change in orientation is attributed to dragfolding associated with faulting along the Engadine line.
Horizontal to vertical scale = 1 : 1. Datum = 700 m a.s.l.

Schmid & Haas (1989) and Schmid & Froitzheim (1993) in the southern part of the cross-section. The position of the Sesvenna basement nappe is additionally based on strong reflections at 1.1 s TWT (~1.5 km b.s.l.) from a seismic reflection experiment in the Kauner valley (Fig. 1), which Giese & Prodehl (1976) attributed to the contact between Penninic Bündnerschiefer and Austroalpine basement.

N-Penninic cover and basement: Comparison with the reflectivity character in lines E1 and E2 (cf. Pfiffner et al. 1990, Pfiffner & Hitz 1996) and surface data suggest that the short, predominantly SSE-dipping reflections between 2 and 7 km depth (Fig. 4) originate from within the N-Penninic Bündnerschiefer unit. Reflectivity is likely to stem from intercalated large-scale lenses of ophiolitic rocks observed also at the surface (cf. Koller & Höck 1987). Reflections labeled *G* in figure 4 are speculatively attributed to a more or less continuous ophiolitic layer, similar to the one encountered in the seismic lines E1 and E2 (Pfiffner et al. 1990, Pfiffner & Hitz 1996). In the W, this layer is correlated with the Grava thrust sheet, a subunit of the N-Penninic Bündnerschiefer (Steinmann 1994).

Based on the correlation with the seismic line E2 (Pfiffner & Hitz 1996, Hitz 1994), the next deeper reflection group *Ad* (Fig. 4) ist interpreted as the top of a large-scale N-Penninic basement unit, which corresponds in the W to the Adula nappe. Reflection group *Ad* forms and exception in the reflection geometry of the E3-transect as it is sub-horizontal to slightly NNE-dipping. Together with the underlying reflection group *B3*, *Ad* forms a triangle indicative of the northern end of this Penninic basement nappe. Reflectivity of *Ad* ist tentatively attributed to the impedance contrast between granitic gneiss basement rocks (Adula) and high-velocity marbles and basalts of the overlying N-Penninic cover (Aul thrust sheet, cf. Pfiffner et al. 1991, Sellami et al. 1990).

Helvetic basement: Reflection group *B3* (Fig. 4) can be correlated with the top of the S-Helvetic basement unit imaged in the E2 seismic line (Pfiffner & Hitz 1996, Hitz 1994). In line E1 (Pfiffner et al. 1990), this discontinuity corresponds to the top of the Gotthard unit and is identical with the basal Penninic thrust or Penninic "Front". Reflectivity is explained by remnants of S-Helvetic cover-sediments (Triassic dolomites) and/or a velocity anisotropy produced by mylonitization along the basal Penninic thrust. In the ALP75 velocity-depth model by Yan & Mechie (1989), the corresponding velocity discontinuity marks the top of a velocity inversion zone (Fig. 4), indicating that the basement rocks might be slower than the overlying cover sediments.

The next deeper reflection group, *B2*, is attributed to the top of a Helvetic basement slice underlying the Engadine Window. Interpretation of line E2 (Pfiffner & Hitz 1996, Hitz 1994) indicates that the latter is only of local extent. Reflectivity could stem from Triassic to Lower Jurassic carbonates sandwiched within crystalline basement rocks.

Reflection group *B1* (Fig. 4) marks the deepest coherent upper crustal reflections along the E3-transect. These reflections are, therefore, interpreted as originating from the top of the seismically transparent European upper crust. As such *B1* corresponds to the Helvetic foreland, i.e. the Aar massif basement as encountered further W and NW. As in the case of *B2*, reflectivity of *B1* can be attributed to a sediment layer sandwiched between crystalline basement. This sediment layer, probably consisting of marbles, might correspond to the high-velocity layer (6.55 km/s, Fig. 4) shown in the ALP75 velocity-depth model by Yan & Mechie (1989).

Lower crust and Moho: Reflections between *X* and *M* (Fig. 3c and Fig. 4) are comparable to the seismic character of the lowermost crust in lines E1 and parts of E2. The high

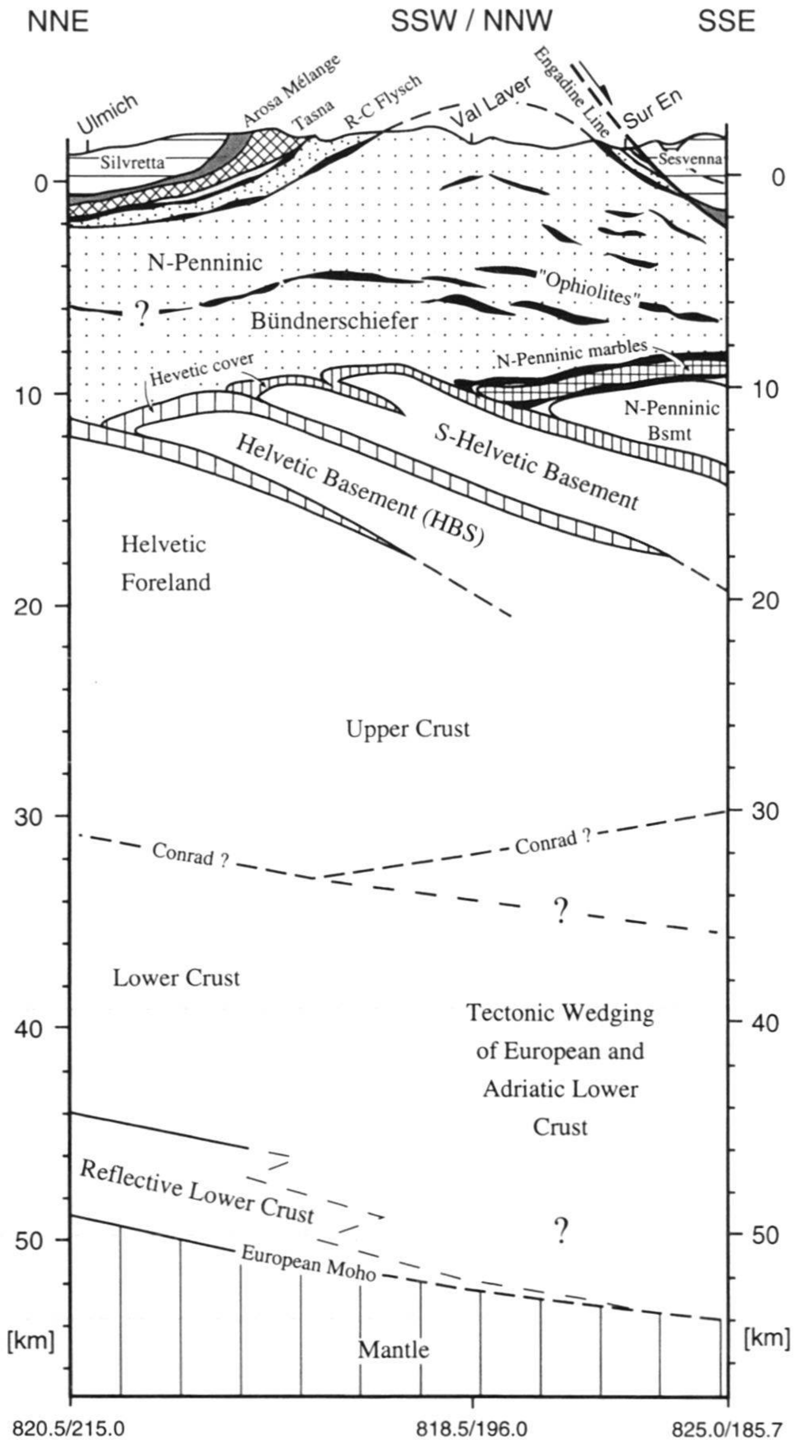


Fig. 6. Crustal cross-section through the Engadine Window based on the interpretation of the E3 seismic reflection data, the intersecting seismic profiles E2 and ALP75 and surface geology. The trace of the cross-section is indicated in Fig. 1.
Coordinates correspond to the Swiss National km-Grid. Horizontal to vertical scale = 1 : 1.

reflectivity may stem from a subhorizontal layering of lamellae with large acoustic impedance contrasts. Synthetic seismogram modeling by Holliger & Levander (1994a) of the Strona-Ceneri/Ivrea cross-section, Southern Alps, has shown that strong reflections result from the contacts of silicic and mafic, mafic and ultramafic or silicic and ultramafic rocks. The subhorizontal layering of these lithologies may either be primary, i.e. magmatic (Holliger & Levander 1994b) or may originate from stretching of a thickened and thermally relaxed heterogeneous lower crust during post-thickening crustal collapse (Rey 1993).

However, this characteristic reflectivity of the lowermost crust is absent in the middle and southern part of the E3-transect. This observation is in agreement with the eastern part of the intersecting line E2, where a reflective lower crust as well as a reflective Conrad discontinuity (top lower crust) are not observable either. This lack of reflectivity is tentatively attributed to the difference in energy scattering between the external and internal Alpine domain (Hitz 1995), i.e. high scattering in the strongly deformed internal domain (upper crustal nappe stack, deformed lower crust) versus low scattering in the less deformed external domain (undeformed foreland and lower crust). Moreover, it is possible that the transition from reflective to non-reflective lower crust coincides with the northern extent of tectonic wedging between European and Adriatic lower crust, as indicated by the reflectivity pattern in the NFP20 seismic network covering the Swiss Alps (cf. Valasek 1992, Laubscher 1994, Hitz 1995). The Conrad discontinuity, although non-reflective in the E3-transect, is thus speculatively drawn with a dip-reversal in the crustal cross-section of figure 6. This shall also reflect the idea that despite the lack of coherent reflections, a differentiation between upper and lower crust is likely to exist.

The base of the crust, i.e. the European Moho, is placed at the bottom of the reflection package between X and M. It dips with approximately 13° to the SSW. As the lower crustal reflectivity disappears to the S, the southward continuation of the European Moho in the cross-section (Fig. 6) corresponds entirely to a speculative extrapolation of M. Note that the extrapolated Moho discontinuity fails to match the refraction-derived Moho by Yan & Mechie (1989) by approximately 3 km (Fig. 4). The misfit suggests depth-distortions due to lateral out-of-plane reflected energy in the ALP75 refraction data. Wide-angle Moho reflections of the latter should thus be migrated out of the vertical plane to the north.

5. Discussion and tectonic implications

Correlation between lines E2 and ALP75, and the E3-transect: The strongly SSE-dipping reflections in the E3-transect are indicative of out-of-plane reflected energy in the seismic strike-lines E2 and ALP75, respectively. It is thus not surprising that none of the intersecting E2-reflections (depth-migrated along strike, see Hitz 1994) and ALP75-velocity-discontinuities (Yan & Mechie 1989) match the migrated reflections of the E3-transect (Fig. 4). A correlation within the error bounds is nevertheless possible and facilitates the identification of the individual reflections. Moreover, a minimum amount of three-dimensional structural information can be gained in the area of intersection. There, the WSE-ENE striking E2 profile shows subhorizontally oriented Penninic and Helvetic basement units whereas in the E3-transect, the same basement units are dipping SSE (Helvetic units) or NNW (Penninic unit). Consequently, an ENE-strike (050°N to 060°N) can be deduced for the basement units underlying the Engadine Window, which closely corresponds to the regional strike of the surface units (Kläy 1957, Cadisch et al. 1963). This ENE-strike of the basement units was confirmed by three-dimensional ray-tracing carried out by Hitz (1995). The good argreement in strike between units at the surface and deep basement units suggests that the formation of the Engadine Window is closely linked to deformation within the underlying basement (see below).

Geologic interpretation of the E3-Transect (Fig. 6): The geologic interpretation of the E3-transect shows that the Engadine Window is underlain by an up to 10 km thick pile of N-Penninic Bündnerschiefer. The latter is likely composed of a number of thrust sheets, as indicated by coherent reflectivity within the Bündnerschiefer. These units form the core of the domal antiform constituting the Engadine Window. This antiform apparently does not affect the underlying basement units, which is compatible with the E2-interpretation (Pfiffner & Hitz 1996, Hitz 1994) where the basement units underlying the Engadine Window are subhorizontally oriented. From this it can be concluded that the N-Penninic Bündnerschiefer units must have detached from the underlying basement nappe-stack during the formation of the antiform, i.e. the Bündnerschiefer of the Engadine Window represent a large-scale detachment fold. Moreover, the Engadine Window seems to be underlain by a Helvetic basement slice (HBS). The latter is also recognized along strike in line E2, where it ends laterally towards the W in the area of the Flüela-Pass (Pfiffner & Hitz 1996, Hitz 1994). The HBS-basement slice is thus of limited lateral extent, and possibly even restricted to the area of the Engadine Window. It could thus be responsible for the axial plunge and therefore for the domal structure of the Window.

Based on fault-slip analysis and large-scale nappe correlation, Schmid & Froitzheim (1993) redefined the Engadine line (Fig. 1) as a post-collisional (Late Tertiary) tectonic lineament along which oblique slip and block rotation took place. In the area of the E3-transect, the Engadine line essentially acts as a brittle normal fault with downfaulting of the SE block (Fig. 6). The vertical throw is estimated at approximately 4 km (Schmid & Haas 1989). Movements along this part of the Engadine line juxtapose Austroalpine basement and N-Penninic Bündnerschiefer. Such a lithologic contrast should give rise to steep reflections and to a lateral P-wave velocity change. SSE-dipping reflections correlating with the surface position of the Engadine line can indeed be observed in the E3 data (Fig. 5). The reflections dip SSE at approximately 55° and agree with the dip range expected from surface data. Moreover, a change in reflection orientation from subhorizontal between 1 and 1.5 s to SSE-dipping further S can be observed in the Bündnerschiefer units below the Engadine fault (Fig. 5). This change may reflect drag-folding in the fault's footwall (Schmid & Froitzheim 1993). Regarding the expected P-wave velocity change across the Engadine line, a short seismic refraction profile in the Radurschl valley (Fig. 1) indeed indicated a lateral velocity inhomogeneity (Scheliga 1971, Giese & Prodehl 1976). We can thus attribute this lateral velocity change to the contact between the downfaulted Austroalpine basement and the N-Penninic Bündnerschiefer.

Model for the formation of the Engadine Window: Large-scale open folds of Late Oligocene age (Domleschg-Phase of Froitzheim et al. 1994) affecting Austroalpine and Penninic units trend E-W to NE-SW and formed in response to dextral transpression along the Insubric lineament and the coeval intrusion of the Bregaglia and Novate batholiths. Given the similar shape and orientation of the NE-striking antiform constituting the En-

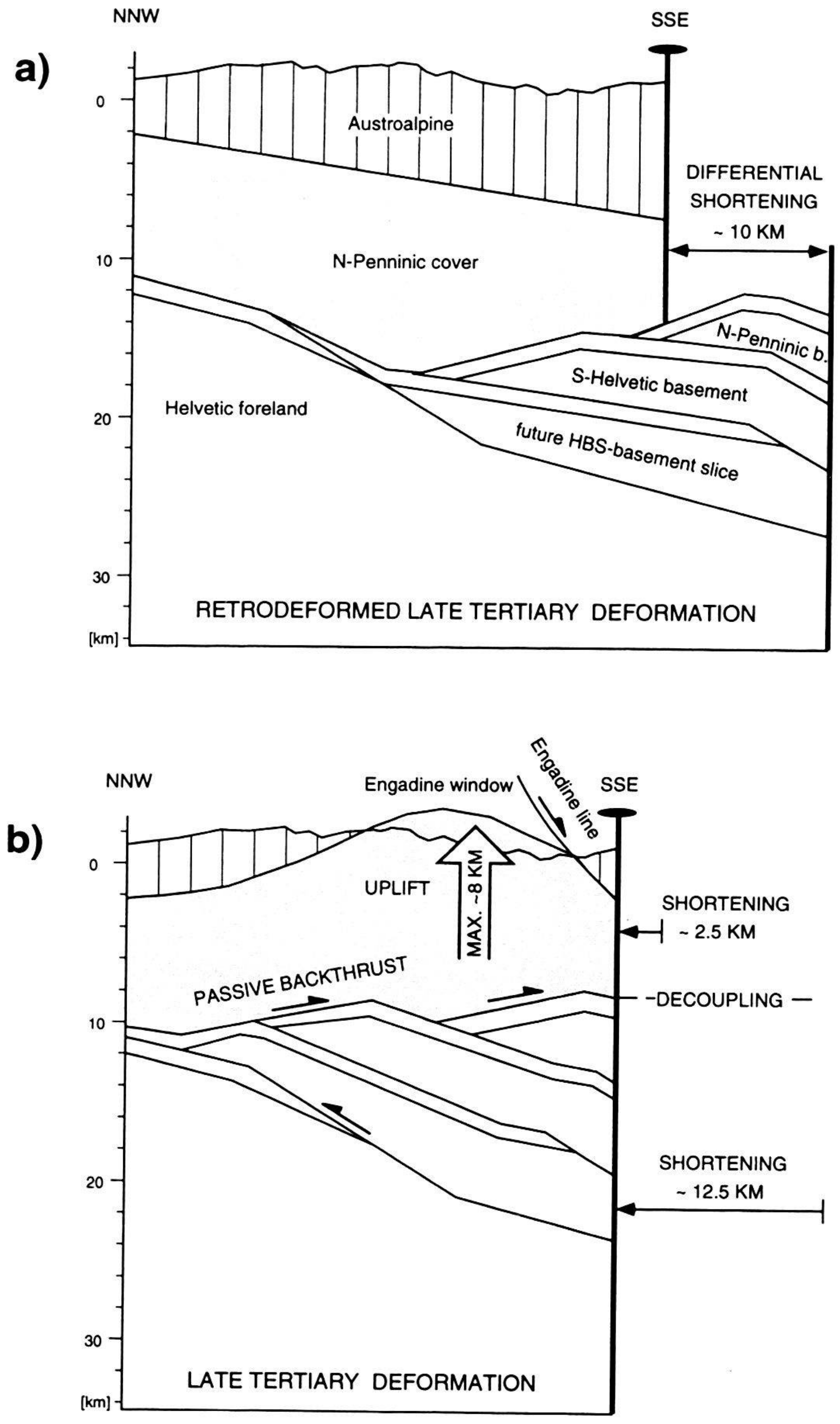


Fig. 7. Tectonic model for the formation of the Engadine Window. (a) Retrodeformation of Late Tertiary deformation shows a differential shortening of approx. 10 km between the Austroalpine lid and the European basement suggesting a decoupling between the two units. (b) Late Tertiary deformation leads to the indentation of an upper crustal basement wedge bounded by a passive back thrust at the top and an active NW-vergent thrust at the bottom. The indentation is associated with detachment folding, local uplift and extension in the cover resulting in the present-day domal shape of the Engadine tectonic window.
Horizontal to vertical scale = 1 : 1.

gadine Window, a correlation with this phase of post-collisional shortening is plausible. Furthermore, thrusting in the external basement is also of Late Tertiary age and equally related to post-collisional NNW-SSE directed shortening (Schmid et al. 1995). From this it is inferred that both open folding of N-Penninic and Austroalpine units and thrusting in the external Helvetic basement are roughly coeval and related to post-collisional shortening in the Late Tertiary.

A retrodeformation of the post-collisional structures in an idealized NNW-SSE cross-section across the Engadine Window shows that shortening associated with the formation of the HBS-basement slice is around 12.5 km, whereas unfolding of the basal Austroalpine thrust in the section considered corresponds to a shortening of only approx. 2.5 km (Fig. 7a). The remarkable difference in shortening suggests a decoupling between the Austroalpine lid and the European basement units during post-collisional deformation. Such a decoupling is likely to be positioned at interfaces with maximum differences in rock strength. In the retrodeformed section (Fig. 7a), a major detachment could be expected at the interface between the European basement and the N-Penninic Bündnerschiefer units (large-scale detachment and thrusting of the Penninic cover nappes follow this contact throughout the Swiss Alps). Thus, the model for the formation of the Engadine Window envisages a protruding European upper crustal basement-wedge bounded by a passive back-thrust at the top and an active NNW-vergent thrust at the bottom (Fig. 7b). Such passive back-thrust models have been reported in external domains from various orogens by Banks & Warburton (1986). Assuming (1), that the HBS-basement slice imaged in lines E2 and E3 is restricted to the area of the Engadine Window, (2), plane strain in the area considered and (3), a complete decoupling between Bündnerschiefer and European basement, the indentation of the upper crustal basement-wedge must lead to a local uplift of 8 km in the area of the Engadine Window (it is important to note that this amount of uplift is probably an overestimate as the assumptions of "plane strain" and "complete decoupling", respectively, are most certainly not fullfilled). The local uplift, accommodated by internal shortening within the Bündnerschiefer, leads to the domal shape of the Engadine Window. Moreover, the resulting tectonic uplift is likely to induce extension in the overlying units and might explain normal faulting along the northern part of the Late Tertiary Engadine line (Schmid & Froitzheim 1993) and a system of extensional brittle faults in the Engadine Window (Kläy 1957). Summarizing, I suggest that the Engadine Window is essentially the result of post-collisional deformation with the superposition of large-scale detachment-folding above a passive back thrust, local uplift and extension in Late Tertiary time.

Viewed on a large scale, the Engadine structural high is arranged in a right-stepping en-echelon pattern with respect to the external basement massifs. Such a geometry is compatible with dextral transpression and NNW-SSE directed shortening between the European and Adriatic plates in Late Tertiary time, as suggested by plate reconstructions (cf. Savostin et al. 1986).

6. Conclusion

The deep seismic reflection data of the E3-transect show that the crust in the area of the Engadine Window is dominated by S-dipping reflectors. Interpretation of the data indicates an up to 10 km thick pile of N-Penninic Bündnerschiefer containing reflective ophiolitic inclusions. These Bündnerschiefer, making up the inner core of the Window, are underlain by an ENE-striking nappe-stack consisting of N-Penninic and Helvetic basement units. They are separated by presumably Triassic to Early Jurassic sediments. The lowest reflections in the E3-transect indicate a crustal thickness of more than 50 km with the European Moho dipping towards the SSE.

Structural considerations suggest that the large-scale antiform observed in the Bündnerschiefer does not affect the underlying basement units. The Bündnerschiefer forming the core of the Engadine Window can thus be considered as a large-scale detachment fold. Detachment probably took place during the indentation of an upper crustal basement-wedge, producing local uplift and extension in Late Tertiary time.

Acknowledgment

I am indebted to J. Ansorge, E. Flüh, M. R. Handy, K. Holliger, N. Froitzheim and H. Laubscher for reviews and comments on the manuscript. The help of R. Marchant, St. Mueller, O. A. Pfiffner and G. Schreurs while writing a first draft is greatly appreciated. I would also like to thank J. Ansorge, St. DeHaas, A. Green, H. Horstmeyer, E. Lanz, St. Mueller and P. Valasek for help, many discussions and hospitality at the Institute of Geophysics ETHZ. This study represents a part of my Ph.D. thesis which was guided by O. A. Pfiffner and St. Mueller.

REFERENCES

BANKS, C. J. & WARBURTON, J. 1986: "Passive-roof" duplex geometry in the frontal structures of the Kirthar and Sulaiman mountain belts, Pakistan. J. Struct. Geol. 8, 229–237.

BERNOULLI, D. & WEISSERT, H. 1985: Sedimentary fabrics in Alpine ophicalcites, South Pennine Arosa zone, Switzerland. Geology 13, 755–758.

BOUSQUET, R., OBERHÄNSLI, R., JOLIVET, L. & GOFFÉ, B. 1995: High Pressure Metamorphism and Detachment in the Bündnerschiefer of the Engadine Window (Eastern Central Alps). Terra abstracts 7, 124.

BOYER, S. E. & ELLIOT, D. 1982: Thrust systems. Amer. Assoc. Petr. Geol. Bull. 66, 1196–1230.

CADISCH, J. 1953: Geologie der Schweizer Alpen. Wepf & Co., Basel.

CADISCH, J., EUGSTER, H., WENK, E., TORICELLI, G. & BURKHARD, G. 1963: Geologischer Atlas der Schweiz 1 : 25 000, Blatt 44: Scuol-Tarasp.

CADISCH, J., EUGSTER, H. & WENK, E. 1968: Geologischer Atlas der Schweiz 1 : 25 000, Blatt 44: Scuol-Tarasp, Erläuterungen.

DEHAAS, ST. 1992: Reflexionsseismisches Querprofil zur Untersuchung der Tiefenstruktur des Unterengadiner Fensters. Unpubl. Diploma thesis, ETH Zürich.

ESCHER, A. & STUDER B. 1839: Geologie von Mittelbündten. N. Denkschr. Schweiz. Naturf. Ges. 3.

FLORINETH, D. & FROITZHEIM, N. 1994: Transition from continental to oceanic basement in the Tasna nappe (Engadine window, Graubünden, Switzerland): evidence for Early Cretaceous opening of the Valais ocean. Schweiz. mineral. petrogr. Mitt. 74, 437–448.

FROITZHEIM, N., SCHMID, S. M. & CONTI, P. 1994: Repeated change from crustal shortening to orogen-parallel extension in the Austroalpine units of Graubünden. Eclogae geol. Helv. 87, 559–612.

GIESE, P. & PRODEHL, C. 1976: Main Features of Crustal Structure in the Alps. In: Explosion Seismology in Central Europe (Ed. by GIESE, P., PRODEHL, C. & STEIN, A.), Springer Verlag, Berlin.

HITZ, L. 1994: Crustal structure at the transition between Central and Eastern Alps: Processing, 3D modeling and interpretation of a network of deep seismic profiles. PhD thesis, Univ. Bern.

– 1995: The 3D crustal structure of the eastern Alps of Switzerland and western Austria interpreted from a network of deep seismic profiles. Tectonophysics 248, 71–96.

HOLLIGER, K. & KISSLING, E. 1991: Ray theoretical depth migration: Methodology and application to deep seismic reflection data across the eastern and southern Swiss Alps. Eclogae geol. Helv. 84, 369–402.

HOLLIGER, K. & LEVANDER, A. 1994a: Structure and seismic response of extended continental crust: Stochastic analysis of the Strona-Ceneri and Ivrea zones. Geology 22, 79–82.

– 1994b: Lower crustal reflectivity modeled by rheological controls on mafic intrusions. Geology 22, 367–370.

KLÄY, L. 1957: Geologie der Stammerspitze – Untersuchungen im Gebiet zwischen Val Sinestra, Val Fenga und Samnaun (Unterengadin). Eclogae geol. Helv. 50, 323–467.

KOLLER, F. & HÖCK, V. 1987: Die mesozoischen Ophiolite der Ostalpen. Mitt. österr. Min. Ges. 132, 61–77.

LAUBSCHER, H. 1983: Detachment, shear, and compression in the central Alps. Geol. Soc. Amer. Mem. 158, 191–211.

– 1994: Deep structure of the Central Alps in the light of recent seismic data. Geol. Rdsch. 83, 237–248.

LITAK, R. K., MARCHANT, R. H., BROWN, L. D., PFIFFNER, O. A. & HAUSER, E. C. 1991: Correlating crustal reflections with geologic outcrops: Seismic modeling results from the southwestern USA and the Swiss Alps. In: Continental Lithosphere: Deep Seismic Reflections (Ed. by MEISSNER, R., BROWN, L.D., DÜRBAUM, H. J., FRANKE, W., FUCHS, K. & SEIFERT, F.), Amer. Geophys. Union, Geodynamics Series 22, 299–305.

MATTMÜLLER, R. 1991: Ueberlegungen zur Deckenkinematik im Engadiner Fenster. Jb. Geol. B.-A. 134, 319–328.

MILLER, H., ANSORGE, J., ARIC, K. & PERRIER, G. 1978: Preliminary results of the Lithospheric Seismic Alpine Longitudinal Profile, 1975, from France to Hungary. In: Alps, Apennines, Hellinides (Ed. by CLOSS, H., ROEDER, D. & SCHMIDT, K.), Schweizerbart, Stuttgart, 33–39.

NOACK, T. 1984: Krustenseismische Untersuchungen im Gebiet des Engadiner Fensters und der Oetztaler Alpen. Unpubl. Diploma thesis, ETH Zürich.

OBERHAUSER, R. 1980: Das Unterengadiner Fenster. In: Der geologische Aufbau Österreichs (Ed. by OBERHAUSER, R.), Springer Verlag, Wien, 291–299.

– 1983: Mikrofossilfunde im Nordwestteil des Unterengadiner Fensters sowie im Verspalaflysch des Rätikon. Jb. Geol. B.-A. 126, 71–93.

PFIFFNER, O. A. & HITZ, L. 1996: Geologic interpretation of the seismic profiles of the eastern traverse (lines E1-E3, E7-E9): eastern Swiss Alps. In: Deep structure of Switzerland – Results from NFP20. Birkhäuser, Basel, in press.

PFIFFNER, O. A., FREI, W., VALASEK, P., STÄUBLE, M., LEVATO, L., DUBOIS, L., SCHMID, S. M. & SMITHSON, S. B. 1990: Crustal shortening in the Alpine orogen: Results from deep-seismic reflection profiling in the Eastern Swiss Alps, line NFP20-EAST. Tectonics 9, 1327–1355.

PFIFFNER, O. A., LEVATO, L. & VALASEK, P. 1991: Crustal reflections from the Alpine orogen: Results from deep seismic profiling. In: Continental Lithosphere: Deep Seismic Reflections (Ed. by MEISSNER, R., BROWN, L., DÜRBAUM, H. J., FRANKE, W., FUCHS, K. & SEIFERT, F.), Amer. Geophys. Union, Geodynamics Series 22, 185–193.

REY, P. 1993: Seismic and tectono-metamorphic characters of the lower continental crust in Phanerozoic areas: a consequence of post-thickening extension. Tectonics 12, 580–590.

RUDOLPH, J. 1982: Tieferes Tertiär im oberen Fimbertal, Unterengadiner Fenster. N. Jb. Geol. Paläont. (Mh.) 3, 181–183.

SAVOSTIN, L. A., SIBUET, J.-C., ZONENSCHAIN, L. P., LE PICHON, X. & ROULET, M.-J. 1986: Kinematic Evolution of the Tethys Belt from the Atlantic Ocean to the Pamirs since the Triassic. Tectonophysics, 123, 1–35.

SCHELIGA, G. 1971: Ergebnisse seismischer Messungen (1965–1970) im Gebiet des Engadiner Fensters. PhD thesis, Ludwig-Maximilians University, München.

SCHMID, S. M. & FROITZHEIM, N. 1993: Oblique slip and block rotation along the Engadine line. Eclogae geol. Helv. 86, 569–593.

SCHMID, S. M. & HAAS, R. 1989: Transition from near-surface thrusting to intrabasement decollement, Schlinig thrust, Eastern Alps. Tectonics 8, 697–718.

SCHMID, S. M., PFIFFNER, O. A. & SCHREURS, G. M. 1996: Rifting and collision in the Penninic zone of Eastern Switzerland. In: Deep structure of Switzerland – Results from NFP20. Birkhäuser, Basel, in press.

SELLAMI, S., BARBLAN, F., MAYERAT, A. M., PFIFFNER, O. A., RISNES, K. & WAGNER, J. J. 1990: Compressional wave velocities of samples from the NFP20 East seismic reflection profile. In: Deep structure of the Alps (Ed. by ROURE, F., HEITZMANN, P. & POLINO, R.), Mém. Soc. géol. France 156, 77–84.

STAMPFLI, G. 1993: Le Briançonnais, terrain exotique dans les Alpes? Eclogae geol. Helv. 86, 1–45.

STEINMANN, M. 1994: Die nordpenninischen Bündnerschiefer der Zentralalpen Graubündens: Tektonik, Stratigraphie und Beckenentwicklung. Jb. geol. B.-A. 137, 675–721.

STUTZ, E. & WALTER, U. 1983: Zu Stratigraphie und Tektonik am Nordostrand der Engadiner Dolomiten am Schlinigpass (Gemeinden Sent, Graubünden und Mals, Südtirol). Eclogae geol. Helv. 76, 523–550.

TERMIER, P. 1903: Sur la fenêtre de la Basse-Engadine. C. R. Acad. Sci. Paris 139b, 648–650.

THÖNI, M. 1988: Rb-Sr Isotopic Resetting in Mylonites and Pseudotachylites: Implications for the Detachment and Thrusting of the Austroalpine Basement Nappes in the Eastern Alps. Jb. geol. B.-A. 131, 169–201.
TRÜMPY, R. 1972: Oekologische Untersuchungen im Unterengadin: Zur Geologie des Unterengadins. Ergeb. wiss. Unters. schweizer. Nat.park 12, 71–87.
– 1980: Geology of Switzerland – a guide book. Part A: An outline of the geology of Switzerland, Wepf and Co., Basel, Switzerland.
TWISS, R. & MOORES, E. M. 1992: Structural Geology. W. H. Freeman and Co., New York.
VALASEK, P. 1992: The tectonic evolution of the Swiss Alpine crust interpreted from a 2D network of deep crustal seismic profiles and an evaluation of 3D effects. PhD thesis Nr. 9637, ETH Zürich.
YAN, Q. Z. & MECHIE, J. 1989: A fine structural section through the crust & lower lithosphere along the axial region of the Alps. Geophys. J. 98, 465–488.

Manuscript received October 28, 1995
Revision accepted February 6, 1996