TECTONOMETAMORPHIC EVOLUTION OF THE AUSTROALPINE NAPPES IN THE NORTHERN ZILLERTAL AREA (TYROL, EASTERN ALPS)

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With 10 Figures and 3 Tables

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Zusammenfassung

Diese Untersuchung behandelt die tektonische Entwicklung der Austroalpinen Decken im Norden des Tauernfensters im nördlichen Zillertal (Tirol). Die bearbeiteten Einheiten sind der Kellerjochgneis (Schwaz Augengneis), der Innsbrucker Quarzphyllit und der Wildschönauer Schiefer. Sechs unterschiedliche Deformationsabfolgen konnten gefunden werden. Die erste Deformationsphase (D_1) ist nur als reliktische Schieferung im Dünnschliff erkennbar. Im Innsbrucker Quarzphyllit manifestiert sich die erste Deformationsphase in Form von isoklinalen Falten. Die dominante Foliation wurde während der zweiten Phase (D_2), welche das Resultat einer NW-SE Einengung ist, gebildet. Diese duktile Hauptdeformationsphase drückt sich ebenso in Form isoklinaler Falten aus. Diese Struktur begleiten Scherbänder, welche einen W-NW-gerichteten Deckentransport anzeigen und somit D_2 daher mit der kretazischen Deckenstapelung korreliert werden kann. Die dritte duktile Deformationsphase (D_3) führte zur Ausbildung offener Falten, welche auf eine NE-SW-gerichtete Kompression hinweisen. Die vierte Deformationsphase (D_4), welche eine NNW-SSE Kompression anzeigt, ist ebenso durch offene Falten und einer Achsenebenenschieferung charakterisiert. Die letzte duktile Phase (D_5) führte zur Ausbildung semiduktiler Knickbänder, welche die älteren Deformationselemente diskordant durchschneiden. Die darauf folgende Sprödverformung (D_6) kann in vier Unterphasen gegliedert werden (D_{6a-d}). Die strukturelle Entwicklung dieses Gebietes kann mit Hilfe der geochronologischen Daten aus dieser Region als tektonometamorphe Entwicklung interpretiert werden. Zusammenfassend kann behauptet werden, dass die Platznahme des Innsbrucker Quarzphyllits, des Kellerjochgneises und der Wildschönauer Schiefer während der Oberkreide nach der Schließung des Hallstatt-Meliata Ozeans unter Bedingungen der oberen bis mittleren Grünschieferfazies stattgefunden hat.

Abstract

This investigation addresses the tectonic evolution of the Austroalpine nappes north of the Tauern Window in the northern Zillertal (Tyrol). The investigated units are the Kellerjochgneiss (Schwaz Augengneiss), the Innsbruck Quartzphyllites and the Wildschönau Schists. Six stages of deformation are distinguished. The first stage (D_1) is present as a relic foliation, observed only in thin sections. In the Innsbruck Quartzphyllite the first deformation stage is represented by isoclinal folds. The dominant foliation is represented in the second stage (D_2), which is the result of a NW-SE-oriented compression. This main ductile deformation event also is expressed by the formation of isoclinal folds. Associated shear bands indicate W-NW-directed transport and thus D_2 is related to the Cretaceous nappe stacking. The third ductile deformation stage (D_3) leads to the formation of open folds most likely associated with the NE-SW contraction. The fourth stage (D_4) is also characterized by open folds and an axial plane foliation, reflecting subsequent NNW-SSE compression. The last ductile stage (D_5) produced semi-ductile kink bands, which crosscut the earlier deformation structures. The subsequent brittle deformation (D_6) can be divided into four stages (D_{6a-d}). This structural succession can be interpreted in terms of the existing geochronological framework for this area, suggesting that nappe stacking of the Innsbruck Quartzphyllites, the Kellerjochgneiss and the Wildschönau Schists took place during the Late Cretaceous under middle- to upper greenschist-facies conditions, related to the closure of the Hallstatt-Meliata Ocean.

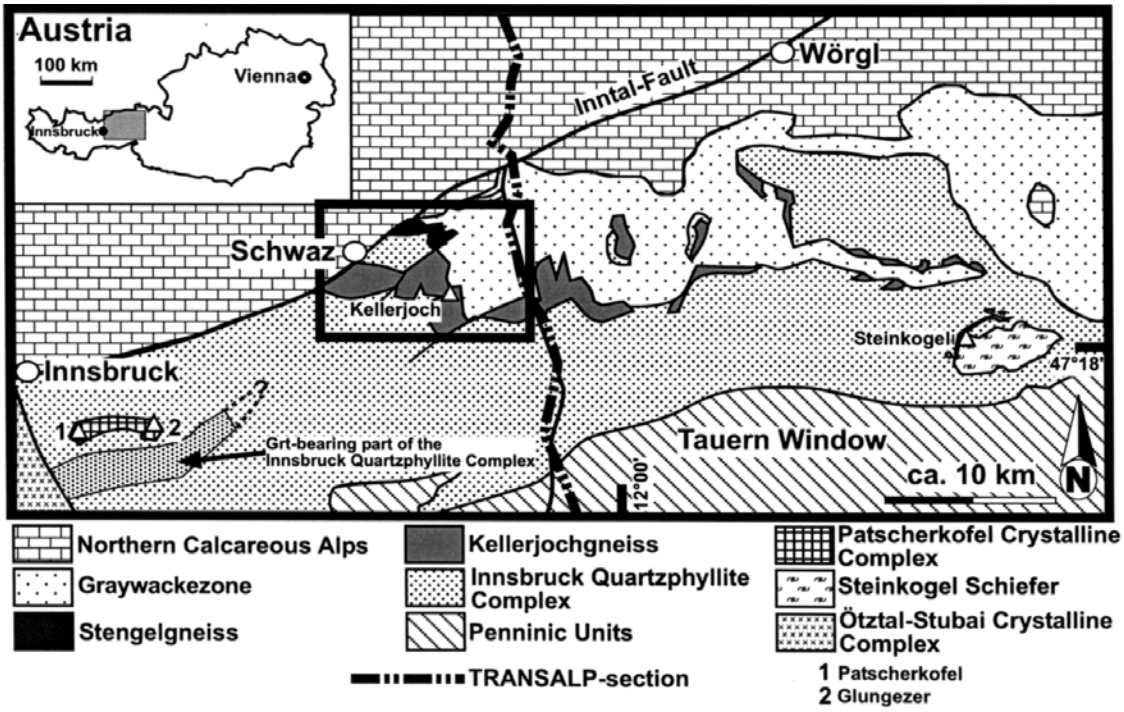
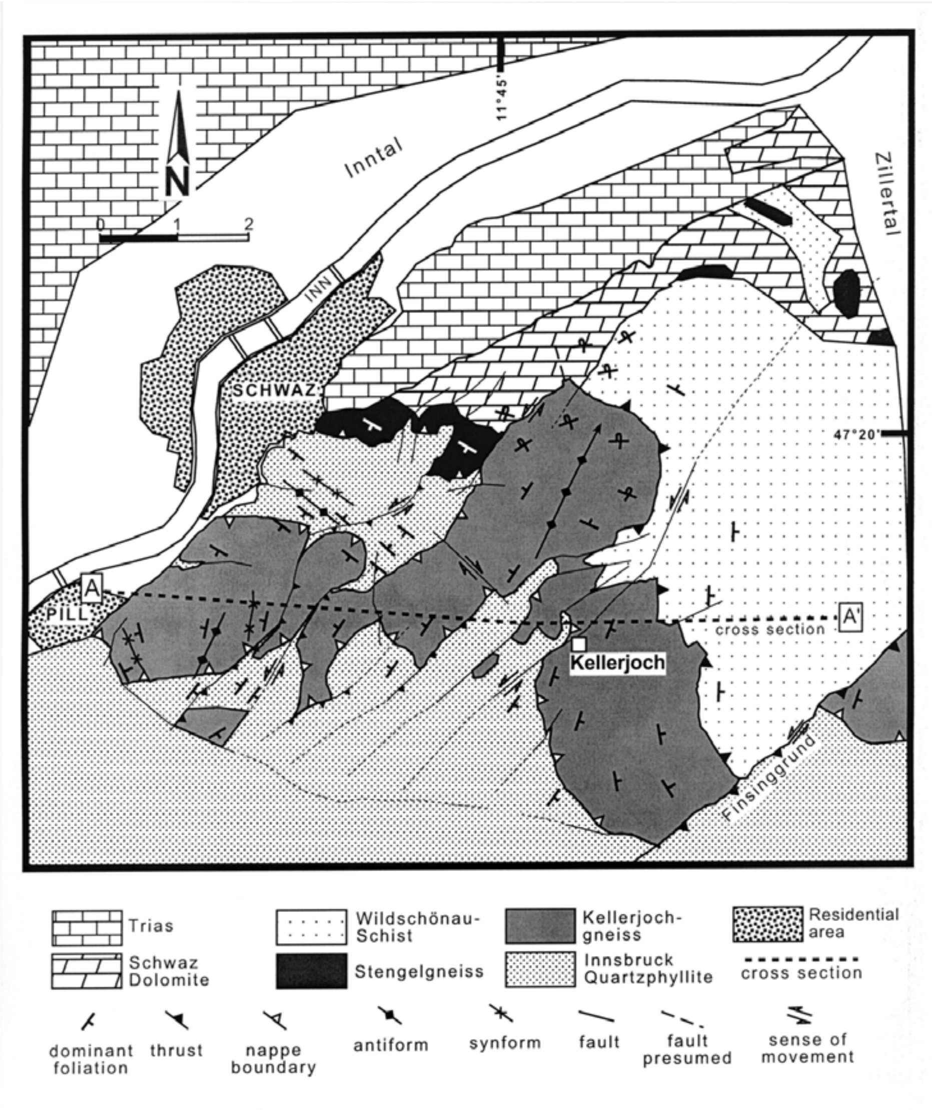


Figure 1: Tectonic overview of the Austroalpine units north of the Tauern Window. The framed area depicts the area of investigation.

1. Introduction

These investigations are closely related to the international geophysical TRANSALP-project, which intends to provide a seismic reflection-profile through the Eastern Alps along a transect between Bad Tölz in the north, located to the south of Munich, and Venice in the south (Transalp Working Group, 2002). The area of the structural investigation covers ca. 60 km^2 in the northern part of the Zillertal near the city of Schwaz (Fig. 1). Lithologically the investigated area consists of polymetamorphic basement units (Kellerjochgneiss or Schwaz Augengneiss), Paleozoic carbonates and quartzphyllites (Schwaz Dolomite, Innsbruck Quartzphyllite and Wildschönau Schists) (Fig. 2A). The Wildschönau Schists mainly consist of meta-greywackes. The units are strongly deformed, with abundant synformal and antiformal structures as shown in a cross-section in Figure 2B. In the northern part of the working area, a strong tectonic imbrication of the above mentioned units occurs. The contact between the three units in the area of investigation is always of tectonic nature, with the Innsbruck Quartzphyllite representing the lowermost unit and the Wildschönau schist representing the uppermost unit. Figure 2B shows a profile through a large antiformal structure in the Kellerjochgneiss, with the Innsbruck Quartzphyllite occurring as the core.

This investigation aims to provide structural data to better constrain the tectonic evolution of the three units, i.e. the Innsbruck Quartzphyllite, the Kellerjochgneiss and the Wildschönau Schists. Our results contribute to the ongoing discussion concerning the paleogeographic setting of these units, as well as providing data for the interpretation of the seismic data along this section of the TRANSALP transect (Transalp Working Group, 2002). Based on its tectonic position in the Austroalpine nappe stack of the western part of the Eastern Alps, the Innsbruck Quartzphyllite has always been unambiguously attributed to the lower Austroalpine units (Tollmann, 1963). The Wildschönau Schists represent the Paleozoic basement of the Upper Austroalpine Tirolic nappe, which is itself a part of the Northern Calcareous Alps and hence it was always attributed to be of upper Austroalpine origin. However, the paleogeographic provenance of the intermediate basement rock units on top of the Innsbruck Quartzphyllite, namely the Patscherkofel Crystalline Complex, the Kellerjochgneiss and other similar bodies located further east (e.g. Steinkogelschiefer) is still a matter of discussion. Tollmann (1963) considered the Kellerjochgneiss to be a middle Austroalpine nappe, together



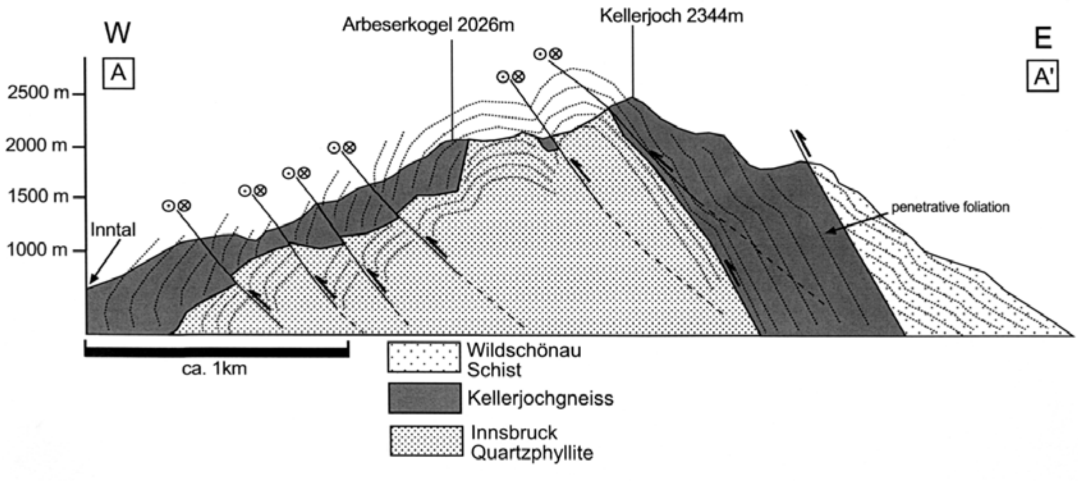


Figure 2: (A) Tectonic map of the area of investigation. (B): E – W cross section. The position of the profile is shown as a stippled line in Figure 2A. The Figure shows a large NW trending fold located in the W of the Kellerjoch. The units are intersected by several sinistral reverse strike-slip faults. These faults are thought to belong to the Inntal Fault system.

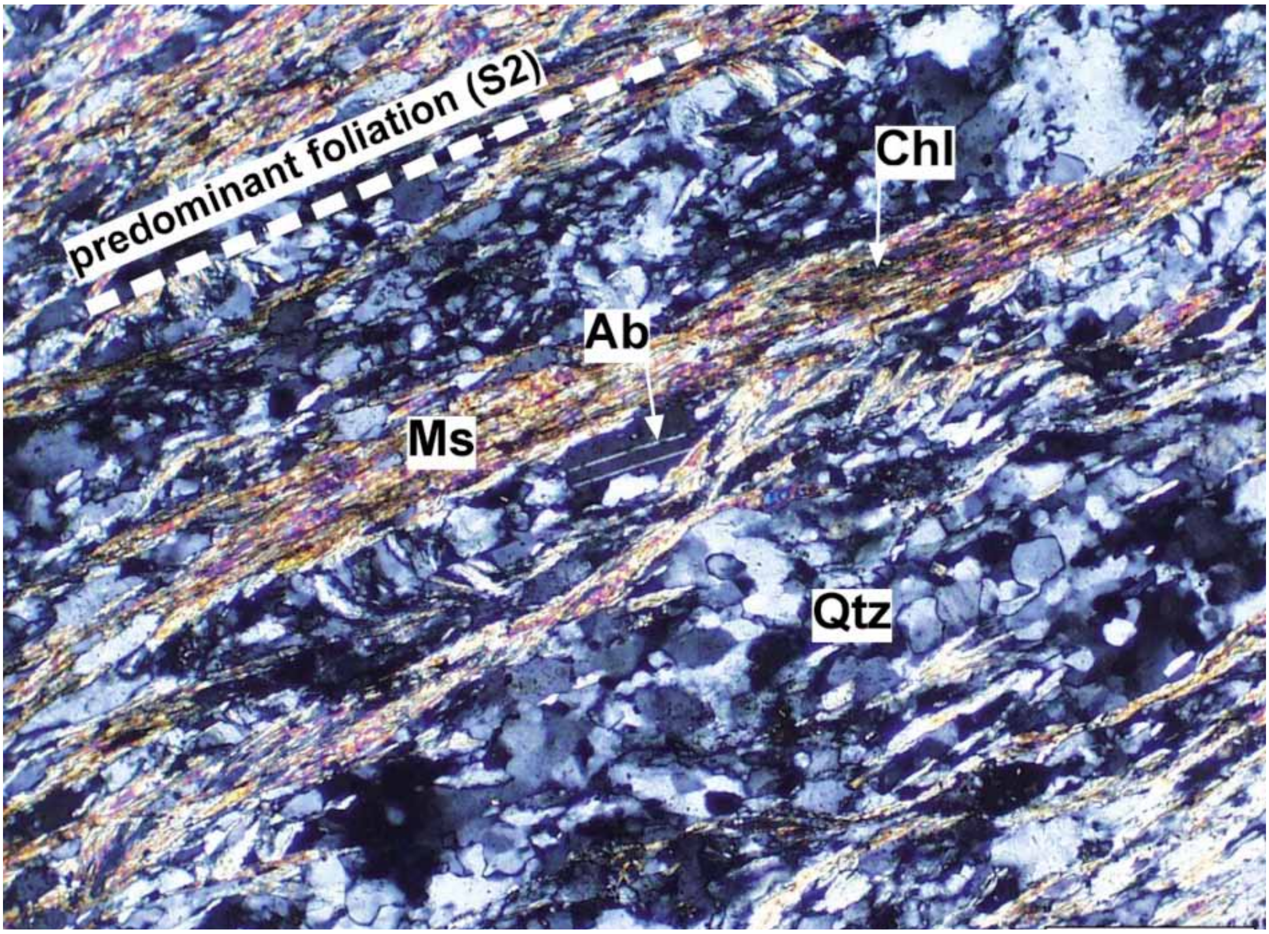


Figure 3: Photomicrograph of the mineral assemblage of the Innsbruck Quartzphyllite. Quartz (Qtz), chlorite Chl), muscovite (Ms) and albite (Ab) can be observed (sample A-133; X Nicols). The predominant foliation (S2) is also shown in the upper left corner.

with the Steinkogelschiefer and the Patscherkofel-Glungezer Crystalline Complex. On the other hand, Schmidegg (1964) interpreted these basement units as representing the base of an inverted lying Innsbruck Quartzphyllite. While the tectonic nature of the contact between the Innsbruck Quartzphyllite and the Kellerjochgneiss has been established, there is still disagreement concerning the timing of movements along this contact (e.g. Steyrer et al., 1996). Satir and Morteani (1978a) interpreted this contact to be of Variscan age, leading to the conclusion that all units, with respect to the Eo-Alpine orogeny, have to be classified as Lower Austroalpine. Tollmann (1977), on the other hand, interpreted the contact as having formed during the Alpine orogeny and thus defined it to be the boundary between the lower- and middle Austroalpine units. Fügenschuh (1995) and Steyrer et al. (1996) described a zone of ultramylonites separating the two units and suggested that the Kellerjochgneiss is a thinned relic of middle Austroalpine units. According to Schmid et al. (2004) The Kellerjochgneiss and the Greywacke Zone are part of the Upper Austroalpine cover and the Innsbruck Quartzphyllite belongs to the Silvretta-Seckau nappe system, which forms the basal nappes of the Upper Austroalpine basement nappe system.

The aim of this study is therefore two-fold: 1) The primary goal is a detailed structural investigation of the area, to determine the structural successions in the Innsbruck Quartzphyllite, the Kellerjochgneiss and the Wildschönau Schists. These results will be compared with previous studies and tectonic models obtained from the three units as well as of neighboring units such as the Northern Calcareous Alps by Schmidegg, (1964), Roth (1983), Eisbacher and Brandner (1995), Ortner and Sachsenhofer (1996), Steyrer et al. (1996), Kolenprat et al. (1999), Ortner et al. (1999), Reiter (2000) and Grasbon (2001) and 2) the other aim is to relate the observed sequence of deformational events to the regional tectonic evolution of this part of the Eastern Alps. The deformational sequence will therefore also be discussed in the context of the available geochronological and thermobarometric framework from the Austroalpine nappes north of the Tauern Window.

2. Geological overview

The Innsbruck Quartzphyllite outcrops between Mittersill in the east and Innsbruck in the west. It is typically a rather monotonous, fine-grained, greenish to grayish phyllitic schist, with the mineral assemblage muscovite + chlorite + albite + quartz ± calcite (Fig. 3). Locally, garnet-bearing schists occur south of the Patscherkofel. It has been divided into three stratigraphical units consisting of Devonian carbonatic black shales, Silurian carbonatic-sericitic phyllites and Ordovician quartzphyllites and greenschists, however numerous transitions may be found (Haditsch and Mostler 1982). Although most of the Innsbruck Quartzphyllites were affected by lower greenschist-facies metamorphism (Hoschek et al. 1980; Sassi and Spiess, 1992; Piber, 2005; Piber and Tropper, 2005), some central parts of the Innsbruck Quartzphyllite have been affected by middle greenschist-facies metamorphism (Kolenprat et al. 1999; Piber, 2005; Piber and Tropper, 2005). Geochronological investigations revealed a complex metamorphic history indicating a possible Permian- and Eo-Alpine overprint (Dingeldey et al., 1997; Rockenschaub et al., 1999; Handler et al., 2000). Recently, a number of new results have been obtained concerning the internal structure of the Innsbruck Quartzphyllite (Kolenprat et al., 1999). Large parts of the Innsbruck Quartzphyllite must therefore be considered as highly deformed, retrograde old (Variscan?) basement. These studies revealed a metamorphic zonation with garnet-free phyllites at the northern and southern rims and garnet bearing phyllites in the central part (Fig. 1), thus reflecting a slightly higher grade of metamorphism in the center. This observation was interpreted in terms of a km-scale isoclinal fold of the Innsbruck Quartzphyllite (Schmidegg 1964, Rockenschaub 1998; Kolenprat 1998). Kolenprat et al. (1999) show, that the Innsbruck Quartzphyllite has a complex deformation history, with structures ranging from pre-Alpine (Variscan) to late Alpine (Neogene) in age. The pre-Alpine foliation is preserved only locally. During the Eo-Alpine orogeny, intensive mylonitization associated with W- to NW-directed nappe stacking, occurred. The Meso (Early Tertiary)- and Neo (Miocene)-Alpine deformation is characterized by the imbrication of the Lower Austroalpine units as a consequence of N-directed thrusting of the Austroalpine nappes over the Penninic Units and subsequent exhumation of the Tauern-Window during N-S-shortening and E-W-extension (Kolenprat et al., 1999).

The Kellerjochgneiss was first mapped on a large scale by Ampferer and Ohnesorge (1918, 1924) and is a mylonitic augengneiss. The mineral assemblage of the Kellerjochgneiss includes biotite + muscovite + plagioclase + K-feldspar + quartz ± stilpnomelane ± clinozoisite (Fig. 4A). Accessories are titanite, rutile, zircon, epidote, apatite, hematite and ore minerals. The protolith of the Kellerjochgneiss was probably an S-type alkaline-feldspar-granite according to Steyrer and Finger (1996) and Gangl et al. (2002, 2005). Only few petrological and structural studies have been carried out so far on these rocks (Satir and Morteani, 1978a, b; Satir et al. 1980; Wezel, 1981; Roth, 1983, 1984; Piber, 2002). Metamorphic P-T conditions of an earlier overprint (Variscan) of 5.3 kbar at 400°C were determined by Satir and Morteani (1978b). A qualitative estimate of the later metamorphic overprint (Eo-Alpine) indicates temperatures <350°C at 2-3 kbar (Satir and Morteani, 1978b). In contrast, the latest P-T estimates yield temperatures between 286° – 345°C at pressures ranging from 4.3 – 6.5 kbar and are thought to represent the Eo-Alpine metamorphic overprint (Piber and Tropper, 2005; Gangl et al., 2005). Single zircon U/Pb analyses point to an intrusion age of 468 ± 1 and 469 ± 2 Ma and thus provide further evidence for pre-Variscan age data in addition to the two dominant metamorphic overprints, the Variscan and the Eo-Alpine event (Satir and Morteani, 1978a, b; Steyrer and Finger, 1996; Handler et al., 2000, Gangl et al., 2005). In his structural investigations, Roth (1983) identified deformation structures that he related to the Variscan and Alpine orogeny respectively. According to these observations early (Variscan) mylonites, related to nappe emplacement were re-activated during the N-directed nappe stacking associated with the Eo-Alpine orogeny. Afterwards, NE-SW striking and NW-verging folds formed which he related to the subsequent continental collision following the nappe transport (Roth, 1983).

The Stengelgneiss occurs only in the NE part of the area of investigation and is a mylonite that is most likely still part of the Kellerjochgneiss as indicated by geochemical investigations (Gangl et al., 2002). Additionally, a single zircon U/Pb age of 479 ± 2 Ma

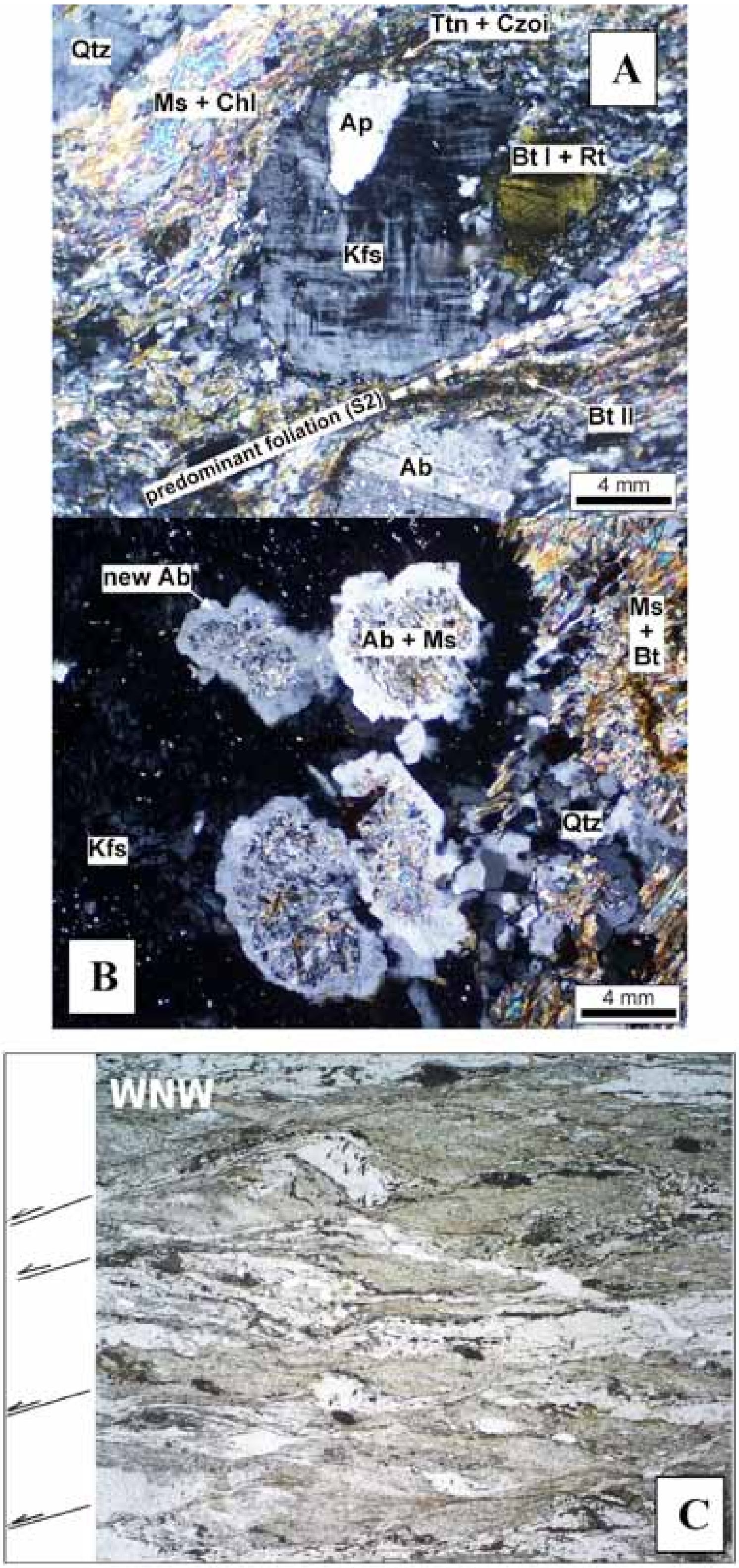


Figure 4: (A): This photomicrograph depicts the characteristic mineral assemblage of the Kellerjochgneiss (sample A-56) with relict K-feldspar (Kfs), albite porphyroblasts and relict biotite (Bt I) containing abundant rutile (Rt) needles, and chlorite (Chl) and muscovite (Ms). On the top of the picture at the rim of the K-feldspar titanite (Ttn) and clinozoisite (Czoi) occur (X Nicols). (B): This photomicrograph shows albite porphyroblasts containing sericite within a relict K-feldspar crystal. Newly grown albite predominately occurs at the rim or along fractures within the old feldspar crystals (sample A-98, X Nicols). (C): This photomicrograph shows shearbands in the Kellerjochgneiss indicating top to WNW movements.

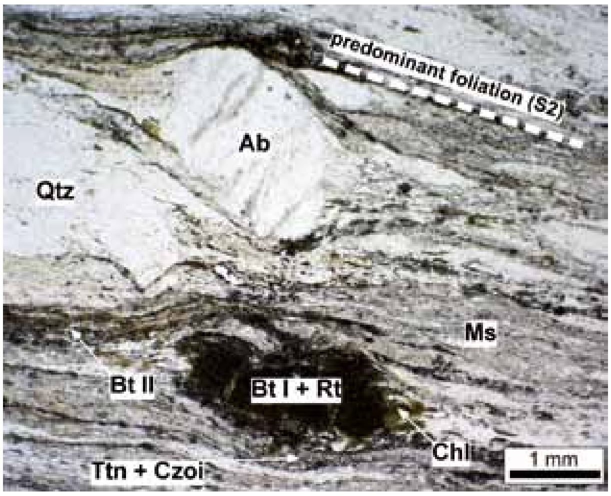


Figure 5: Photomicrograph of the comparison of pre - and synkinematically grown biotite in the Stengelgneiss. The synkinematically grown minerals, such as muscovite (Ms), biotite (Bt II), albite (Ab), chlorite (Chl) and quartz (Qtz) are strongly flattened, while the older biotite (Bt I) was rotated during deformation and titanite (Ttn) and clinozoisite (Czoi) grew along its rims. Chlorite occurs in the pressure shadow of Bt I (sample A-106, II Nicols).

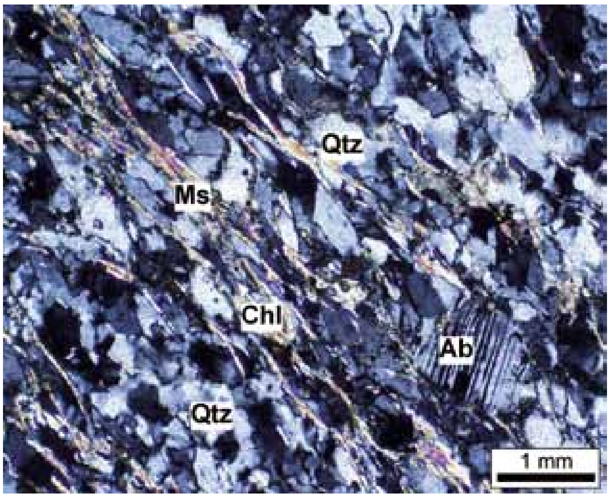


Figure 6: Photomicrograph of the mineral assemblage of the Wildschönau Schists containing muscovite (Ms), quartz (Qtz), albite (Ab) and chlorite (Chl) (sample A-101, X Nicols).

indicates an affiliation to the Kellerjochgneiss (Gangl et al., 2005). Similar to the Kellerjochgneiss, the Stengelgneiss displays also a mylonitic fabric but the minerals are stronger elongated along the NE-SW striking stretching lineation. The mineral assemblage of the Stengelgneiss consists of biotite + muscovite + plagioclase + K-feldspar + quartz. As accessories, titanite, rutile, zircon, epidote, apatite, hematite and ore minerals occur (Fig. 5). Strongly deformed quartz grains are stretched parallel to the lineation and quartz aggregates form rods which gave the Stengelgneiss its name.

The Wildschönau Schists and the Schwaz Dolomite are part of the Greywacke Zone (Ortner and Reiter, 1999) and according to Mostler (1973) the Western Greywacke Zone is a stratigraphic sequence of meta-sediments with volcanic intercalations, ranging from the Ordovician to the Late Devonian. The Wildschönau Schists are composed of light gray phyllites similar to the Innsbruck Quartzphyllite. Roth (1983) characterized two different varieties of the Wildschönau Schists, the sandy type and the phyllitic type. Grasbon (2001) established that these two varieties of Wildschönau Schists are intercalated even on outcrop scale and therefore these two variations will be treated together in this investigation. The mineral assemblage of the Wildschönau Schists is very similar to the Innsbruck Quartzphyllites containing the mineral assemblage muscovite + chlorite + albite + quartz ± calcite (Fig. 6). Muscovite ^{40}Ar-^{39}Ar ages (Handler et al., 2000) from the Wildschönau Schists indicated a Variscan or Permian metamorphic overprint at 267 ± 6 Ma. In addition Angelmaier et al. (2000) obtained ^{40}Ar-^{39}Ar ages of 264 ± 11 Ma on muscovite, which correlates very well with the age of Handler et al. (2000). Although few ^{40}Ar-^{39}Ar data from the Wildschönau Schists yield late Variscan ages (Handler et al., 2000), ^{40}Ar-^{39}Ar ages from the central Greywacke Zone yield 102 – 98 Ma (Schmidlechner et al., 2006) and ^{87}Rb-^{87}Sr ages of 137 to 127 Ma and ^{40}K-^{39}Ar ages of 113 to 92 and 113 to 106 Ma from the Greywacke Zone close to Zell am See give reasonable evidence for an Eo-Alpine metamorphic overprint around ca. 300°C (Kralik et al., 1987).

In the Western Greywacke Zone, modern thermobarometric data were lacking until recently. Based on index minerals, Hoschek et al. (1980) estimated lower greenschist facies conditions for the Wildschönau Schiefer. Piber (2005) obtained *P-T* conditions of 4.5 kbar and 330°C, based on multi-equilibrium thermobarometry on one sample of the Wildschönau Schists. Geochronological investigations by Handler et al. (2000) and Anglmeier et al. (2000) in this area indicate only a Permian metamorphic overprint so far. However, investigations from the central Greywacke Zone yield clear evidence for a Cretaceous metamorphic overprint around ca. 300°C (Kralik et al., 1987; Schmidlechner et al., 2006).

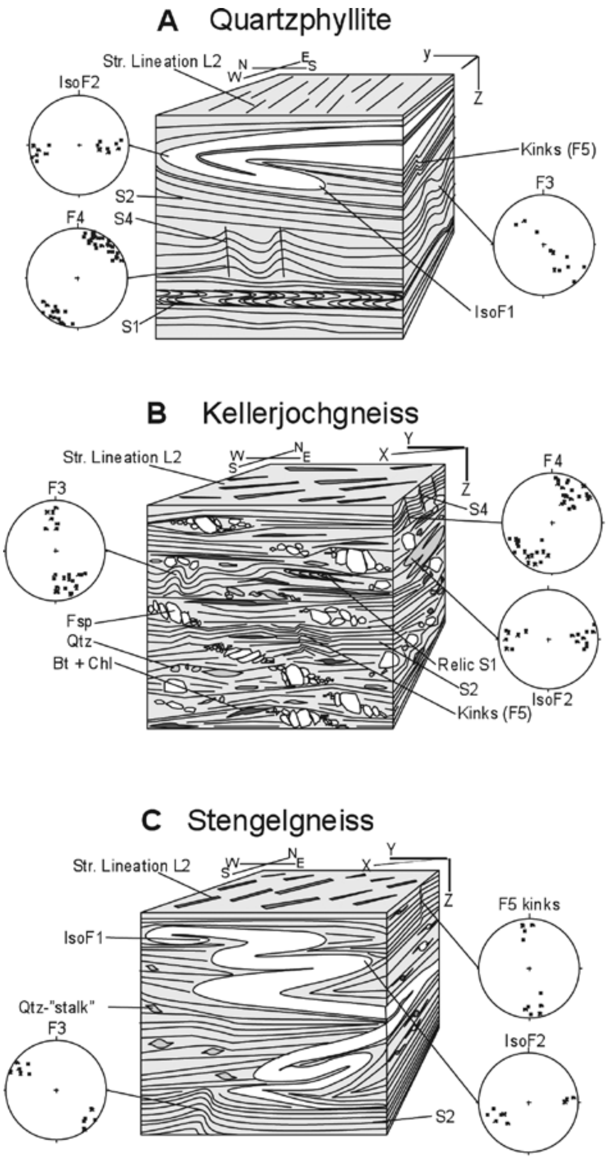


Figure 7: Block diagrams showing the tectonic structures of the Innsbruck Quartzphyllite (A) the Kellerjochgneiss (B) and the Stengelgneiss (C). In addition, stereo plots showing the orientation of the different fold axes and stretching lineations, are added to the tectonic block images.

3. Structural data

Ductile deformation

Based on structural data obtained in the field and petrographic and textural observations in oriented thin sections, four stages of ductile (D_1 – D_4) and one stage of semiductile (D_5) deformation could be distinguished. The spatial relationship of the structural elements is illustrated in Figures 7 A – C, showing idealized block diagrams of a sample of each of the units discussed. The structural successions of the investigated units are also shown in Table 1, which give a comprehensive overview of the observed structures.

Deformation D_1

Relict D_1 structures, such as a foliation and isoclinal folds, are preserved in all investigated units. In the Innsbruck Quartzphyllite and in the Kellerjochgneiss, a relict of an earlier foliation (S_1) is visible in very few thin sections. Due to the intensive overprint of the earlier foliation S_1 by S_2, the orientation of S_1 could not be determined in these units. Remnants of a stretching lineation (L_1), which seems to accompany S_1, rarely occur and exhibit no clear orientation. In the Wildschönau Schists, remnants of a relict S_1 foliation show a strike ranging from NNE-SSW to NW-SE. In addition, this deformational event also causes isoclinal folding (iso-F_1) of intercalated quartz segregations in the Innsbruck Quartzphyllite and the Stengelgneiss with wavelengths up to a few centimeters as shown in Figure 7A, B and 8A, B. These folds are absent in the Kellerjochgneiss and the Wildschönau Schists.

Deformation D_2

A younger foliation (S_2), which is the dominant foliation in the area of investigation, overprints S_1 in the Innsbruck Quartzphyllite (Fig. 7A). Occasionally a stretching lineation occurs in the Innsbruck Quartzphyllite in quartz-rich aggregates, quartz- and calcite-rich ribbons and/or carbonate-rich aggregates. This lineation (L_2) strikes ENE-WSW (Fig. 7A). During this stage of deformation, the relict isoclinal folds (iso-F_1) in the Innsbruck Quartzphyllite were also refolded and formed a second generation of isoclinal folds (iso-F_2) with hinge lines striking ENE-WSW (Fig. 7A, Fig. 8A). The S_2 foliation is also the dominant mylonitic foliation in the Kellerjochgneiss and the Stengelgneiss (Fig. 7B, C, Fig. 8B, C). Stretching lineations (L_2) in the Kellerjochgneiss and the Stengelgneiss trend NE-SW (Fig. 7B, C). Isoclinal folds (iso-F_2) with WSW-ENE striking hinges, similar to the Innsbruck Quartzphyllite, were also found in the Kellerjochgneiss and Stengelgneiss (Fig. 7B, C, Fig. 8B, C). Accompanying the ENE-WSW striking isoclinal folds (iso-F_2), a stretching lineation (L_2), which strikes NE-SW, also occurs. Locally small top-NW

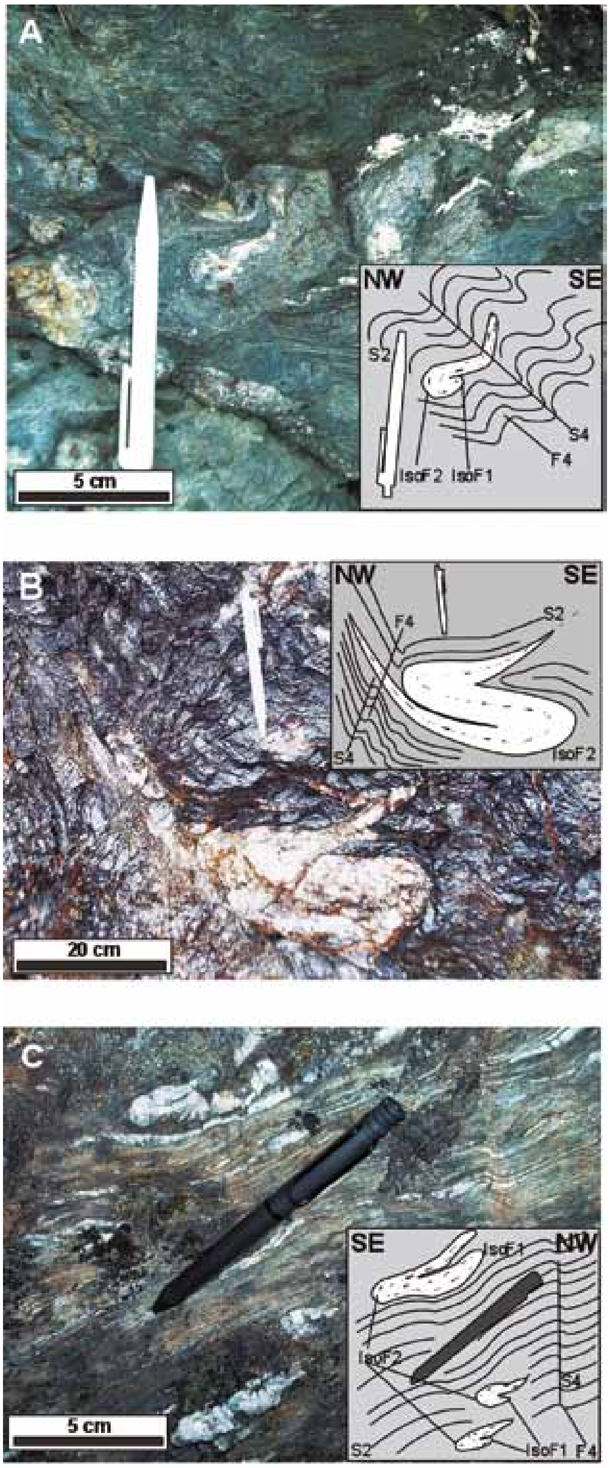


Figure 8: This image shows a sequence of fold structures in the Innsbruck Quartzphyllite (A), the Kellerjochgneiss (B) and the Stengelgneiss (C). Referring to (A) and (B) the folds (F_3) with NW-SE striking hinge lines can not be seen because of the NW-SE orientation of the outcrop. The same applies to the kink bands in the Stengelgneiss (C).

to WNW shear bands (Fig. 4B), crosscutting S_2, also occur in the Kellerjochgneiss. These shear bands indicate ongoing deformation under cooler conditions. The Stengelgneiss shows the same structural features as the Kellerjochgneiss and therefore ENE-WSW striking isoclinal folds (iso-F_2) accompany the stretching lineation (L_2), which strikes NE-SW, (Fig. 7C). In the Wildschönau Schists, S_2 shows a wide range in orientations with strikes ranging from WNW-ESE to NE-SW whereas NW-SE to N-S striking directions are dominant (Fig. 9). During this deformation stage, tight folds (F_2), striking ENE-WSW were also formed (Fig. 9). Similar to the two units discussed above, the stretching lineation in the Wildschönau Schists shows preferred orientation varying from NNE-SSW to ENE-WSW (Fig. 9). Preferred orientation may also be indicated by stretched mineral fibers trending NNE-SSW (L_2) which coincides with the stretching lineation in the Kellerjochgneiss.

Deformation D_3

During this stage, folding of S_2 led to the generation of open folds (F_3) with NW-SE striking hinge lines (Fig. 7A). These folds were observed in the northern part of the studied area, especially in the vicinity of tectonic contacts between the Kellerjochgneiss and the Innsbruck Quartzphyllite. These folds vary in size and occur as small scale folds with wavelengths ranging from several centimeters up to a few meters. Their interlimb angle can be open to tight (down to ca. 35°). A probably younger, second lineation (crenulation lineation), striking NW-SE (L_3), was observed in the Innsbruck Quartzphyllite. This crenulation lineation is formed by chlorite. In the Kellerjochgneiss, tight folds (F_3), overprinting the S_2 foliation, with NW-SE striking hinge lines similar to the Innsbruck Quartzphyllite, also occur (Fig. 7B). These folds show a vergence towards the NE (Fig. 7C) and only occur sporadically in the NW and W of the area of investigation, in proximity to the tectonic boundary between the Kellerjochgneiss and the Innsbruck Quartzphyllite. In the Kellerjochgneiss, a second lineation (crenulation lineation - L_3), striking NW to SE was occasionally found, which is also formed by chlorite. The Stengelgneiss shows similar structural features as the Kellerjochgneiss, but younger NW-SE (F_3) striking open folds, overprinting F1 and F2 isoclinal folds are rare (Fig. 7C, Fig. 8C). A NW-SE striking lineation has not been found in the Stengelgneiss. NW-SE striking

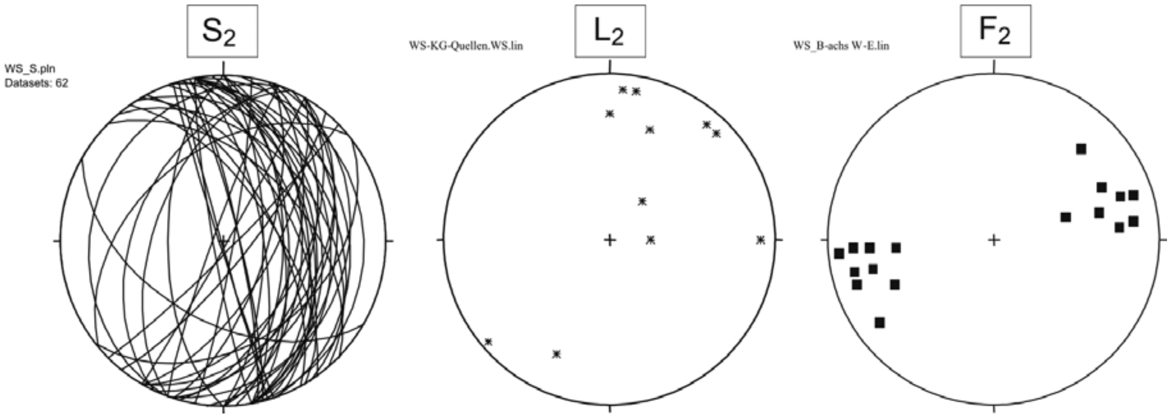


Figure 9: These stereo plots show the orientation of the predominant foliation (S_2), lineation (L_2) and folds (F_2) of the Wildschönau Schist.

folds (F_3) also occur rarely in the Wildschönau Schist. Similar to the stretching lineation L_2 which formed during D_2, a possible second generation of lineations (crenulation lineation - L_3) striking in NW-SE direction occurs locally, which is also formed by chlorite. Due to the broad spread in the measured directions, these data have to be considered with caution.

Deformation D_4

In the Innsbruck Quartzphyllite the subsequent deformation stage led to the formation of a younger generation of folds, (F_4), which show NE-SW striking hinge lines (Fig. 7A, Fig. 8A). The interlimb angles of these folds are gentle to tight (ca. 25°) (Fig. 8A). Locally another foliation (S_4) developed as an axial plane foliation to F_4, which ordinarily strikes E-W. A large fold structure with a hinge line striking SW to NE and a wave length of more than one kilometer occurs in the central section of the area of investigation (Fig. 2B). Its hinge line dips towards the NE. In the Wildschönau Schists, numerous open chevron folds (F_4) occur, which strike NNE-SSW, and represent the youngest fold generation observable in this unit.

Deformation D_5

The latest semi-ductile structures occur as kink bands and can be found in all units. Due to different lithological characteristics their orientation varies strongly and thus no characteristic strike direction could be discerned.

Brittle deformation

An analysis of the brittle faults was done using the program TECTONIC FP v. 1.6.01 by Ortner et al. (2002). Since the brittle structures are part of the youngest tectonic activity (D_6) in the area, they crosscut all lithologies. The data from all units showed that brittle deformation took place in four stages (D_{6a} – D_{6d}).

(1) The oldest brittle faults are NW-SE to WNW-ESE striking strike-slip faults (D_{6a}) with a dextral sense of motion and conjugate sinistral strike-slip faults, which strike NNW-SSE (Fig. 10A). (2) The next generation of brittle faults, overprinting D_{6a}, is expressed through thrust faults (D_{6b}) which strike E-W to NW-SE (Fig. 10B). (3) The younger Zillertal-parallel faults, which crosscut (D_{6b}) in the working area, strike NNW-SSE (D_{6c}) (Fig. 10C). They commonly dip steeply to the NE and are normal faults with oblique dextral motions. (4) The youngest faults are the Inntal–parallel faults which are the dominant faults occurring in the whole area. These faults strike NE-SW and are mostly strike slip faults (D_{6d}) with an oblique normal or reverse sense of motion (Fig. 10D, Fig. 2B). These NE-SW striking faults are more common toward the tectonic contact between Innsbruck Quartzphyllite and Kellerjochgneiss. These faults and their subsystems cause an intensive imbrication of the units, especially in the northern part of the area of investigation, where Innsbruck Quartzphyllite, Stengelgneiss and Schwaz Dolomite are strongly imbricated. The NE-SW striking faults cause lateral displacements which can range up to several kilometers. The largest sinistral lineament, crosscutting the

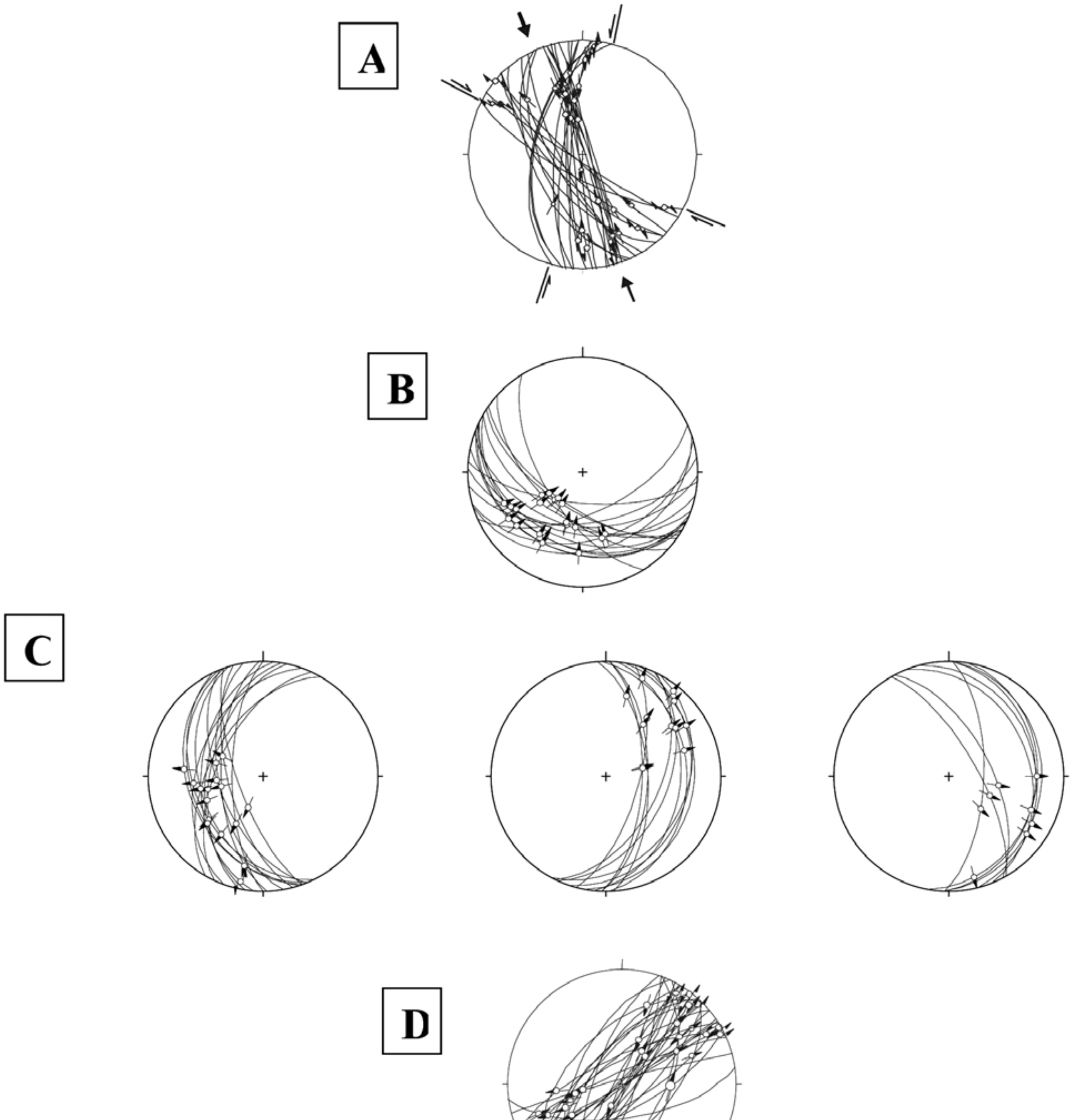


Figure 10: (A): This stereo plot shows the orientation of the oldest brittle faults, representing D_{6a}, occurring in the area of investigation. Conjugated sinistral strike-slip faults are also illustrated in this plot. (B): Examples of thrust faults (D_{6b}), which lead to strong imbrication of the lithologies to the vicinity of the Inn Valley, indicating a NE-SW contraction. (C): Examples showing normal faults from the area of investigation caused by E-W extension (D): Examples of faults reflecting the ongoing Miocene deformation. The plot shows Inn-Valley parallel sinistral strike-slip faults. They are accompanied by synthetic Riedel shear faults.

1A	Deformation Sequence of the Innsbruck Quartzphyllite		
lithological unit	**deformation stage**	**tectonic structures**	**character of deformation**
Innsbruck Quartzphyllite	D1	relic S_1 axial plane foliation of iso F_1	ductile
	D2	penetrative S_2 foliation; WSW-ENE striking iso F_2 folds E-W striking stretching lineation L_2	ductile
	D3	NW-SE striking mineral lin. L_3 NW-SE striking F_3 folds	ductile
	D4	NE-SW striking open to tight F_4 folds S_4 foliation	ductile
	D5	kink bands	semi ductile
	D6a	NW to SE striking dextral strike-slip faults	brittle
	D6b	NW-SE to W-E striking thrust faults	brittle
	D6c	N to S striking normal faults	brittle
	D6d	NE-SW to NNE-SSW striking sinstral strike-slip faults	brittle

1B	Deformation Sequence of the Kellerjochgneiss & Stengelgneiss		
lithological unit	**deformation stage**	**tectonic structures**	**character of deformation**
Kellerjochgneiss	D1	relic S_1 foliation N-S striking relic stretching lineation	ductile
	D2	penetr. S_2 foliation; NE-SW to E-W striking stretching lineation ENE-WSW striking iso F_2 folds shear bands top to the WNW - NW	ductile ductile
	D3	NW to SE striking mineral lin. L_3 NW to SE striking F_3 folds	ductile
	D4	NE to SW striking open to tight small scale F_4 folds	ductile
	D5	kink bands	semi ductile
	D6a	NW to SE striking dextral strike-slip faults	brittle
	D6b	NW-SE to W-E striking thrust faults	brittle
	D6c	N to S striking normal faults	brittle
	D6d	NE-SW to NNE-SSW striking sinstral strike-slip faults	brittle

1C	Deformation Sequence of the Wildschönau Schist		
lithological unit	**deformation stage**	**tectonic structures**	**character of deformation**
Wildschönau Schist	D1	S_1 foliation	ductile
	D2	S_2 foliation; NE to SW striking stretching lineation L_2 ENE to WSW striking F_2 folds	ductile
	D3	NW to SE striking mineral lin. L_3 NW to SE striking F_3 folds	ductile
	D4	NNE to SSW striking F_3 folds	ductile
	D5	kink bands	semi ductile
	D6a	NW to SE striking dextral strike-slip faults	brittle
	D6b	NW-SE to W-E striking thrust faults	brittle
	D6c	N to S striking normal faults	brittle
	D6d	NE-SW to NNE-SSW striking sinstral strike-slip faults	brittle

Table 1: Compilation of the deformation sequence of the Innsbruck Quartzphyllite, the Kellerjochgneiss the Stengelgneiss and the Wildschönauer Schists from this investigation.

Wildschönau Schists and the Kellerjochgneiss, is represented by the Finsinggrund Fault (Fig. 2A), which strikes NE-SW with an oblique motion trending to NE. This fault offsets the Wildschönau Schists from the Kellerjochgneiss by about 3 kilometers, which was also established from previously published geological maps by Roth (1983).

4. Discussion

Comparison of the structural successions with previous investigations

The structural data from this work (Table 1) may be compared to structural data from other authors, such as Roth (1983), Ortner and Sachsenhofer (1996), Steyrer et al. (1996), Kolenprat et al. (1999), Ortner et al. (1999) and Grasbon (2001) as shown in Tables 2, 3A-C. Recently Kolenprat et al. (1999) developed a structural model for the Innsbruck Quartzphyllite to the south of Innsbruck (Table 2). In their model, the authors correlate the observed deformation stages with the deformation sequence in the Eastern Alps from further west near the Swiss border, obtained by Froitzheim et al. (1994). Kolenprat et al. (1999) describe a relic Pre-Alpine foliation (S_2), which is the axial plane foliation of relict isoclinal folds (iso-F_1). An indicator for the Pre-Alpine age of the foliation (S_2) is the post-S_2/pre-S_3 garnet growth of Permian garnets in mica schists. The Cretaceous evolution of the Innsbruck Quartzphyllite has been associated with the Trupchun Phase by these authors. These structures are expressed as a penetrative mylonitic foliation (S_3) with E-W stretching lineations and W–E striking isoclinal folds (iso-F_3). Shearbands within layers of chlorite–bearing schists indicate top-to-NW motions that post-date the Trupchun Phase. These movements were interpreted as being associated with post-Trupchun NW directed nappe stacking. Kolenprat et al. (1999) found no structural features that could be correlated with the Ducan Ela Phase, which is associated with the extensional collapse and formation of Gosau basins during the Uppermost Cretaceous (80 – 67 Ma, Froitzheim et al. 1994). Deformation structures, associated with the Alpine Tertiary evolution during the Blaisun Phase (50-35 Ma) are open chevron folds with NE to SW trending hinge lines (F_{4a}) and an axial plane foliation (S_4). Subsequent semi-ductile structures are expressed as kink bands, which were correlated with the Turba Phase (35 – 30 Ma.). The following brittle deformation is polyphase (D_{6a}-D_{6d}).

Concerning the Innsbruck Quartzphyllite, our relic S_1 axial plane foliation and the F_1 isoclinal folds (Tab. 3A) are in a good correlation with the relic S_2 foliation from the structural succession scheme of Kolenprat et al. (1999) in Table 2. Furthermore, the dominant D_2 and D_3 deformation structures agree with their observations, except that the NW-SE striking folds and NW-SE striking stretching lineations were not observed by Kolenprat et al. (1999) and we did not observe top to the NW shear bands (Tab. 3A). The data from the structural succession scheme of Grasbon (2001) are also similar to the structural data from this work, except that she did not observe any relic D_1 structures.

Concerning the Kellerjochgneiss the structural succession of Grasbon (2001) as seen in Table 3B, is again very similar to the structural data from this investigation, except for the absence of relic D_1 deformation structures and the NE-SW striking small scale folds (F_4). Steyrer et al. (1996) also proposed a similar succession of structures. Our D_2 shearbands are in accordance with their shear bands indicating motions top to the W to NW during D_2. Their NE-SW striking folds can also be correlated with the ENE-WSW striking folds (F_2). Furthermore, they observed chevron folds which are similar to our NE-SW striking open F_4 folds (Tab. 3B). The NE striking folds described by Roth (1983) may be compared to the ENE-WSW striking folds assigned in our scheme to D_2. His W-NW striking folds may also be correlated to the F_3 folds, which strike NW-SE. However, the remainder of our deformation scheme does not correlate with the deformation sequence of Roth (1983).

Concerning the Wildschönau Schists, the structural data from this work are compared in Table 3C with the structural succession of Grasbon (2001). Similar to the Innsbruck Quartzphyllite and the Kellerjochgneiss, Grasbon (2001) did not identify any relic D_1 deformation structures within the Wildschönau Schists. Her N(E)-S(W) striking folds with the accompanying (N)NE-(S)SW striking stretching lineation can be correlated to the ENE-WSW striking F_2 folds and the NE-SW striking stretching lineation (L_2). The NE-SW striking chevron folds may be compared with the NNE-SSW striking open folds (F_4) from this investigation (Tab. 3C).

Tectonic Scheme of the Innsbruck Quartzphyllite		
Kolenprat et al. (1999 & oral com.)		
presumed age	**Deformation stage**	**structures**
Permian or Variscan	Dv1 Dv2	relic iso F_1 S_2 foliation Garnet post S_2 pre S_3
Cretaceous Trupchun Phase 100-80 ma.	D3a	mylonitic S_3 str. lineation top to the W W-E striking iso F_3 folds
post Trupchun Phase	D3b	shear bands top to the NW
Blaisun Phase/50-34 ma.	D4	NE-SW striking open F_{4a} folds S_4 foliation
Blaisun Phase/50-34 ma.	D5	kink bands

Table 2: Tectonic scheme of the westernmost part of the Innsbruck Quartzphyllite by Kolenprat et al. (1999).

3 A	Comparison of the Deformation Sequence of the Innsbruck Quartzphyllite		
Kolenprat (1999 & oral com.)		**this study**	
Deformation stage	**structures**	**structures**	**Deformation stage**
Dv1 Dv2	relic iso F_1 S_2 foliation Garnet post S_2 pre S_3	relic S_1 axial plane foliation of iso F_1	D1
D3a	mylonitic S_3 str. lineation top to the W W-E striking Iso F_3 folds	penetrative S_2 foliation WSW-ENE striking iso F_2 folds E - W striking str. lineation L_2	D2
D3b	shear bands top to the NW		
		NW-SE striking mineral lin. L_3 NW-SE striking F_3 folds	D3
D4	NE-SW striking open F_{4a} folds penetrative S_4 foliation	NE-SW striking open to tight F_4 folds S_4 foliation	D4
D5	kink bands	kink bands	D5
Grasbon (2001)		**this study**	
Deformation stage	**structures**	**structures**	**Deformation stage**
		relic S_1 axial plane foliation of iso F_1	D1
D1	NE-SW striking folds NE-SW striking stretching lineation	penetrative S_2 foliation WSW-ENE striking iso F_2 folds E - W striking str. lineation L_2	D2
D1	shear bands top to the NW		
D2	NW-SE striking folds NW-SE striking stretching lineation	NW-SE striking mineral lin. L_3 NW-SE striking F_3 folds	D3
D3	E-W striking folds shear bands top to the N/S NE-SW striking chevron folds	NE-SW striking open to tight F_4 folds S_4 foliation	D4
		kink bands	D5

Table 3A: Correlation between the deformation sequence of the Innsbruck Quartzphyllite from this investigation with the deformation sequences deduced by Kolenprat et al. (1999) and Grasbon (2001).

Geochronological constraints on the evolution of the Austroalpine nappes north of the Tauern Window

Recently there have been several geochronological investigations in the western part of the Innsbruck Quartzphyllite in the vicinity of the Brenner Fault and the overlying Patscherkofel Crystalline Complex. Dingeldey et al. (1997) conducted one Ar-Ar stepwise heating experiment on a sample from the western part of the Innsbruck Quartzphyllite. They found a rejuvenation of the phengite age from 250 Ma to 35 Ma, indicating that the temperature of the Alpine metamorphic overprint probably exceeded 350°C in this area. Recently, Ar-Ar and Rb-Sr dating has been performed on samples from the Brenner area by Rockenschaub et al. (1999). The Ar-Ar plateau ages (206 – 268 Ma) and Rb-Sr ages (229 – 255 Ma) of phengites from porphyritic orthogneisses within the Innsbruck Quartzphyllite, as well as one monazite microprobe age (280 ± 25 Ma), gave indications for a Permian event (Rockenschaub et al., 1999). They also obtained Eo-Alpine Ar-Ar ages of 135 Ma for synkinematically grown phengites from the dominant foliation S_2 in the northern and central parts of the Innsbruck Quartzphyllite. This result might indicate the onset of the Eo - Alpine metamorphic event and hence put an age constraint on the earliest stage of the Alpine deformation. While these ages show considerable spread due to incomplete resetting and partial mineral growth during the Eo-Alpine orogeny, these results represent the only current absolute age constraint on Alpine deformation in the sequence. In addition to these metamorphic mineral ages, there are also a few data available on the low temperature cooling history (<300°C), based on fission track measurements, available. Fügenschuh et al. (1997) obtained two fission track ages on zircon from the western part of the Innsbruck Quartzphyllite which yielded ages of 42 and 67 Ma. A fission track age on apatite yielded 13 ± 2 Ma. This age is similar to the apatite fission track age of 14.3 ± 2.8 Ma, obtained by Grundmann and Morteani (1985).

Satir and Morteani (1978a) conducted the first geochronological investigations in the Kellerjochgneiss. They obtained a protolith intrusive age of the orthogneisses of 425 Ma based on a Rb-Sr isotope study. Latest protolith intrusive age data based on U/Pb single zircon dating yield 468 ± 1 and 469 ± 2 Ma (Gangl et al., 2005). Satir and Morteani (1978a) also applied the Rb-Sr whole rock isochrone method to the Kellerjochgneiss to infer the age of the metamorphic overprint, which yielded 322 ± 24 Ma, which is clearly Variscan. Additional Rb-Sr data on phengites from the Kellerjochgneiss yielded cooling ages of 260 and 273 Ma. Furthermore, their data also constrain the Variscan age of the metamorphic overprint. Based on Th-U-Pb model ages of monazite and thorite, Steyrer and Finger (1996) obtained ages of 323 ± 9 and 353 ± 26 Ma. In addition, there are a few data constraining the low-temperature evolution of the Kellerjochgneiss. There are only two fission track ages of apatites from the study of Grundmann and Morteani (1985) available, which yielded 14.5 ± 2.2 and 17.6 ± 1.5 Ma. Zircon and apatite ages from Angelmaier et al. (2000) yielded ages of 57 – 63 Ma and 13 ± 1 Ma.

Muscovite Ar-Ar ages (Handler et al., 2000) from the Wildschönau Schiefer indicate a Variscan or Permian metamorphic overprint at 267 ± 6 Ma. In addition Angelmaier et al. (2000) obtained Ar-Ar ages of 264 ± 11 Ma, which correlates very well with the age of Handler et al. (2000). $_{40}$Ar-$_{39}$Ar ages from the central Greywacke Zone yielded 102 – 98 Ma (Schmidlechner et al., 2006), ^{87}Rb-^{87}Sr ages and $_{40}$K-$_{39}$Ar close to Zell am See yielded 137 to 127 Ma and 113 to 106 Ma. One zircon and one apatite fission track age available from Wildschönau Schists yielded 116 ± 4 Ma and 38 ± 5 Ma (Angelmaier et al., 2000), respectively.

Compiling the published muscovite Ar-Ar data (Handler et al., 2000; Schmidlechner et al. 2006), biotite Rb-Sr data (Satir and Morteani, 1978a,b), zircon fission track ages (Angelmaier et al., 2000) and apatite fission track data (Grundmann and Morteani, 1985; Angelmaier et al., 2000; Fügenschuh, 1995) from this area, allows time constraints to be placed on the deformation sequence in the three units. While D_1 is clearly related to a pre-Alpine event of probably Variscan age, D_2 can unambiguously be attributed to the early stages of the Eo-Alpine event. Since the closure temperature of the zircon fission track system is ca. 260-220°C (Fügenschuh, 2005, pers. comm.), this puts time constraints on the last stages of ductile (D_4) and/or semiductile (D_5) deformation. These data establish that all three units experienced temperatures of 300 – 400°C at pressures ranging from 4 to 6.5 kbar at around 90 – 135 Ma, based on available Ar-Ar and Rb-Sr age data (Rockenschaub et al., 1999). Although some Ar-Ar data from the Wildschönau Schists yielded late Variscan ages (Handler et al., 2000), Ar-Ar ages from the cen-

3 B	Comparison of the Deformation Sequence of the Kellerjochgneiss		
Grasbon (2001)		this study	
Deformation stage	structures	structures	Deformation stage
		relic S_1 foliation N-S striking str. lin. L_1	D1
D1	NE-SW striking folds NE-SW striking stretching lineation	penetr. S_2 foliation WSW-ENE striking iso F_2 folds NE-SW to E-W str. lin. L_2	D2
D1	shear bands top to the NW-W	shear bands top to the NW-W	D2
D2	NW-SE striking folds NW-SE striking stretching lineation	NW-SE striking F_3 folds NW-SE striking mineral lin. L_3	D3
D3	E-W striking folds shear bands top to the SSW (N)E-(S)W striking chevron folds	NE-SW striking open F_4 small scale folds	D4
		kink bands	D5
Steyrer et al. (1996)		this study	
Deformation stage	structures	structures	Deformation stage
Dv1/Dv2	penetrative mylonitic foliation top N sF_1: muscovite1 stretch. lin. N-S/NNE-SSW	relic S_1 foliation N-S striking str. lin. L_1	D1
D1	semiductile shearbands deform. of musc. 1/2nd mica gener. lineation N-S, S-vergent transport	penetr. S_2 foliation WSW-ENE striking iso F_2 folds NE-SW to E-W str. lin. L_2	D2
		shear bands top to the NW-W	
D2	(S)E-(N)W contraction N-S to NE-SW striking folds	NW-SE striking F_3 folds NW-SE striking mineral lin. L_3	D3
D3	chevron folds	NE-SW striking open F_4 small scale folds	D4
D4	brittle deformation	kink bands	D5
Roth (1983)		this study	
Deformation stage	structures	structures	Deformation stage
Dv1/Dv2	1. N-S contraction S-vergent nappe stacking/ 2. E-W contraction early zenith of T, following variscan double mylonitization stretch. lin. N-S/folds strike NE-N	relic S_1 foliation N-S striking str. lin. L_1	D1
D1	nappe stacking top (N)NE folds strike W-NW	penetr. S_2 foliation WSW-ENE striking iso F_2 folds NE-SW to E-W str. lin. L_2 shear bands top to the NW-W	D2
D2	motions top to (S)E folds E-SE vergent folds strike N-NE	NW-SE striking F_3 folds NW-SE striking mineral lin. L_3	D3
D3	N-S contraction conjugated faults strike NE-SW and NW-SE	NE-SW striking open F_4 small scale folds	D4
D4	brittle deformation	kink bands	D5

Table 3B: Correlation between the deformation sequence of the Kellerjoch Gneiss from this investigation with the deformation sequences deduced by Grasbon (2001), Steyrer et al. (1996) and Roth (1983).

tral Greywacke Zone yielded 102 – 98 Ma (Schmidlechner et al., 2006) and Rb-Sr ages of 137 to 127 Ma and K-Ar ages of 113 to 92 and 113 to 106 Ma from the Greywacke Zone close to Zell am See give reasonable evidence for an Eo-Alpine metamorphic overprint around ca. 300°C (Kralik et al., 1987). Zircon fission track ages from the Wildschönau Schists indicate temperatures of ca. 260-220°C already at 116 Ma, which is in disagreement with the Ar-Ar data from Schmidlechner et al. (2006). Clearly more zircon fission track data are needed for this unit. Concerning the correlation to the structural sequence of Kolenprat et al. (1999) and the ages of synkinematically grown phengites, ductile deformation in the area of investigation (D_2 – D_4) probably took place during the Eo-Alpine metamorphic event. These conditions prevailed until approximately 40 – 60 Ma when then the zircon fission track ages indicate temperatures <220-260°C. Probably around this time, semi-ductile deformation (D_5) took place which is in agreement with the proposed tectonic model of Kolenprat et al. (1999)

Tectonic implications for the evolution of the Austroalpine nappes in the northern Zillertal area

Tectonic data indicate that the Kellerjochgneiss as a recumbent fold structure "embedded" between the Innsbruck Quartzphyllite below, and the Wildschönau Schist above. The first deformation stage, which is responsible for the folding of the Kellerjochgneiss, probably is D_2. This event caused tight folding of the Kellerjochgneiss and the Innsbruck Quartzphyllite, resulting in a large scale fold structure. Compression from NW to SE during D_3 led to an open refolding of these lithologies. Afterwards, this structure was intersected and imbricated due to subsequent brittle deformation (D_{6a-d}). Especially SE-NW striking sinistral strike slip faults with oblique thrust motions are responsible for strong imbrication of the different lithologies in the vicinity of the Inn Valley. The data from the TRANSALP seismic profile from the area north of the Tauern Window show S-dipping reflectors, especially in the Northern Calcareous Alps, indicating strong imbrication. The area between the NCA and the Tauern Window shows rather weak reflections, indicating thrusting of the crystalline units on top of the NCA in the North (Transalp Working Group, 2002). These thrusting movements along SE-digging faults, as shown in Figure 2B, were also found in the Kellerjochgneiss (D_{6b}). No other structural features could be discerned in this area from the seismic data, due to insufficient resolution of the data and the lack of lithological contrast.

The data presented above display the similarity of deformation structures occurring within the Innsbruck Quartzphyllite, the Kellerjochgneiss and the Wildschönau Schist. Each lithological unit also exhibits a similar succession of deformation processes. S_2 forms the penetrative foliation in all three units. The D_2 stretching lineations of the Innsbruck Quartzphyllite, the Kellerjochgneiss and the Wildschönau Schists indicate a E-W movement during D_2. In accordance with the structural succession scheme of the Innsbruck Quartzphyllite given by Kolenprat et al. (1999), the W-E to SW-NE striking stretching lineations (L_2), the isoclinal F_2 folds (iso-F_2) of the Innsbruck Quartzphyllite and the isoclinal F_2 folds (iso-F_2) of the Kellerjochgneiss are thought to have formed during a W-directed nappe transport. Subsequent deformation continuing during D_2 caused the formation of shear bands, which can be seen in the Innsbruck Quartzphyllite and the Kellerjochgneiss, which also indicate a top to W-NW motion. These structures are interpreted to be the result of ongoing nappe stacking towards W-NW under somewhat cooler conditions. During D_3, the NW-SE striking folds (F_3), occurring subordinated in all three lithological units, are interpreted as extensional collapse folding as a result of E-W extension. Similar folds with comparable axial trend also have been reported by Froitzheim et al (1994) from the Austroalpine tectonic units in Graubünden (Switzerland). In addition, similar folds were described by Brandner and Eisbacher (1996) in the adjacent Northern Calcareous Alps and by Reiter (2000) in the Triassic sediments near Schwaz. In contrast to extensional collapse folding, the folds described by Brandner and Eisbacher (1996) and Reiter (2000) are attributed to NNE-SSW-directed contraction, which is thought to have taken place in the latest Cretaceous or even the Paleocene. In analogy to the observations and interpretations made by Froitzheim et al. (1994) and Fügenschuh (1995) D_4 and the formation of F_4 folds can be attributed to northwards thrusting of the Alpine basement nappes onto the Penninic units. Since this part of Austroalpine nappe pile cooled to temperatures below 200°C (Fügenschuh, 1995), the open NE-SW striking chevron folds are most probably related to this event. Kink bands reflect the youngest structures in the ductile-semiductile regime.

3 C	Comparison of the Deformation Sequence of the Wildschönau Schist		
Grasbon (2001)		this study	
Deformation stage	structures	structures	Deformation stage
		S_1 foliation	D1
D1	N(E)-S(W) striking folds (N)NE-(S)SW striking stretching lineation	S_2 foliation WSW-ENE striking F_2 folds NE-SW striking str. lin. L_2	D2
D1	shear bands top to the N(W)		
D2	NW-SE striking folds shear bands top to the NE	NW-SE striking F_3 folds NW-SE striking mineral lin. L_3	D3
D3	shear bands top to the S NE-SW striking chevron folds	NNE-SSW striking F_4 chevron folds	D4
		kink bands	D5

Table 3C: Correlation between the deformation sequence of the Wildschönauer Schiefer from this investigation with the deformation sequence deduced by Grasbon (2001).

In accordance with the geodynamic model of Froitzheim et al (1994) and the two-stage model of Neubauer et al. (2000), the ductile structural data can be viewed in a larger geodynamic context. Both models suggest the Alpine geodynamic evolution can be considered in terms of two orogenic cycles with five stages of tectonic evolution: (1) Late Cretaceous nappe imbrication with sinistral transpression (Trupchun phase), (2) Late Cretaceous extension (Ducan-Ela phase), (3) Early Tertiary collisional deformation (Blaisun phase), (4) Early to Mid – Oligocene extension (Turba phase), (5) Late Oligocene post-collisional shortening (Domleschg phase).

The ENE-WSW striking folds (F_2) and the accompanying stretching lineations (L_2), which strike E-W to NE-SW, are all in agreement with the W directed Eo-Alpine nappe stacking of the Austroalpine units during the Late Cretaceous, related to the closure of the Hallstatt-Meliata Ocean. Thermobarometric investigations of the Kellerjochgneiss and the Stengelgneiss by Piber (2002) were based on synkinematically grown minerals, which constitute the predominant foliation (S_2). Therefore the *P-T* results from these lithologies can be directly related to the D_2 deformation, which therefore took place under Eo-Alpine greenschist-facies metamorphic conditions. The data suggest that the Kellerjochgneiss has been metamorphosed under similar pressures (4.3 – 6.5 kbar) as the Innsbruck Quartzphyllite and the Wildschönau Schists (4.4 – 5.9 kbar) at a similar temperatures ranging from 286 to 345°C (Piber, 2005; Piber and Tropper, 2005). The NW-directed shearbands, which Kolenprat et al. (1999) attributed to D_2, reflect displacement under greenschist conditions and may also be related to this event. According to Froitzheim et al. (1994) the NW-SE striking folds (F_3 of the Innsbruck Quartzphyllite, the Kellerjochgneiss and the Wildschönauer Schists) can be related to the initial extensional collapse during the Late Cretaceous and Paleocene. This rarely observed "collapse folding" displays folds which show no axial-plane cleavage. These folds also could be an expression of changing in contraction regime of clockwise rotation of 60° during the early Oligocene caused by collision processes and blocking of the Alpine wedge (Thöny et. al, 2004). Zircon fission track data from the Innsbruck Quartzphyllite Complex (Fügenschuh, 1995) and the Kellerjochgneiss (Angelmaier et al., 2000) show evidence for cooling of the Alpine basement nappes during latest most Cretaceous and Paleocene, hence extensional collapse folding would be more reasonable for the formation of F_3 folds in contrast to NNE-SSW directed contraction as described by Brandner and Eisbacher (1996) and Reiter (2000) for the same time.

The open NE-SW striking folds (F_4 of the Innsbruck Quartzphyllite and the Kellerjochgneiss) and the NNE-SSW striking chevron folds of the Wildschönau Schists (F_4) are comparable with the NW-N directed ductile to semiductile shear within the Austroalpine nappe pile during the Early Eocene, which was postulated by Froitzheim et al. (1994) and Fügenschuh (1995). The kink bands (D_5) may be correlated to the ongoing contraction and the initial exhumation of the Tauern Window.

The temporal sequence of the brittle deformation can be interpreted in terms of the established geological framework developed by authors working in surrounding areas (Ortner et al, 1999; Reiter, 2000). The oldest brittle faults (D_{6a}) in the area of investigation are NW-SE striking faults with a dextral shear sense, which are conjugate to NNW-SSE striking sinistral strike-slip faults. These faults are correlated with similar faults in the Angerberg area, which are described by Ortner et al. (1999). The faults in the Angerberg area considered to be part of a pre-Oligocene deformation with a NW-SE/NNW-SSE contraction (Ortner et al., 1999). The subsequent deformation (D_{6b}) in the Early Oligocene (NE-SW/NNE-SSW contraction) caused thrust faults showing motions towards the NE, crosscutting the faults of D_{6a}. These faults can be correlated to faults occurring in calcareous marls and turbiditic sandstones in the Angerberg area described by Ortner et al. (1999). Normal faults indicating E-W extension (D_{6c}) are assumed to be generated during the Miocene by E-W (WSW-ENE) extension and may be associated with the uplift of the Tauern Window. Ortner et al. (1999) found similar faults in Miocene deposits. The youngest faults (D_{6d}) that can be determined in the area of investigation are sinistral strike-slip faults, which are mostly parallel to the Inntal-Fault. These faults are probably the result of the ongoing Miocene deformation characterized by N-S contraction, which were described by Reiter (2000) and Ortner et al. (1999). Overall, the brittle deformation (D_{6a-d}) sequence may be the consequence of continuing contraction of the Austroalpine realm and coeval uplift of the Tauern Window.

5. Conclusions

Based on geochronological and structural evidence from the three lithological units, it is possible to distinguish between pre-Alpine (D_1) and Alpine (D_2 – D_6) deformation structures. The earliest stage of deformation (D_1) can be linked with a pre-Alpine event (Permian and/or Variscan). The first stage of Eo-Alpine deformation (D_2) can be correlated with the W-directed nappe stacking during the Middle to Late Cretaceous. Thermobarometric data indicate that the onset of this event during Early to Mid Cretaceous took place under greenschist-facies conditions. The ongoing W-directed nappe transport led to intensive folding of all units and mylonitization of the Kellerjochgneiss. The subsequent nappe transport and stacking under progressive cooling accompanied by detachment of upper crustal parts during the Mid- to Late Cretaceous led to the formation of shear-bands within the basement nappes. This event was then followed by the extensional collapse during the Uppermost Cretaceous (D_3), which was succeeded by Early Tertiary collisional deformation events and the overriding of the Austroalpine nappe pile onto the Penninic units (D_4). The early to middle Oligocene extension related to the onset of exhumation of the Tauern Window resulted in the last ductile deformation stage (D_5). The last brittle stages (D_{6a-d}) of the deformation sequence are probably associated with movements along the major fault lines in the area due to late Oligocene post-collisional shortening.

Thermobarometric estimates indicate that the Kellerjochgneiss, the Innsbruck Quartzphyllites and parts of the Wildschönau Schists seem to have been in similar crustal positions during low-grade metamorphic overprint. The *P-T* conditions of 286 – 345°C and 4.3 – 6.5 kbar also indicate that the Eo-Alpine metamorphic overprint possibly took place in a geodynamic setting with a moderate to low geotherm. U/Pb zircon age constraints of the Kellerjochgneiss and the bordering Stengelgneiss, which are in good accordance to zircon ages of metaporphyric rocks of the Greywacke zone (Gangl et al., 2005), and the similarity of the temperature – time data of the Innsbruck Quartzphyllite, the Kellerjoch Gneiss and the Wildschönau Schists from the Eo-Alpine metamorphic event therefore indicate that all units are part of the Upper Austroalpine unit, which agrees with the paleogeographic model by Schmid et al. (2004).

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