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Kinematics of the Inntal shear zone–sub-Tauern ramp fault system and the interpretation of the TRANSALP seismic section, Eastern Alps, Austria

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Abstract

A new interpretation of the Inntal–Tauern sector of the TRANSALP seismic section is presented. One of the most prominent contrasts in reflectivity in the TRANSALP seismic section is the contact between the Bajuvaric unit in the footwall and the overlying Tirolic unit and its basement across a moderately south-dipping interface. We trace this contact from the surface at the southern margin of the Inn valley to a depth of 5 km. There, the contact is deformed or cut by the Tauern Window northern margin. We define the contact between Bajuvaric and Tirolic units as Brixlegg thrust, which is older than Miocene Tauern window exhumation and has a Paleogene age. The sub-Tauern ramp connects with the Inntal fault system at the surface and roots below the Tauern window. Oblique thrust movements across this fault system in the Miocene caused exhumation of the hanging wall, where the fault has a ramp geometry, which is in the area of the TRANSALP cross section and west of it. East of the TRANSALP cross section, the fault system merges with Alpine basal thrust, which is a flat. No Miocene exhumation occurred above the flat.

Keywords: Inntal shear zone; Exhumation; Oblique thrusting; Kinematics

1. Introduction

1.1. Geologic setting

Today's Eastern Alps formed by inversion of two passive margins, the first bordering the Meliata ocean toward the NW from Triassic to Late Jurassic times. Sedimentary facies belts on this margin, as preserved in the Austroalpine units of the Eastern Alps, display deeper water conditions to the SE (e.g. Mandl, 2000). The second formed the southeastern margin of the Penninic ocean from the Jurassic to the Cretaceous (e.g. Froitzheim and Manatschal, 1996). Accordingly, the Eastern Alps were involved in two orogenies, the first of which took place during the Cretaceous and was related to closure of the Meliata ocean, whereas the second Cenozoic orogeny closed the Penninic ocean (Thöni and Jagoutz, 1993; Froitzheim et al., 1994, 1996; Faupl and Wagreich, 2000; Neubauer et al., 2000). The first orogeny caused stacking of nappes within the Adriatic microplate, which was then in a foreland position with respect to the closure of the Meliata ocean to the southeast (e.g. Neubauer, 1994; Froitzheim et al., 1996; Fig. 1a). In the Northern Calcareous Alps, which presently form the northernmost part of the Adriatic microplate, thin-skinned

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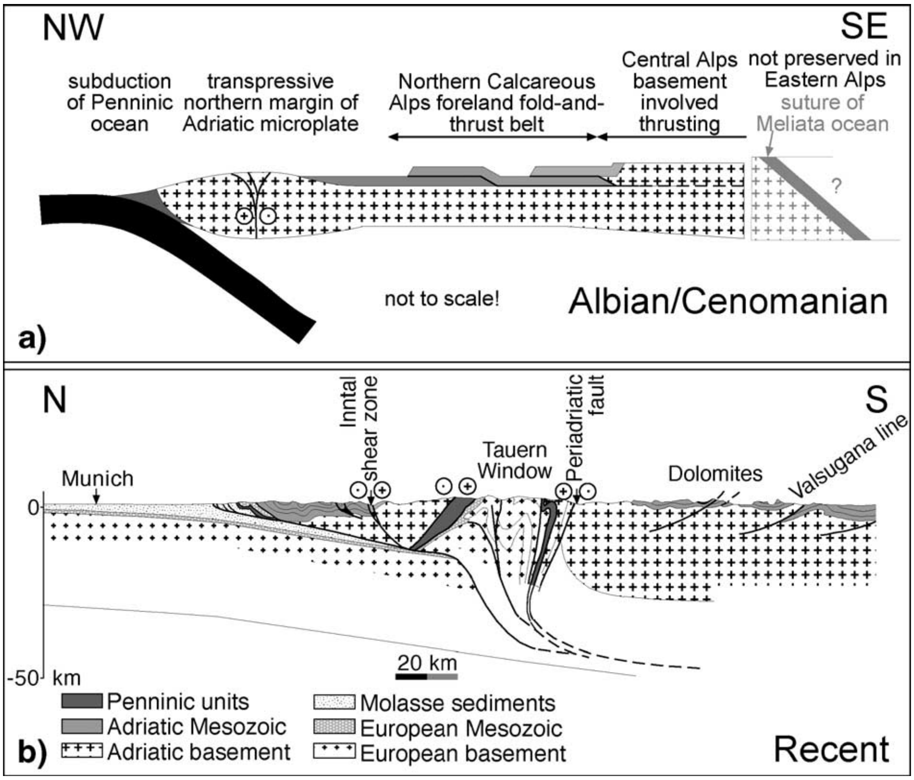


Fig. 1. Conceptual models illustrating the two stages of Alpine orogeny in Eastern Alps. a) Cretaceous orogeny, when today's Eastern Alps were in a foreland position to the closure of the Meliata ocean (modified from Wagreich, 2003), and b) Cenozoic orogeny, in which the Eastern Alps formed the upper plate during closure of the Penninic ocean (modified from Lammerer and Weger, 1998).

nappes were transported in the range of tens of kilometers to the northwest (Linzer et al., 1995; Eisbacher and Brandner, 1996; Ortner, 2003a; Auer and Eisbacher, 2003; Behrmann and Tanner, this volume), so that the Mesozoic facies belts were not completely destroyed (e.g. Tollmann, 1976b). The Bajuvaric nappe complex, and the higher Tirolic nappe complex (Hahn, 1912), which is in sedimentary contact to the Greywacke zone, were then formed. In the western part of the Northern Calcareous Alps, the Bajuvaric unit is further subdivided into the Allgäu and the tectonically higher Lechtal nappes, whereas the Inntal nappe is thought to be part of the Tirolic nappe complex (Tollmann, 1976b; Fig. 2). The basement units of the Adriatic microplate in the Eastern Alps, presently exposed to the south of the Northern Calcareous Alps, were stacked by thick-skinned west-directed thrusting (e.g. Ratschbacher, 1986; Ratschbacher and Neubauer, 1989; Froitzheim et al., 1994), leading to thickening of the continental crust and thus to metamorphism (e.g. Frey et al., 1999). East of the Brenner normal fault, these include from bottom to top the Lower Austroalpine Innsbruck Quartzphyllite unit, the thin Middle Austroalpine Kellerjochgneis unit and the Upper Austroalpine Greywacke zone (Tollmann, 1977; Fig. 2).

The second orogeny, which gave the Eastern Alps much of their present structure, took place during the Cenozoic, and was related to the closure of the Penninic ocean separating the Adriatic microplate and the European plate between the Early Jurassic and the Eocene (e.g. Frisch, 1979; Schmid et al., 1996). Cenozoic orogeny led to accretion of material from the lower plate to the Alpine orogen. Successively, sedimentary units from the Penninic ocean (Rhenodanubian Flysch nappes; Bünden schists of the Tauern Window), units from the southern passive margin of the European plate (Helvetic nappes) and from the northern Alpine foreland basin (allochthonous molasse) were incorporated into the Alpine wedge (Fig. 1b). Post-Early Eocene continental collision was associated with stacking of lower plate crustal wedges in the area of today's Tauern window (Zentralgneis cores; Lammerer and Weger, 1998; Fig. 1b) and subsequent major oblique backthrusting in the central part of the orogen (Periadriatic line south of the Tauern Window; see Fig. 2; e.g. Mancktelow et al., 2001). The load of the thickened crust caused flexural bending of the lower plate and thus formation of the

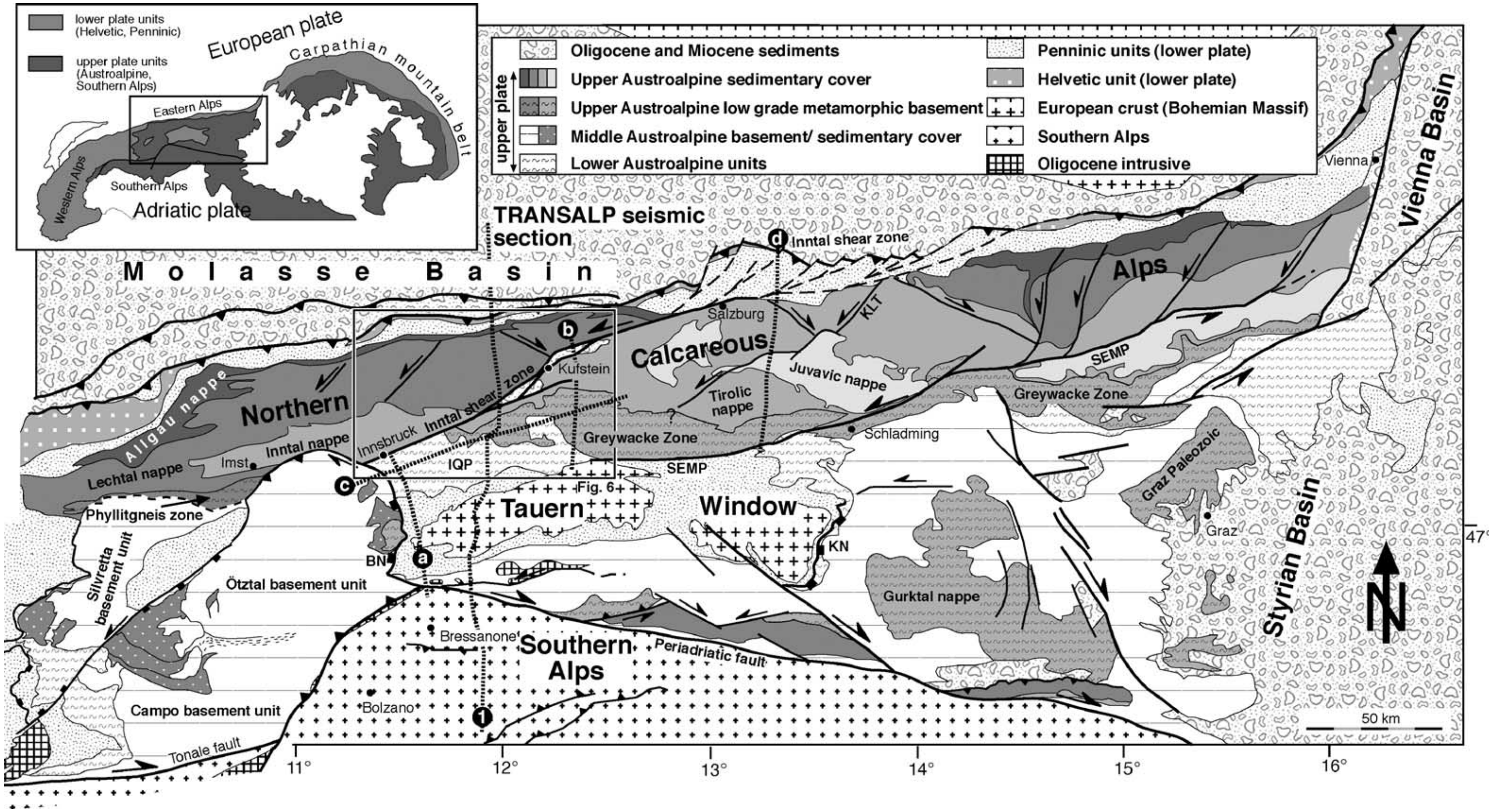


Fig. 2. Geological sketch of the Eastern Alps. Thick lines delineate the Neogene fault pattern of the Eastern Alps. BN = Brenner normal fault, KN = Katschberg normal fault, SEMP = Salzachtal–Ennstal–Mariazell–Puchberg line, KLT = Königssee–Lammertal–Traunsee fault. IQP = Innsbruck Quartzphyllite nappe. 1 = trace of the TRANSALP seismic section (Fig. 4); a–d: traces of sections in Fig. 7a–d. Frame indicates position of Fig. 6.

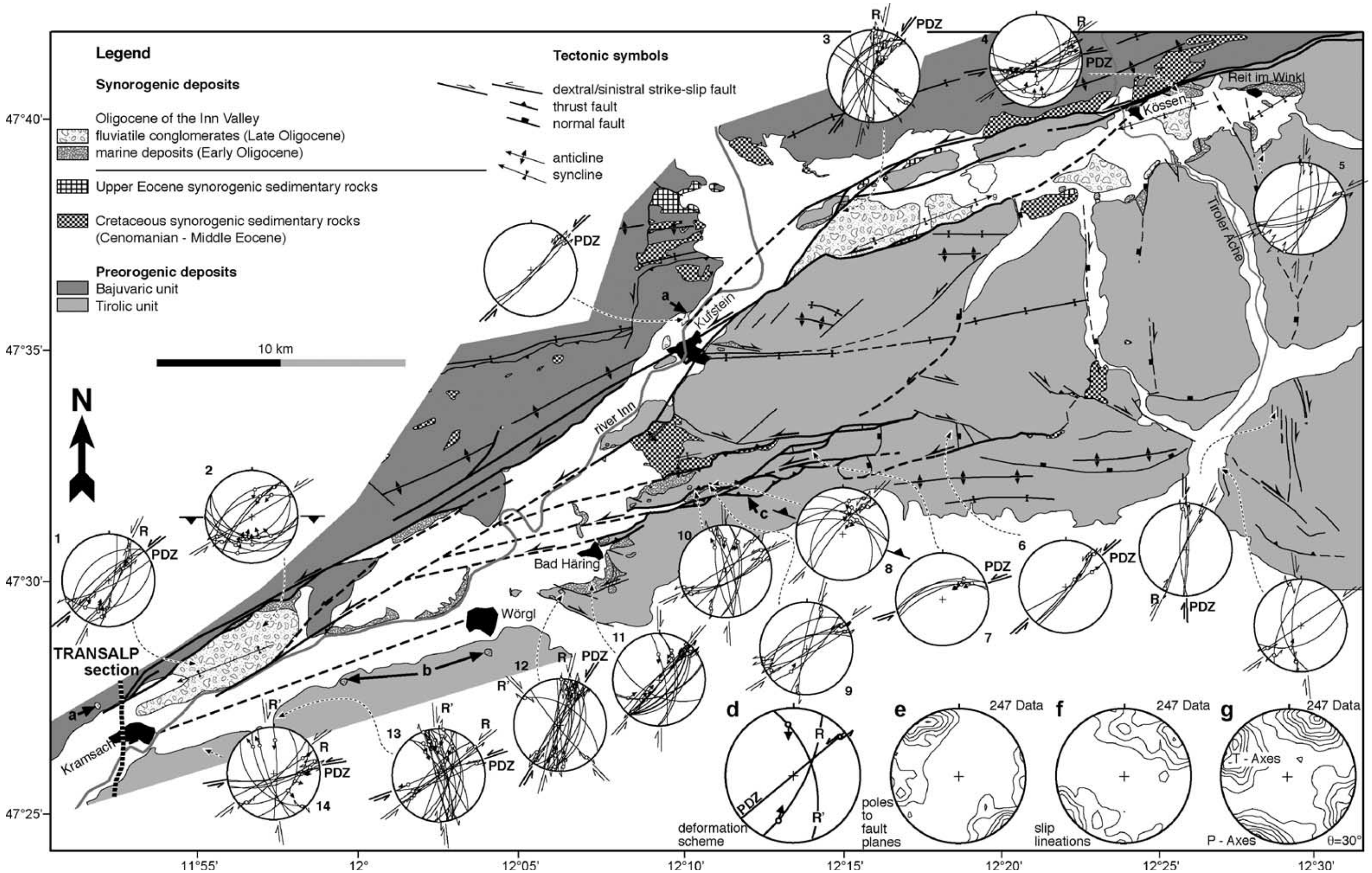


Fig. 3. Miocene brittle deformation in the Inntal shear zone. Most data were measured in Oligocene rocks. PDZ = principal displacement zone, R = Riedel shear, R′ = Anti-Riedel shear. See text for explanation of (a) to (c). d) Typical fault pattern observed in data sets associated with sinistral shearing across the Inntal shear zone with oblique reverse slip on Riedel and Anti-Riedel shears. e) Contour plot of all fault planes measured associated to sinistral shearing across the Inntal shear zone indicating that the majority of fault planes is subvertical to steeply south-dipping. f) Contour plot of all slip lineations measured associated to sinistral shearing across the Inntal shear zone indicating that slip across the Inntal shear zone was essentially horizontal. g) Contour plot of all compression and tension axes, which were calculated using an angle of internal friction θ of 30°. The maximum densities give approximate mean orientations of NNE and ESE for σ_1 and σ_3, respectively, irrespective of complexities regarding the boundary conditions of shearing. For exact location see Fig. 6.

Alpine peripheral foreland basin (e.g. Lemcke, 1984). One of the reasons for major orogen-parallel extension within the Eastern Alps during the Miocene was crustal thickening within the orogen due to pre-Miocene thrusting and Oligo–Miocene indentation of the Southern Alps. Orogen-parallel extension was accommodated by low-angle normal faults in the central part of the orogen (Brenner and Katschberg normal faults; Fig. 2; Selverstone, 1988; Behrmann, 1988, 1990; Genser and Neubauer, 1989), which led to exhumation of the Tauern window, and by eastward extrusion of crustal wedges (Ratschbacher et al., 1991). To the north, the laterally extruding crustal wedges were delimited by sinistral strike slip faults, to the south dextral strike slip faults formed the boundary of the extrusion channel (Ratschbacher et al., 1991). The westernmost crustal wedge moving to the east was delimited to the north by the sinistral Inntal shear zone and to the south by the dextral Periadriatic line (Fig. 2). The Inntal shear zone is kinematically connected to the Brenner normal fault (Ortner, 2003b), obliquely cuts across the Northern Calcareous Alps and the Rhenodanubian Flysch zone and connects with the basal Alpine thrust at the Alpine front (Fig 2).

1.2. Cretaceous to Oligocene synorogenic sedimentation on top of the Alpine orogen

Deposition of synorogenic sediments accompanied nappe thrusting in the Late Cretaceous, continued into the Cenozoic and reaches into the middle Eocene (Gosau Group, among other synorogenic deposits; e.g. Wagreich and Faupl, 1994). Synorogenic deposition was interrupted during collision and resumed in the Oligocene.

The frontal part of the Alpine wedge was part of the foreland basin during the Oligocene (Ortner and Stingl, 2001). Erosional remnants of a wedge-top basin are preserved in the area of the Inn valley (Fig. 2), and were also previously considered to be part of the Molasse basin (“Inneralpine Molasse”; Fuchs, 1976, 1980). Subsidence of the Alpine nappe stack to deep marine conditions was recorded by southward climbing transgression of marine deposits onto the Northern Calcareous Alps (Lindenberg, 1965). Subsidence accelerated in the Late Oligocene, when terrestric sedimentation started, as a subsidence model controlled by the thermal history based on vitrinite reflectance data of the Oligocene sediments demonstrated (Ortner and Sachsenhofer, 1996). Thus, the main process controlling sedimentation was foreland subsidence (Ortner and Stingl, 2001).

From the Chattian onwards, debris from the Central Eastern Alps eroded during exhumation after continental collision was channelized along the Inn valley and further east to the Alpine foreland basin via a paleo-Inn valley (Ortner and Sachsenhofer, 1996; Mair et al., 1996; Brügel et al., 2000). Upper Oligocene conglomerates in contact with Triassic rocks of the Lechtal nappe north of the Inntal shear zone (a in Fig. 3; Zerbes and Ott, 2000; Ortner and Stingl, 2003) seal a topography created at the end of the Early Oligocene, which was the reason for the orogen-parallel transport of debris.

1.3. Aim of this study

The TRANSALP deep seismic section imaged the Eastern Alps in an approximately N–S cross section from Munich (Germany) to Treviso (Italy). In a first crustal scale interpretation by the TRANSALP Working Group (2002), a moderately south-dipping ramp reaching from the deep crust to the surface in the area of the Inn Valley was described. According to the initial publication of the TRANSALP Working Group (2002), this “sub-Tauern ramp” was responsible for uplift of the Tauern Window in the Oligocene and Miocene. An important drawback of this hypothesis is that the frontal Alpine thrust must have been abandoned as an important shortening structure, when the sub-Tauern ramp came into existence. The Tauern Window was exhumed from the Eocene onwards (Selverstone, 1988, 1993; Fügenschuh et al., 1997), but the youngest sediments deformed by the frontal Alpine thrust are Middle Miocene in age (e.g. Schwerd and Thomas, 2003). An alternative solution is needed.

In this paper, we present a new interpretation of the Inntal–Tauern sector of the TRANSALP seismic line and discuss the “sub-Tauern ramp” in the light of synorogenic sedimentation and collisional to post-collisional deformation in the vicinity of the TRANSALP seismic section. The new interpretation is aided by an analysis of Miocene faulting along the surface trace of the sub-Tauern ramp, which is the Inntal shear zone according to our interpretation (see below), and by the discussion of previously published thermochronologic data from the area. We intend to show how the sub-Tauern ramp and other faults in the area are related to Paleogene and Neogene thrusting and Neogene lateral extrusion.

2. Description of TRANSALP seismic line in the Inntal segment

2.1. Reflections associated with autochthonous rocks on the European plate

Below the northern foreland basin, basement rocks of the European plate are overlain by a Jurassic to

Paleogene sedimentary succession deposited on the northwestern passive margin of the Penninic ocean (= autochthonous sedimentary succession of the European plate, ASSEP). These sequences form prominent reflections at the base of the foreland basin and were drilled by several wells during hydrocarbon exploration (e.g. Well Anzing 3; Well Miesbach 1: Jacob and Kuckelkorn, 1977; Grambach 1: Hiltmann et al., 1999; Well Staffelsee 1: Jacob et al., 1982). The reflections associated with these rocks can be traced to the south beyond the front of the Alps to the Inn Valley in a depth of 8 to 9 km, where they end (1 in Fig. 4a). Between CDP 3600 and CDP 3200, a group of reflections with the same characteristics as those related to the ASSEP apparently downlap onto the southernmost part of the reflections associated to the ASSEP (2 in Fig. 4a) and can be traced further south (3 in Fig. 4a). As the reflections associated with the ASSEP are the deepest clear reflections in the interpreted part of the seismic section, and this is also true for the the southern continuation of the reflections (3 in Fig. 4a), we interpret the downlap as a hanging wall ramp on a footwall flat on top of ASSEP (2 in Fig.

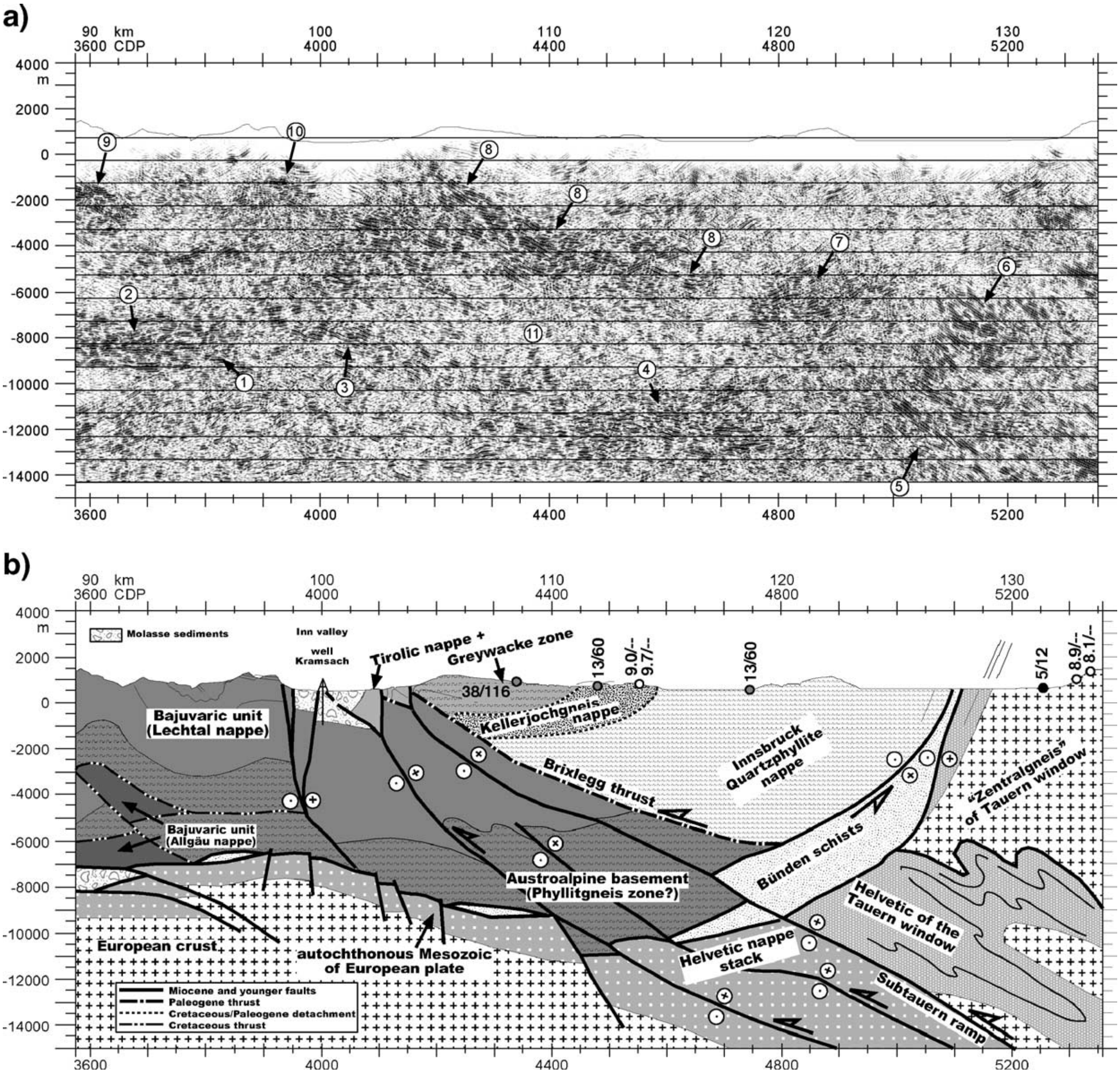


Fig. 4. The TRANSALP seismic section from CDP 3600 to CDP 5300. a) Migrated seismogram (Lüschen, pers. comm., 2002). Numbers refer to explanation in text. b) Interpretation of the seismogram. Interpretation of Northern Calcareous Alps north of the Inn valley taken from Auer and Eisbacher (2003). Black circles: Apatite fission-track ages by Most et al. (2003), grey circles: Apatite/zircon fission-track ages by Angelmaier et al. (2001), white circles: Apatite fission-track ages by Grundmann and Morteani (1985).

4a). Therefore the ASSEP ends at a footwall ramp toward the south, where basement rocks are thrust onto the sediments. The reflections of the autochthonous Mesozoic can be traced further south to a position between CDP 4400 and CDP 4800, where they run into a zone of more diffuse subhorizontal reflections, deeper than north of the Inn Valley (10 to 13 km; 4 in Fig. 4a). The complete structure between 3600 and CDP 4800 closely resembles the structure of inverted half-grabens (e.g. Buiter and Pfiffner, 2003). The discontinuous nature of the reflections within the structure is possibly a result of faulting of the rocks due to flexural bending during inversion. The reflections associated to the autochthonous sedimentary succession have constant thickness across the inverted half-graben, growth strata are not observed. Therefore, half-graben formation must have a post-Paleogene age. Within the more diffuse reflections south of the inverted half-graben (4 in Fig. 4a; CDP 4500–CDP 5100) reflections bend from a subhorizontal position in the northern part to a 30° south-dipping position in the southern part. Here, the thickness of the reflections is about 5 times the thickness of the reflections associated with the ASSEP. We interpret these reflections to be related to the ASSEP and several allochthonous tectonic slices cut out from the ASSEP, which probably compare to the Helvetic nappe stack at the Alpine front in the westernmost part of the Eastern Alps (Fig. 2).

2.2. Reflections in the Tauern window

Above a line dipping 30° to the south (5 in Fig. 4a), the character of the reflections changes. Between 13 and 19 km depth, a 6 km thick bundle of reflections dips 30° to the south (6 in Fig. 4a), parallel to its lower boundary. Compared to reflections below the line, reflections above are more closely spaced and straight. At the surface, the north-dipping northern margin of the Tauern window crosses the trace of the seismic section at CDP 5100. Therefore, these reflections are most probably inside the Tauern window, and the lower boundary of the bundle of reflections corresponds to a fault plane across which the ASSEP and a Helvetic nappe stack are in contact with exhumed metamorphic rocks of the Tauern window. In previous interpretations of the TRANSALP seismic section, this line was termed *sub-Tauern ramp* (TRANSALP Working Group, 2002; Lüschen et al., 2004). The sharp reflections might be associated with compositional layering in sedimentary rocks parallel to a mylonitic penetrative foliation. This interpretation is valid, if the lowermost Helvetic slice of the Tauern window is mainly composed of sediments. Given the thickness of the sediments on top of crystalline units exposed at the surface, which is a few 100 m (Lammerer, 1986), either isoclinal folding, internal stacking, or both, in this slice of the Tauern window must be assumed to account for the observed thickness of 6 km.

The south-dipping reflections discussed above end to the north. Instead, north-dipping reflections in 12 to 15 km depth becoming steeper toward the surface are observed. The reflections could be associated with metamorphic Flysch sediments in the northernmost part of the Tauern window (Bünden schists; 7 in Fig. 4a). They probably connect with the Bünden schists at the surface, where they are in a subvertical attitude; we assume that the reflections from this sediment package are lost toward the surface as its attitude becomes steeper.

2.3. Reflections within the Austroalpine units

From north to south, the units within the Alpine nappe stack mapped at the surface (Pflaumann and Stephan, 1968) are: the allochthonous Molasse, the Helvetic zone and the Rhenodanubian Flysch zone and the Northern Calcareous Alps. Only the Molasse zone shows a characteristic reflection pattern near the surface, which was analysed in more detail by Schwerd and Thomas (2003). The Helvetic zone, Rhenodanubian Flysch zone and the Allgäu nappe of the Northern Calcareous Alps do not show any characteristic reflection pattern. At the surface, these are strongly disrupted discontinuous units which were probably boudinaged during transport onto the tectonically deeper units. According to Auer and Eisbacher (2003), the Flysch and Helvetic units rapidly taper toward the south. In the part of the seismic section discussed in this paper, only thin, isolated slices, which are probably not resolved by the seismic section, are to be expected.

The overlying, less deformed Lechtal nappe of the Northern Calcareous Alps has two main potentially reflective stratigraphic intervals (see Tollmann, 1976a; Fig. 5a): The Lower to Middle Triassic sedimentary succession is built by an alternation of evaporites, marls, clays and carbonates (Reichenhall Fm., Muschelkalk Group and Partnach Fm.). These are overlain by a thick Middle Triassic carbonate platform (up to 1750 m; Wetterstein Fm.) which probably appears transparent in the seismic section. Another up to 300 m thick succession of alternating clays, carbonates and evaporites follows (Raibl Group). In previous interpretations of seismograms from the

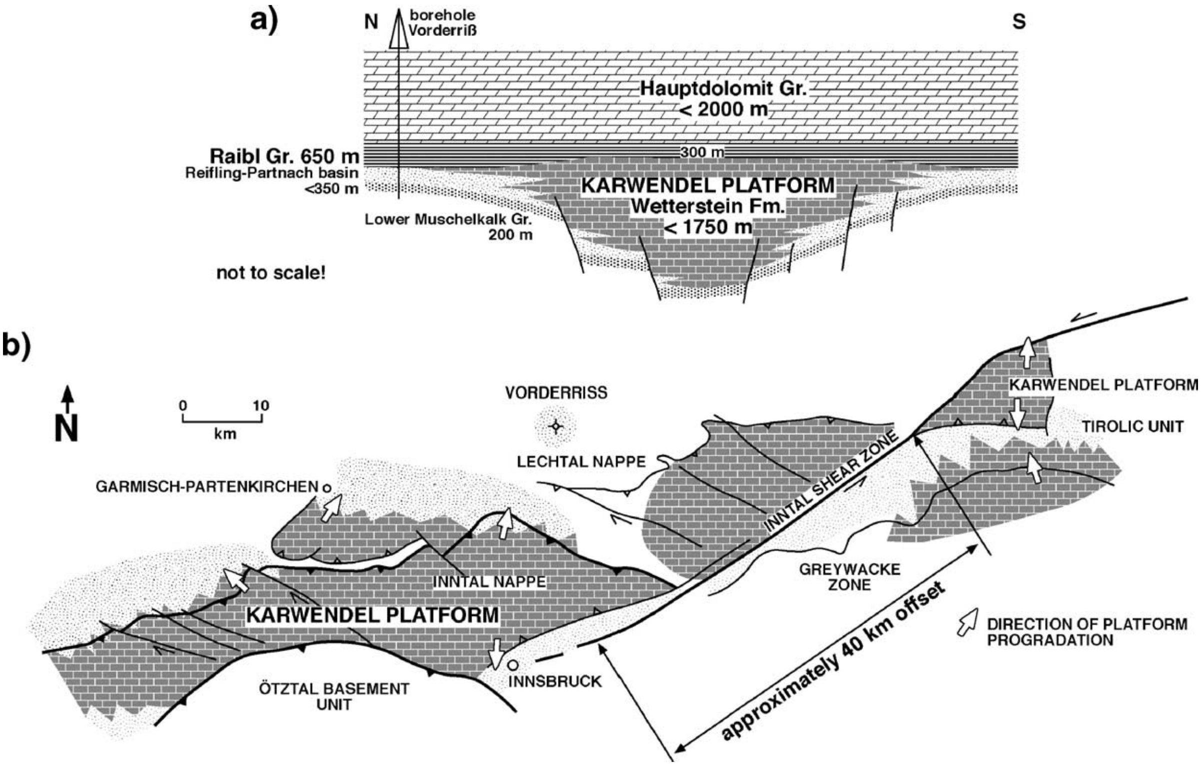
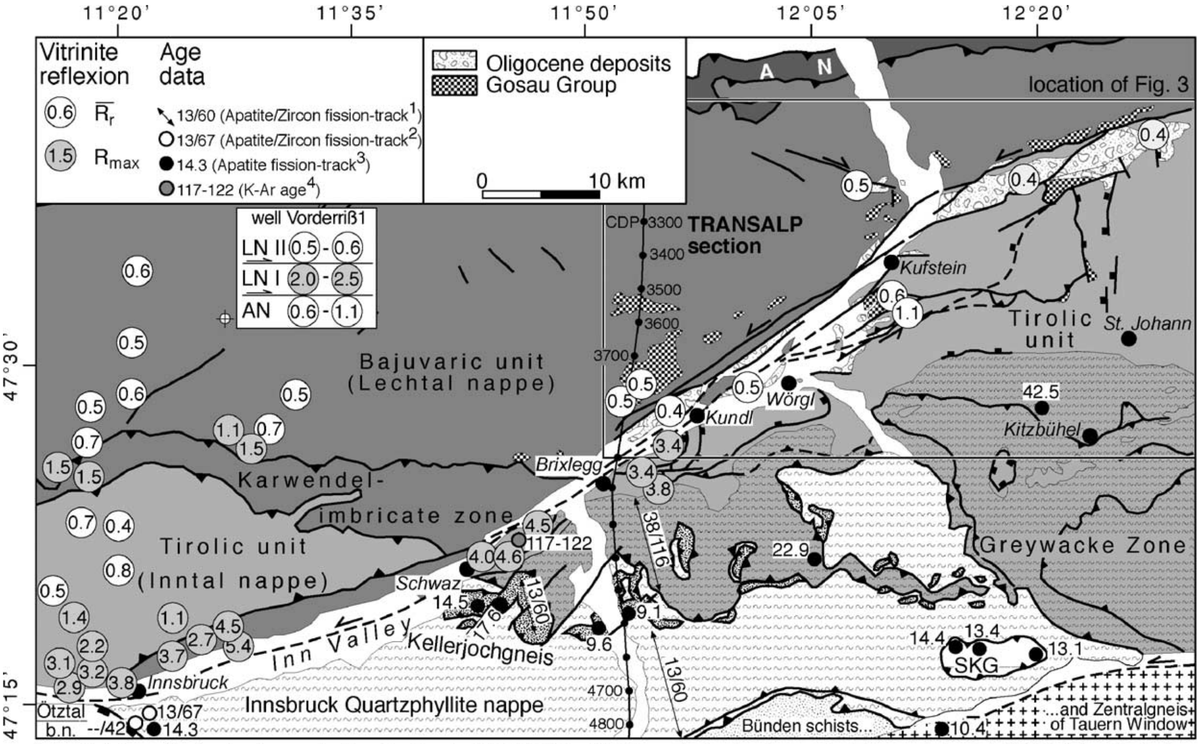


Fig. 5. a) Schematic cross section through Triassic facies of the Northern Calcareous Alps. Note isochronous carbonate platform-basin development of Middle- to Upper Triassic age with differing thicknesses of platform and basin sediments. b) Offset of the Inntal shear zone as estimated from the distribution of Middle to Upper Triassic facies.

Northern Calcareous Alps, zones of high reflectivity were attributed to the Raibl Group (Dohr, 1981; Geutebrück et al., 1984; Linzer et al., 2002; Auer and Eisbacher, 2003). An up to 2000 m thick Upper Triassic carbonate platform (Hauptdolomit Fm.) will again appear transparent in a seismic image. An alternation of carbonates, marls and clastic sediments forms the post-Triassic sedimentary succession of the Northern Calcareous Alps, which has varying thickness, which locally reaches more than 1000 m, but not on the trace of the TRANSALP seismic section.

South of the Inn valley, a thick strongly reflective sediment package dips below weakly reflective rocks (8 in Fig. 4a). Comparably strong reflections are associated to the Raibl Group of the Northern Calcareous Alps, as seen between − 1 km and − 3.5 km at CDP 3600 (9 in Fig. 4a). The reason for the large thickness of reflective rocks observed south of the Inn valley could be an end of the Middle Triassic carbonate platform (Wetterstein Fm.) toward the south, which would then be replaced by a thick succession of marls and carbonates (Partnach Fm., 350 m), directly overlain by the Upper Triassic succession of alternating clays, carbonates and evaporites (Raibl Group, 650 m; Fig. 5a). Therefore, the cumulative thickness of the Lower to Upper Triassic sedimentary sequence built by reflective alternating marls, carbonates and evaporites could be up to 1000 m. In the well Vorderriß (see Fig. 6 for location), which penetrated the Triassic sedimentary sequence north of the end of the Middle Triassic carbonate platform, such a succession was drilled and amounts to more than 1000 m thickness (Bachmann and Müller, 1981). However, to fill the space of strongly reflecting rocks in the TRANSALP seismic section, still several slices are required.

On the northern side of the Inn valley, some of the reflections terminate against subvertical discontinuities, which are thought to be part of the Inntal shear zone (10 in Fig. 4a). At the southern margin of the Inn valley, the strongly reflective rocks dip moderately south below rocks appearing more transparent above. The contrast in reflectivity (8 in Fig. 4a) can be traced to a depth of approximately 5 km, where it bends to a more horizontal position. The rocks above the contrast in reflectivity are characterized by moderately north-dipping reflections, in contrast to the rocks below with dominantly south-dipping reflections. At the surface, the nappe stack of the Austroalpine basement units north of the



¹ Apatite/Zircon fission-track ages by Angelmaier et al (2001), ² Apatite/Zircon fission-track ages by Fügenschuh et al (1997), ³ Apatite fission-track ages by Grundmann and Morteani (1985), ⁴ K/Ar age by Krumm (1984).

Fig. 6. Coalification and geochronologic data north and south of the Inn valley in the area of the TRANSALP seismic section. Coalification taken from Petschick (1989), Schulz and Fuchs (1991), Ortner and Sachsenhofer (1996), Reiter (2000) and Rantitsch (pers. comm.).

Tauern Window includes from bottom to top and from south to north the Innsbruck Quartzphyllite nappe, the Kellerjochgneis nappe and the Greywacke zone, which are separated by Cretaceous nappe boundaries (Tollmann, 1977). On a large scale, the nappe boundaries strike E–W and dip to the north, as tectonically deeper units are exposed toward the south (Fig. 2). Therefore the nappe boundaries are probably parallel to the north-dipping reflections and must terminate against the south-dipping contrast in reflectivity. The contrast in reflectivity corresponds to a fault plane across which the Northern Calcareous Alps were overthrust by their basement and will be termed *Brixlegg thrust* in the following. In the seismic section, reflections in the footwall of the Brixlegg thrust are subparallel to the thrust, whereas reflections in the hanging wall terminate against it (6 in Fig. 4a). In a ramp-flat model, this would be the situation of a hanging wall ramp. In analogy to the interpretation of surface near weakly reflecting rocks south of the Inn valley, we interpret weakly reflecting rocks below the reflections of the Northern Calcareous Alps and above the reflections associated to ASSEP below the Inn valley as Austroalpine basement (11 in Fig. 4a).

3. Exhumation history of Austroalpine units south and north of the Inn valley

The observation that rocks belonging to the Northern Calcareous Alps continue to the south below Austroalpine basement rocks is one of the most remarkable new results of the TRANSALP deep seismic line. This observation is a starting point for the further discussion and interpretation of the seismic line. We will define the age of activity and discuss the offset of the sub-Tauern ramp and Brixlegg thrust by considering the exhumation history of the tectonic units on both sides of the Inn valley, as the surface trace of both faults is located within the Inn valley (see Section 5). Therefore we review published data on coalification and geochronology, and discuss the distribution of synorogenic deposits in the area.

Exhumation is the displacement of rocks with respect to the surface (England and Molnar, 1990). It can be assessed in several ways: The most widely used way to constrain exhumation is by geochronologic data. The cooling age of a mineral records the time at which it became cool enough to retain the daughter products of radioactive decay or the fission tracks produced by the decay of radioactive isotopes. Hence it records the age when a rock rose above an isotherm. Coalification of sedimentary rocks is related to the maximum temperatures to which a rock was exposed to, and to the time these thermal conditions lasted. Therefore coalification of a rock exposed at the surface indicates the amount of total exhumation since maximum burial of the rock. For both methods of estimation of exhumation a thermal profile or thermal history has to be assumed to get the depth at which a rock was buried, when it crossed an isotherm or experienced maximum burial. Retransgression of sediments onto older deposits can also be used to estimate exhumation. The amount of exhumation beneath an unconformity is equivalent to the thickness of the sediment column eroded prior to transgression. In the following paragraphs we will use all three methods to discuss exhumation of blocks adjacent to the Inn valley. Then we separate exhumation events which affect all units from those events affecting only the block north or south of the Inn valley.

3.1. Synorogenic sediments

In the direct vicinity of the TRANSALP seismic section south of the Inn valley (Tirolic unit), from east to west, successively deeper stratigraphic and tectonic units are exposed (Fig. 2). Santonian synorogenic sediments transgress onto Upper Triassic to Jurassic rocks 20 km east of the seismic section and taper 10 km east of the seismic section (Fig. 3). 10 km east of the seismic section Lower Oligocene synorogenic sediments transgress on anchimetamorphic Middle Triassic rocks (Ampferer, 1922; Pirkl, 1961; Sanders, pers. comm.; b in Fig. 3). Further east, these sediments overlie Late Cretaceous to Late Eocene synorogenic sediments (Gruber, 1997). This illustrates several phases of exhumation: (1) before the Santonian (max. 1 km erosion below the Gosau Group sediments), (2) prior to deposition of Lower Oligocene rocks (erosion of the Gosau Group sediments west of Wörgl) and (3) Miocene (erosion of Oligocene sediments west of Kundl). Exhumation must have been more important in the west, as Late Cretaceous and Oligocene synorogenic sediments overlie older deposits in the west than in the east, suggesting differential exhumation or tilting to the east during exhumation.

North of the Inn valley (Bajuvaric unit), Upper Cretaceous synorogenic sedimentary rocks generally transgress onto Upper Triassic sediments. Most of the Upper Cretaceous sediments are removed by erosion, and locally Upper Oligocene continental conglomerates transgress onto Upper Triassic rocks directly north of the Inn valley (a in Fig. 3). Therefore the Bajuvaric unit was exhumed prior to sedimentation of Cretaceous synorogenic sediments (max. 1 km erosion below the Gosau Group sediments) and prior to sedimentation of Upper Oligocene sediments.

3.2. Maximum uplift estimated from coalification

Lower Triassic sediments in the Tirolic unit in direct vicinity of the TRANSALP seismic line show a coalification between 3.5% and 4.5% $R_{\max}$ (anchimetamorphism; Ortner and Reiter, 1999), whereas Upper Triassic sediments in the Bajuvaric unit of the footwall show coalifications around 0.5 R_r% (Petschick, 1989; Fig. 6). Several studies on coalification in the Northern Calcareous Alps concluded, that the coalification pattern is essentially pretectonic (Petschick, 1989; Ferreiro-Mählmann, 1994). Therefore, exhumation of the Austroalpine basement units did mainly lead to erosion of the sedimentary cover on top of the Greywacke zone. K/Ar ages determined from illite concentrates from Lower Triassic sediments in the hanging wall of 117–122 Ma (Early Cretaceous; Krumm, 1984) and a zircon fission-track age of 116 Ma from the Greywacke zone (Angelmaier et al., 2001) set an upper age limit of anchimetamorphism and maximum burial in the area. The maximum possible exhumation calculated from coalification by modelling of the thermal history (Rantitsch, pers. comm.) suggests a second, Jurassic or Cretaceous thermal event which would reduce the total exhumation to about 3 km in direct vicinity of the TRANSALP seismic section. 20 km east of the seismic section, Upper Triassic rocks exposed at the surface have coalifications around 1 R_r%, which is similar to the coalification of Upper Triassic rocks exposed in the Bajuvaric unit (Fig. 6).

3.3. Geochronologic data

Apatite fission-track ages from the Innsbruck Quartzphyllite unit and the Kellerjochgneis unit south of the of the Inn valley between 14 and 9 Ma (Grundmann and Morteani, 1985; Angelmaier et al., 2001; Fig. 6) indicate a Middle to Late Miocene phase of exhumation. Fügenschuh et al. (1997) deduced 4–5 km of exhumation from apatite fission-track ages around 13 Ma from the Innsbruck Quartzphyllite unit further west, assuming that all the exhumation since closure of the zircon fission-track system at ca. 60 Ma took place during the same event, which also caused closure of the apatite fission-track system in the Kellerjochgneis and Quartzphyllite units. The zircon ages around 60 Ma were interpretd by these authors to be related to an older cooling event. Zircon fission-track ages from the Kellerjochgneis and Quartzphyllite units reported by Angelmaier et al. (2001; Fig. 6) around 60 Ma confirm a Paleocene cooling event similar to the one observed west of the Brenner normal fault by Fügenschuh et al. (2000). Apatite fission-track ages of 38 Ma (Angelmaier et al., 2001) and 42.5 Ma (Grundmann and Morteani, 1985; Fig. 6) were reported from the northern part of the Greywacke zone near the TRANSALP transect, and an age of 22 Ma further southeast (l.c.). Additional data come from Hejl and Grundmann (1989) and Staufenberg (1987), who got apatite ages of 67 and 56.7 Ma from the Tirolic unit of the Northern Calcareous Alps and the Greywacke zone south of Salzburg, respectively, and demonstrate that the Austroalpine nappes south of Salzburg were not affected by Miocene exhumation, but only by the Paleocene event.

In the following, we separate exhumation events that affected units both north and south of the Inn valley from those causing differential exhumation across the Inn valley:

1) The Austroalpine units south of the Inn valley were exhumed in Cretaceous times, prior to sedimentation of the Gosau Group, however this exhumation did also take place in the Bajuvaric units north of the Inn valley and was a consequence of Cretaceous nappe stacking (e.g. Sanders, 1998).
2) A Paleogene cooling event is recorded by closure of the zircon fission-track system in the Kellerjochgneis and Quartzphyllite units, but neither in the Greywacke and Tirolic units on the top nor in the Bajuvaric unit north of the Inn valley. In the absence of decisive structural data, we speculate that the Greywacke and Tirolic units were in the hanging wall of a major normal fault. The zircon fission track system was closed in the Greywacke zone already in the early Late Cretaceous. Probably the Greywacke zone came into contact with the Kellerjochgneis and Quartzphyllite units during Paleogene exhumation of these units by extensional faulting across a detachment. Late Cretaceous to Paleogene exhumation was previously recognized in other Austroalpine basement units to the west (Froitzheim et al., 1997; Fügenschuh et al., 2000) and to the east (Neubauer et al., 1995), and on top of the Kellerjochgneis and Quartzphyllite units in the Greywacke zone and Tirolic unit (Ortner and Reiter, 1999) and occurred in all cases across normal faults with approximately top east displacement. In analogy, we interpret Paleogene exhumation of the Kellerjochgneis and Quartzphyllite.
3) At the turn from Lower to Upper Oligocene, the Bajuvaric unit north of the Inn valley was exhumed relatively to Tirolic unit in the south, as is shown by the transgressive contact of Upper Oligocene conglomerates to the Bajuvaric unit. As far as it can be judged from the thickness of Lower Oligocene deposits on top of the Tirolic unit, which are also overlain by Upper Oligocene conglomerates, the amount of relative exhumation of the Bajuvaric unit must have been in the order of several 100 m.
4) The most dramatic phase of exhumation caused closure of the Apatite fission-track system of the Innsbruck Quartzphyllite unit and Kellerjochgneis unit at 13 Ma (Middle Miocene). The distribution of cooling ages suggests that Middle Miocene exhumation affected mainly the Innsbruck Quartzphyllite and overlying units west of a SSE-trending line running through Wörgl (Fig. 6). Successive erosional removal of Oligocene deposits west of this line indicates increasing Miocene exhumation toward the west. In the Greywacke zone the apatite fission-track system was closed already by 40 Ma (Late Eocene), but it is not clear whether this cooling is related to the same process and exhumation started around 40 Ma, recorded in the tectonically highest units, or an additional event caused closure of the apatite fission-track system. A possible alternative explanation would be exhumation due to thrusting onto the European margin around 40 Ma. South of the Inn valley, the Tirolic Greywacke units east of Wörgl and the Bajuvaric units north of the Inn valley did not experience major Miocene exhumation.

4. Miocene movements at the Inntal shear zone

To define the kinematics of the Inntal shear zone, brittle deformation in Oligocene sediments in the vicinity of the Inntal shear zone was studied. In structurally homogeneous stations, faults, lineations and sense of movement were recorded according to well-established methods (see Hancock, 1985; Petit, 1987). As the measured fault data sets were kinematically inhomogeneous in most cases, homogeneous subsets were extracted based on kinematic compatibility and cross cutting relationships recorded in the field and observed at map scale.

The faults measured in the Oligocene sediments record a polyphase deformation history. Generally, ENE to NE-striking sinistral faults offset folds with wavelengths in the order of 1 km, demonstrating that sinistral shearing across ENE-striking folds was preceded by post-Oligocene WNW–ESE compression (Fig. 3). The fault pattern within the sinistral Inntal shear zone is anastomosing, with long fault segments striking ENE and shorter segments striking NE. The latter fault segments commonly connect the ENE-striking faults. The fault pattern compares to the main fault–Riedel relationship also described from other major strike slip faults (e.g. Christie-Blick and Biddle, 1985). Fault patterns in individual data sets repeat the map scale pattern. Faults measured in stations near ENE-striking segments of the Inntal shear zone display an ENE-striking principal displacement zone and NE-striking Riedel shears and NNW-striking Antiriedel shears (diagrams 1, 2, 4, 13, 14 in Fig. 3). Fault data sets measured near NE-striking map-scale Riedel shears have a NE-striking principal displacement zone and NNE-striking Riedel shears and NW-striking Antiriedel shears (diagrams 3, 11, 12 in Fig. 3). A common feature of many data sets is the oblique reverse slip on Riedel- and Antiriedel shears (diagrams 1, 2, 3, 4, 12, 13 in Fig. 3; Fig. 3d), which indicates transpression (e.g. Mandl, 1988). Transpression is also indicated by outcrop-scale folds formed adjacent to fault planes with axes parallel to the fault plane, and by map scale flower structure formed at some branches of the Inntal fault (Gruber, 1997; c in Fig. 3). Statistical analysis of all measured fault planes (Fig. 3e) and slip lineations (Fig. 3f) related to shearing at the Inntal shear zone indicates subhorizontal sinistral slip at subvertical ENE-striking fault planes.

The estimated post-Oligocene sinistral offset across the Inntal shear zone, based on the cumulative offset of the base of Oligocene sediments, is 22 to 30 km (Ortner, 2003b), however this estimate does not include offset across the northernmost branch of the Inntal shear zone, as north of this fault the base of Oligocene sediments is not preserved. Another estimate of total offset of approximately 40 km is based on the offset of the carbonate platform of the Middle Triassic Wetterstein-Fm., which is exposed north and south of the Inntal shear zone (Fig. 5b).

5. Interpretation and discussion

In the following, we mainly discuss the relation of exhumation to structures seen in the seismic section and at the surface. Exhumation of the Tauern window occurred from 35 Ma onwards (Selverstone, 1988; Behrmann, 1988, 1990; Fügenschuh et al., 1997). For interpretation of the seismic section, it is important to note that faults of the same age or younger than Tauern window exhumation must be rooted beneath the Tauern window, whereas older structures must be deformed by exhumation of the Tauern window. In this context, an important observation in the seismic section is the contrast in reflectivity (6 in Fig. 4a, Brixlegg thrust in Fig. 4b) terminating against or bending into parallelity with north-dipping reflections at depth. Thus the Brixlegg thrust must have an age older than the Miocene exhumation of the Tauern window, and must also be older than Miocene exhumation of Austroalpine units discussed above.

The Inntal shear zone is the only major structure of Miocene age seen at the surface, where it seems to be a subvertical shear zone (Fig. 3). In spite of its large offset of about 20–40 km, it is not clearly visible in the TRANSALP seismic section. At the surface, the Inntal shear zone is found across the whole width of the Inn valley, but in the seismic section terminations of reflections against subvertical faults are only seen near the northern side of the Inn valley (5 in Fig. 4a). As discussed in Sections 4 and 5, the Inntal shear zone was active during the Oligocene, when the northern block was exhumed in relation to the southern block, and during the Miocene, when the southern block was exhumed relatively to the northern block, beside the sinistral lateral displacement. As the faults which are part of the Miocene Inntal shear zone are not seen in the seismic section, it is proposed that they are parallel to the reflections seen in the seismic section. Consequently, drawing such faults parallel to the reflections to depth, they must be connected to the faults, which stack the Helvetic slices below the Tauern window (Fig. 4b). Because large offsets across the Inntal shear zone postdate Oligocene sedimentation, and major exhumation of the tectonic units south of the Inn valley is also younger than Oligocene, we think that oblique thrust movements across the south-dipping Inntal shear zone at depth were responsible for the Miocene exhumation. Therefore, the Inntal shear zone at the surface must connect with the sub-Tauern ramp in the sense of the TRANSALP Working Group (2002) at depth.

5.1. 3D-geometry of Neogene exhumation

In the TRANSALP seismic section and further west, Neogene exhumation of the Innsbruck Quartzphyllite nappe occurs above the sub-Tauern ramp–Inntal shear zone fault system (Figs. 4b and 7a). A possible reason for exhumation is thrusting across the sub-Tauern ramp and stacking of Helvetic slices on top of the European plate, as seen in the cross sections of Figs. 4a and 7a.

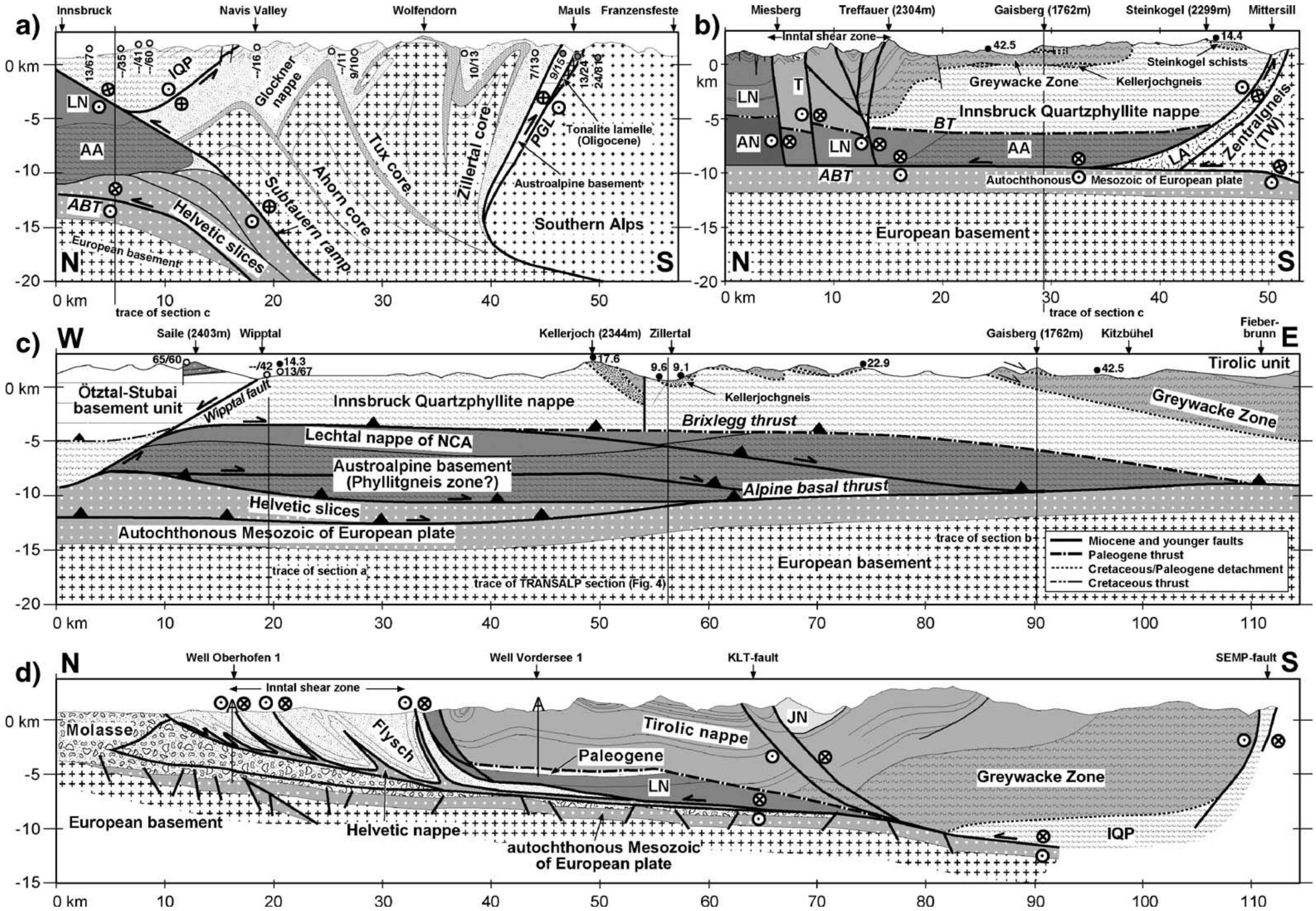


Fig. 7. Cross sections parallel and perpendicular to the TRANSALP seismic section to illustrate the 3D-geometry of main tectonic boundaries seen in the seismic section. For location of traces of the sections see Fig. 2a to d. Possible flakes of Rhenodanubian Flysch and Helvetic nappes below the Northern Calcareous Alps in sections b and c omitted for clarity. a) Cross section Innsbruck–Franzensfeste east of the Brenner pass. b) Cross section Miesberg–Mittersill. c) Cross section Saile–Fieberbrunn south of the Inntal shear zone. d) Cross section from the Molasse basin to the Tauern window east of Salzburg, redrawn and modified from Hejl et al. (1988) and Brix and Schultz (1993). Black circles: apatite fission-track ages by Grundmann and Morteani (1985), grey circles: apatite/zircon fission-track ages by Mancktelow et al. (2001), white circles: apatite/zircon fission-track ages by Fügenschuh et al. (1997). AN = Allgäu nappe, LN = Lechtal nappe (Bajuvaric nappes), T = Tirolic nappe, JN = Juvavic nappe, AA = Austroalpine basement, LA = Lower Austroalpine, ABT = Alpine basal thrust, BT = Brixlegg thrust, TW = Tauern window, PGL = Pustertal–Gailtal line.

The Innsbruck Quartzphyllite nappe is in the footwall of the Brenner normal fault, and exhumation was coupled with normal movements across this fault (e.g. Fügenschuh et al., 1997). Combining these two observations, we conclude that the Brenner normal fault partly moved in response to thrusting across the sub-Tauern ramp, as depicted in Fig. 7c. To quantify movements across the faults discussed we use the exhumation observed in the Innsbruck Quartzphyllite unit and the offset observed across the Inntal shear zone. The first is in the order of 3–5 km, which is equivalent to 6–10 km dip-slip thrusting across the sub-Tauern ramp which dips 30° to the south. Stacking of Helvetic slices documents much more shortening and must therefore predate activity of the sub-Tauern ramp. Offset across the Inntal shear zone is in the range of 20 to 40 km (see Section 4). Particle paths consistent with both thrusting across the sub-Tauern ramp and sinistral shearing across the Inntal shear zone plunge between 7° and 25° to the WSW. Therefore slip lineations at the Inntal shear zone should plunge moderately to the west. However, observed slip at the Inntal shear zone is rather subhorizontal (Fig. 3f). We suggest, that total offset was partitioned into thrusting, accommodated by the upper shear planes of the Inntal shear zone (Fig. 4b), whereas sinistral shear was transmitted to the subvertical, northern strike-slip faults.

As seen in Fig. 6, the zone of Neogene exhumation corresponds to the zone where the Innsbruck Quartzphyllite nappe is exposed at the surface. Toward the east, this zone tapers against the Salzachtal fault. Where Neogene exhumation decreases or is not observed, the thrust plane must become horizontal as depicted in Fig. 7b and c. This transition zone is located east of the TRANSALP seismic section and is also documented by increasing thicknesses of Oligocene deposits to the east (from b in Fig. 3 eastwards). In map view, the distance between the Inntal shear zone and the sub-Tauern ramp below the Tauern window increases to the east, which requires a fault plane flattening out to the east (Fig. 7b). Where the Neogene fault plane is horizontal, offset of the thrust below the Tauern window is entirely transferred into the Alpine basal thrust (ABT in Fig. 7). East of the TRANSALP seismic section slip across the Inntal shear zone is therefore expected to be subhorizontal.

Apatite and zircon fission-track ages from the Tauern window in the TRANSALP transect indicate that exhumation within the Tauern window was upward and southward since at least 20 Ma (Most et al., 2003), which is consistent with the distribution of fission-track ages in the Brenner cross section (Fig. 7a; Fügenschuh et al., 1997). Before the sub-Tauern ramp did break to the surface, and the Inntal shear zone became active, which was approximately before 13 Ma, the Tauern Window must have been exhumed by thrusting on the sub-Tauern ramp, balanced by subvertical and lateral extrusion (Fig. 8). Minor amounts of shortening were transmitted to the front of the Alpine wedge, where post-Oligocene shortening amounts to at least 14 km near the TRANSALP seismic section (Jacob et al., 1982). Folding of Oligocene rocks of the Inn valley also gives evidence of post-Oligocene shortening north of the Tauern window (Fig. 3). Stacking of Helvetic slices below the Tauern window should have been active during this time. When the basal Alpine thrust was blocked, the sub-Tauern ramp propagated to the surface, creating the Inntal shear zone, however the exhumation pattern of the Tauern window remained the same.

5.2. Oligocene faulting

A few of the geometries observed in the TRANSALP seismic section cannot be explained by movement across the sub-Tauern ramp–Inntal fault system. Faults

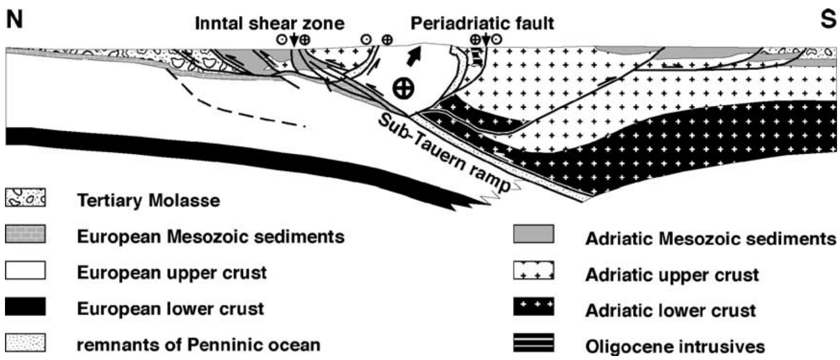


Fig. 8. Interpretation of the TRANSALP seismic section modified from TRANSALP Working Group (2002), lateral extrusion model. Length of section = 300 km.

parallel to the Inntal shear zone, which downthrow the southern block, are kinematically not compatible with Miocene thrusting. One of these faults is the northernmost branch of the Inntal shear zone as seen in Fig. 4b. The age of the normal offset is pre-Late Oligocene, because Late Oligocene conglomerates seal the offset (see Section 3.3). Based on the finding of Ortner and Stingl (2001), that the Northern Calcareous Alps were part of the subsiding foreland basin, we relate this topography to the activity of normal faults, which formed in the downgoing European plate due to tangential strain during flexure. The base of the Alpine foreland basin has a dense network of such normal faults, partly with large offsets, which were documented in the course of hydrocarbon exploration (e.g. Bachmann et al., 1982). The differing orientation of these faults compared to the Inntal shear zone can be explained by a Miocene anticlockwise rotation of the Northern Calcareous Alps, as described by Thöny et al. (this volume).

5.3. Interpretation of the Brixlegg thrust

Activity of the Brixlegg thrust should be older than uplift of the Tauern window, as it bends into the contact of the Austroalpine units against the Tauern window (Fig. 4). Apparent offset across the Brixlegg thrust is 10 km parallel to the thrust plane, as indicated by the offset of the base of the Northern Calcareous Alps. In the present orientation of the Brixlegg thrust, which dips 28° to the south, this translates into 5 km of exhumation. If the Brixlegg thrust would be part of the sub-Tauern ramp–Inntal fault system, these 5 km would have to be added to the offset of the deeper branches of the fault system, which amounts to 2.5 km, if measured at the base of the Northern Calcareous Alps. The total of 7.5 km exhumation is not consistent with 3–5 km Miocene exhumation as observed. Considering both geometry and exhumation of the hanging wall, the Brixlegg thrust can not be part of the sub-Tauern ramp–Inntal fault system.

The well Vordersee 1 penetrated the Tirolic unit SE of Salzburg and reached the underlying Bajuvaric unit with Paleogene sediments on top (Fig. 7d; Geutebrück et al., 1984). Therefore the thrust of the Tirolic unit onto the Bajuvaric unit has a Paleogene age and most probably displaced the original lateral boundary between the two units. Due to the large thrust distance of at least 20 km (l.c.), the original boundary between the units is north of the present-day northern margin of the Tirolic unit in the air and south of the Bajuvaric unit buried below the Tirolic unit. If extrapolating the geologic units from the east into the TRANSALP seismic section, the Brixlegg thrust corresponds to the boundary between the Bajuvaric and Tirolic unit as seen in Fig. 7d and is a Paleogene thrust plane. The hanging wall ramp geometry as seen in the TRANSALP seismic section would then correspond to the hanging wall ramp in the Austroalpine basement units on a footwall flat on top of the Bajuvaric unit as seen in Fig. 4b. In this context, the Paleogene apatite fission-track ages in the Greywacke zone of the hanging wall possibly can be interpreted to be related to exhumation due to Paleogene out-of-sequence thrusting.

6. Conclusion

Structures related to several stages in the evolution of the Alpine wedge are imaged in the Inntal–Tauern sector of the TRANSALP seismic section: A Paleogene out-of-sequence thrust plane termed Brixlegg thrust forms the contact between the Tirolic unit and Austroalpine basement units above to Bajuvaric units below. The Brixlegg thrust is in the hanging wall of the sub-Tauern ramp–Inntal fault system, which was active in the Middle Miocene. The distribution of Middle Miocene cooling ages in the hanging wall constrains the 3D-geometry of the fault plane, which changes from a deep reaching ramp in the TRANSALP seismic section and further west to a flat identical with the basal Alpine thrust east of the TRANSALP seismic section. Thrust movement across the sub-Tauern ramp–Inntal fault system was balanced by vertical exhumation and lateral extrusion so that the frontal Alpine thrust became inactive, when the Inntal shear zone became active. Oligocene normal faulting throwing the southern block down is kinematically not compatible with Paleogene and Neogene thrusting and is related to breakup of the European plate during flexure when the foreland basin formed. These normal faults predetermined the course of the younger Inntal shear zone.

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