Geochronological constraints on the exhumation of the Austroalpine Seckau Nappe (Eastern Alps)

Stefan PFINGSTL[1)], Walter KURZ[1)*)], Ralf SCHUSTER[2)] & Christoph HAUZENBERGER[1)]

[1)] Institut für Erdwissenschaften, Universität Graz, Heinrichstrasse 26 / Universitätsplatz 2, A- 8010 Graz; Member of NAWI Graz (an InterUniversity cooperation between the University of Graz and the Graz University of Technology), Austria;

[2)] Geologische Bundesanstalt, Neulinggasse 38, 1030 Wien, Austria;

[*)] Corresponding author, walter.kurz@uni-graz.at

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Abstract

New Rb-Sr biotite age data from meta-granitoids of the Seckau Nappe (Eastern Alps) are discussed to constrain its tectonometamorphic evolution. Within the basement of the Seckau Nappe a clear distinction between S- and I- Type granitoids can be established. The S- type granites are mainly part of the structurally uppermost sections and are covered by Permian to Late Triassic metasedimentary sequences of the Rannach-Formation. Within the AFM diagram all granitoids are characterized by a calcalkaline trend. This suggests formation of the melts during a subduction process. The granitoids are related to both pre-plate collision, syn-collision and post-collision uplift settings.

The Rb-Sr biotite age data (biotite - whole rock isochrons) range from 76 to 86 Ma, with eight samples showing ages around 84 to 86 Ma. The Rb-Sr biotite-ages are interpreted to date cooling below 300±50°C. Therefore the investigated part of the Seckau Nappe cooled down below ~300°C at about 85 Ma in the Santonian.

Referring to microstructural observations, the contact between the basement of the Seckau Complex and the Rannach-Formation was strongly overprinted by the formation of distinct shear zones that are characterised by extensional fabrics. Kinematics is characterized by conjugate sets of top-to-the-WNW and top-to-the-ESE. As feldspar is deformed by cataclastic deformation mechanisms, whereas quartz shows deformation mechanisms of dislocation creep and bulging dynamic recrystallization we assume that the conditions of deformation along the Seckau Complex with the Rannach-Formation are in the range of 300°C to 400°C. A comprehensive interpretation of the Rb-Sr biotite age data combined with deformation structures suggests that extension-reated exhumation of the Seckau complex occurred around 85 to 80 Ma.

Neue Rb-Sr Biotitaltersdaten aus Metagranitoiden der Seckau-Decke innerhalb der Seckauer Tauern (Ostalpen) werden im Zusammenhang mit der tektonometamorphen Entwicklung dieser Einheit diskutiert. Innerhalb des Basements der Seckau-Decke können I- und S- Typ Granitoide klar unterschieden werden. Die S-Typ Granitoide sind mehrheitlich in den struturell höheren Abschnitten vorhanden und werden von den permisch bis untertriassischen Metasedimenten der Rannach-Formation überlagert. Im AFM Diagramm zeigen alle Granitoide einen kalkalkalinen Trend. Dies lässt auf eine subduktionsbezogene Schmelzbildung schliessen. Die Granitoide zeigen eine prä- syn- und postkollisionale geochemische Signatur.

Die Rb-Sr Biotitaltersdaten (Biotit – Gesamtgesteins Isochronen) liegen zwischen etwa 76 und 86 Millionen Jahren. Acht Alter liegen bei etwa 84 bis 86 Millionen Jahren. Diese werden als Abkühlalter (Schließungstemperatur bei 300±50°C) interpretiert. Die Abkühlung dieses Teiles der Seckau-Decke unter 300°C erfolgte daher um etwa 85 Millionen Jahre im Santon.

Mikrostrukturelle Analysen zeigen, dass der Kontaktbereich zwischen Rannach-Formation und dem darunter liegenden Basement durch einzelne Scherzonen, die Extensionsstrukturen zeigen, überprägt wird. Die Kinematik entlang dieser Scherzonen zeigt WNW- und ESE- gerichtete Kinematik. Feldspat zeigt überwiegend kataklastische Deformation, Quarz zeigt Deformationsmechanismen von Dislokationskriechen sowie dynamische Rekristallisation durch Bulging. Die Deformationsbedingungen innerhalb dieser Scherzonen liegen daher im Bereich von etwa 300 bis 400°C. Daraus kann geschlossen werden, dass das Basement der Seckau-Decke innerhalb eines Dehnungsregimes im Zeitraum um 85 bis 80 Millionen Jahre exhumiert wurde.

1. Introduction

The understanding of the tectono-metamorphic evolution of the Austroalpine Unit has made significant progress in the last few years (Schmid et al., 2004; Froitzheim et al., 2008). An essential key to reveal the tectonostratigraphy of Austroalpine nappes and the sequence of nappe emplacement was the analysis of the Alpine and pre-Alpine metamorphic evolution of distinct nappes (e.g., Schuster et al., 2004; Handy and Oberhänsli, 2004). Studies on these units, however, are rather unequally distributed. Strong emphasis was given on the investigation of units showing an Eo-Alpine high-grade metamorphic evolution including eclogite facies metamorphism, whereas the amount of structural, metamorphic, and geochronological data from other units is quite low.

Thöni and Jagoutz (1993), Neubauer (1994), Plasienka (1995), and Froitzheim et al. (1996) and Neubauer et al. (2000) among others, developed a picture where the Eo-Alpine metamorphism is related to the collision of the Austroalpine Unit with another continental fragment after closure of the Meliata Ocean to the south or southeast, the Austroalpine being in a lower plate position. An alternative model is given by Stüwe and Schuster (2010) where the formation of the Alpine orogenic wedge initiated at an intracontinental subduction zone which developed from a transform fault with a sinistral offset linking the Penninic (Alpine Tethys) Ocean and Neotethys (Meliata) Ocean in Late Jurassic times.

"Eo-Alpine" (as term for Early Cretaceous to early Late Cretaceous) deformation and metamorphism (e.g., Frank, 1987), however, is frequently taken uncritically to be related to Cretaceous nappe imbrication associated with general top-to-the-west emplacement. This concept, elaborated about 20-30 years ago, does actually not sustain critical review. Age data (e.g., Dal Piaz et al., 1995; Dallmeyer et al., 2008) and the sedimentary record (e.g., Frisch and Gawlick, 2003) suggest a large time span or time gap between the subduction of the Triassic part of the Neotethys Ocean (Meliata oceanic realm) at ca. 160 Ma (Missoni and Gawlick, 2010) and classical "Eo-Alpine" ages

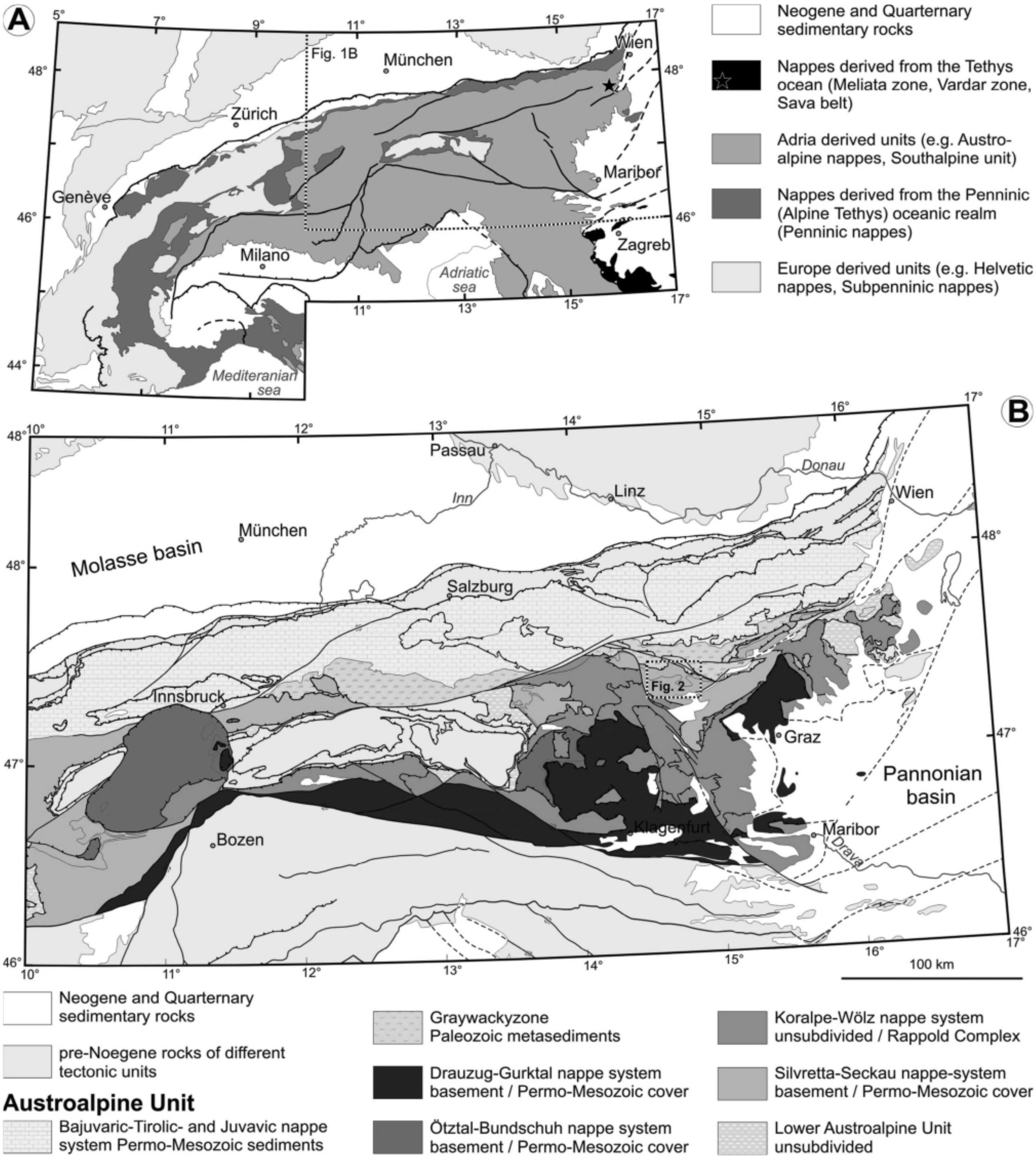


Figure 1: Overview maps (A) showing the paleogeographic origin of the main tectonic units of the Alps, and (B) the tectonic subdivision of the Austroalpine unit based on Schmid et al. (2004).

dating high pressure metamorphism around 100-90 Ma (e.g., Thöni and Jagoutz, 1992, 1993; Thöni et al., 2008). So the question arises whether a continuous process or distinct phases of convergence, collision, and subsequent extension formed the Austroalpine nappe pile as post-collisional extension was recognized to play a major role in Alpine orogeny (Ratschbacher et al., 1989).

In this study the lithosthratigraphic and tectonic subdivision of the Silvretta-Seckau Nappe System in the area of the Seckauer Tauern is reviewed. Based on new Rb-Sr biotite ages the cooling history of the Seckau Complex is discussed in the frame of regional geology.

2. Geological setting of the Austroalpine Unit

The Austroalpine Unit forms a complex nappe stack of crustal material which can be subdivided into a Lower Austroalpine and Upper Austroalpine Subunit (Schmid et al., 2004; Froitzheim et al., 2008) (Fig. 1). The Lower Austroalpine Subunit derived from the continental margin towards the Penninic (Alpine Tethys) Ocean and was affected by extension during the Jurassic opening and by nappe stacking during Late Cretaceous to Eocene closure of this oceanic realm, respectively (Schmid et al., 2004; Froitzheim et al., 2008). It is overlying the Penninic nappes of the Eastern Alps derived from the Penninic oceanic domain. The Upper Austroalpine Subunit represents a nappe pile which formed mainly during the Eo-Alpine event in the Early Cretaceous to early Late Cretaceous. Its lowermost part is the Silvretta-Seckau Nappe System consisting of a basement with a dominating Variscan metamorphic imprint and remnants of Permian to Lower Triassic cover sequence. The basement is dominated by paragneisses (partly migmatic) and orthogneisses with minor intercalations of micaschists, quartzites, amphibolites, hornblende bearing gneisses and local occurrences of serpentinites and eclogites. Most of the amphibolites and orthogneisses developed from Cambrian to Ordovician precursors and are interpreted to reflect pre-Cambrian to Ordovician collision, subduction and rifting processes (Neubauer, 2002). Additional some Carboniferous intrusions are present (Schermair et al., 1997). The magmatic inventory indicates Neoproterozoic to Ordovician educt ages of the metasedimentary rocks. The medium to high grade imprint in these basement rocks occurred during the Variscan tectonometamorphic event (Neubauer et al., 1999). In the structurally deepest part of the westernmost element represented by the Silvretta Nappe also a Permian metamorphic overprint can be recognized (Schuster et al., 2004). The post-Variscan cover is best preserved in the Silvretta Nappe which is overlain by un-metamorphosed Permian to Triassic sediments in the Landwasser and Ducan synclines and a more or less stratigraphic contact to the Permomesozoic sequences of the Bajuvaric Nappe System (Nowotny et al., 1993; Nagel, 2006). Further to the east tectonically truncated sequences show an Eo-Alpine greenschist facies overprint. They comprise only Permian metaconglomerates and metapelites as well as Lower Triassic quartzites and locally Middle Triassic greyish marbles rauhwacke and dolomite. In the basement units the Eo-Alpine imprint reaches sub-greenschist to epidote-amphibolite facies conditions causing a retrograde overprint in most of the Variscan metamorphic rocks (Neubauer et al., 1995; Schuster et al., 2004; Hoinkes et al., 2010). Nappes of the Silvretta-Seckau Nappe System build up antiformal structures in the western (Schladminger Tauern) and eastern part (Seckauer Tauern) of the Niedere Tauern mountain ridge.

To the north the Silvretta-Seckau Nappe System is overlain by the nappes of the Greywacke zone, which consists of greenschist facies metamorphic Paleozoic sequences, and the Juvavic, Tirolic-Noric and Bajuvaric Nappe Systems. The latter form the Northern Calcareous Alps, mostly comprising un-metamorphosed to lowermost greenschist facies metamorphic Permian to Mesozoic sediments deposited on the shelf facing originally towards the Meliata Ocean.

To the south the Silvretta-Seckau Nappe System is overlain by the Koralpe-Wölz Nappe System which represents an Eo-Alpine metamorphic extrusion wedge (Schmid et al., 2004). Its Permian to Mesozoic cover was completely stripped off during an early phase of the Eo-Alpine orogenic event and it therefore consists exclusively of metamorphic basement nappes. The Ötztal-Bundschuh Nappe System shows a similar lithological composition as the Silvretta-Seckau Nappe System, but is positioned on top of the Koralpe-Wölz Nappe System. Within this nappe system Eo-Alpine metamorphic grade decreases upwards from epidote-amphibolite facies at the base to diagenetic conditions at the top of the nappe pile. In other words, the high-grade nappes of the Koralpe-Wölz Nappe System are sandwiched between nappes affected by rather medium to low- grade Eo-Alpine metamorphism (for summary, see Schmid et al., 2004; Froitzheim et al., 2008). The overlying Drauzug-Gurktal Nappe System is made up of a Variscan metamorphic basement, anchizonal to greenschist facies Paleozoic metasedimentary sequences and by lower greenschist facies or un-metamorphosed Permian to Triassic sediments (Rantitsch and Russegger, 2000).

3. Geology of the Silvretta-Seckau Nappe System in the area of the Seckauer Tauern

The Seckau Nappe as part of the Silvretta-Seckau Nappe System (Fig. 1) covers a triangle shaped area extending in the north from the Bösenstein massif and Seckauer Tauern in the eastern part of the Niedere Tauern to the Fischbacher Alps over nearly 100 km. There it is cut off by the sinistral, east-west trending Trofaiach fault. Its continuation is represented by the Troiseck Floning Nappe (Neubauer, 1988). The southern edge is at Ameringkogel in the northern part of the Koralpe mountain ridge (Becker, 1979, 1980). The north south-extension is about 50 km.

The nomenclature used in literature for the crustal piece referred to as Seckau Nappe in here is quite complicated and confusing. In the past it is attributed to the so called Muriden unit in contrast to the overlying Koriden unit. However, this subdivision was never extended over the whole Austroalpine Unit (e.g., Neubauer and Frisch, 1993). Terms used for the area of the Bösenstein massiv and the Seckauer Tauern, which is dominated by orthogneisses, paragneisses and migmatic paragneisses (Metz, 1976) were "Seckauer Gneis" (Schmidt, 1921, p. 103 ff), „Seckauer Masse", „Seckauer Massiv" (Tollmann, 1977), „Kristallin der Seckauer Tauern" (Metz, 1980) and „Seckauer Kristallin" (Scharbert, 1981, Tollmann, 1977, p. 287). The term Seckau Complex (Faryad and Hoinkes, 2001, Gaidies et al., 2006) should be favoured as it matches recent lithostratigaphic standards.

For the eastern continuation „Mugel-Rennfeldzug" (Schwinner, 1951, S. 110; Metz, 1971, S. 56; Tollmann, 1977, S. 222) and „Rennfeld Mugel Kristallin" (Neubauer, 1988) can be found. In the southern part two units had been distinguished. A lower Amering-Komplex (Flügel and Neubauer, 1984) („Ammeringserie bzw. Gneiskomplex" in Becker, 1980) formed by biotite-plagioclase paragneisses and some orthogneis intercalations is overlain by the Speik-Komplex (Flügel and Neubauer, 1984), („Speikserie bzw. Amphibolitkomplex" in Becker, 1980) dominated by amphibolites with some ultramafic rocks and an eclogite at Hochgrössen mountain (Fig. 1). However, the individual

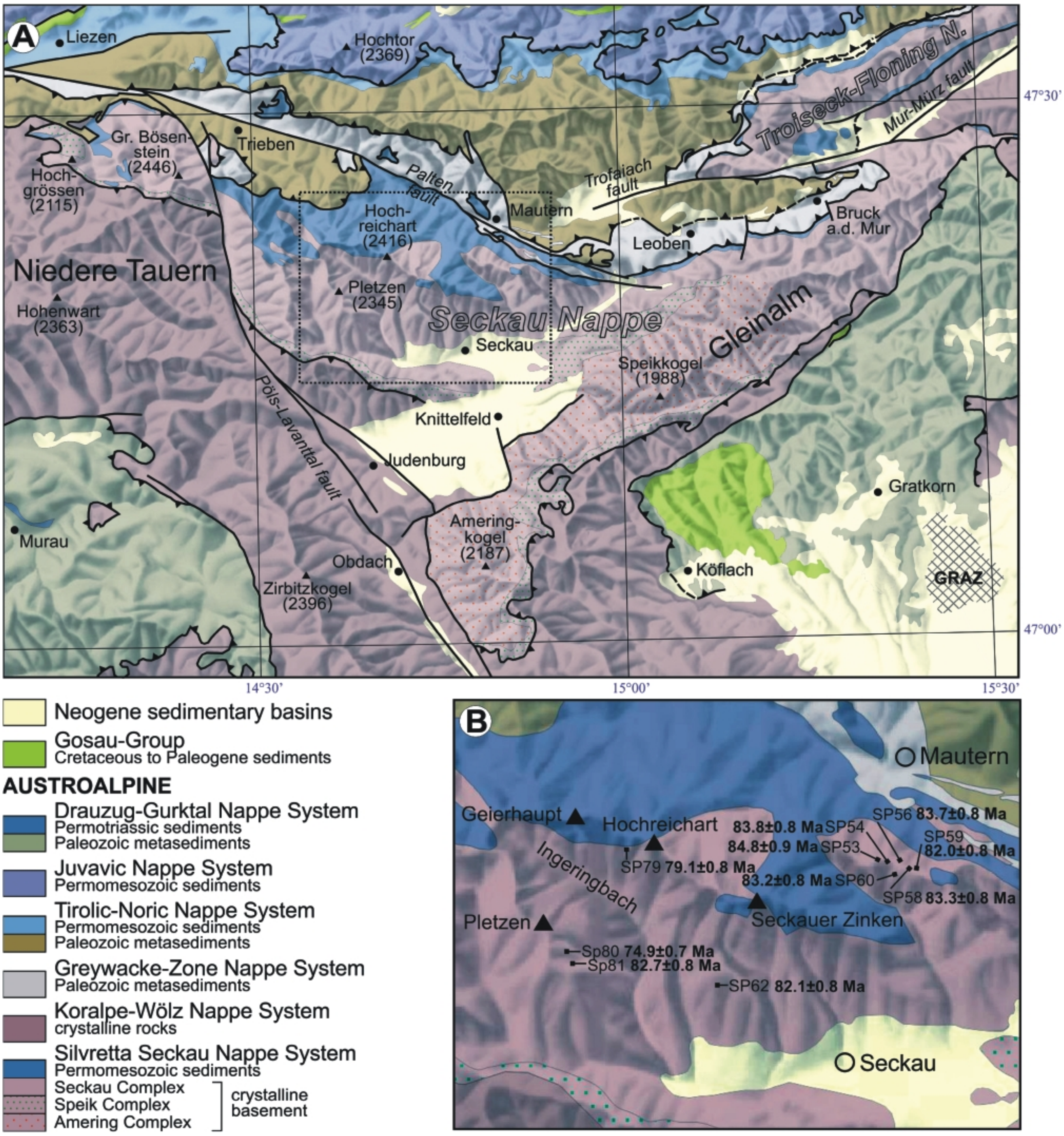


Figure 2: (A) Geological map of the study area in the Seckauer Tauern, based on Metz (1967, 1979), Flügel and Neubauer (1984) and Schubert et al. (2009). (B) Enlargement of the sampling area with sites of samples and the revealed Rb-Sr isochron ages.

complexes are not well defined and their boundaries are not clear. The overlying Permian to Lower Triassic metasediments are summarized as Rannach-Formation (Flügel and Neubauer, 1984),(after "Rannachserie" from Schwinner, 1929). It has to be mentioned that the term Rannach-Formation is problematic because there is a Rannach-Group defined in the nappes of the Graz Paleozoic just 30 km to the southeast (Flügel, 2000).

In the northern part of the Seckau Complex the Rannach-Formation is dipping northward, whereas in the south the Speik Complex is the uppermost element. Further, the Gaal Zone (Metz, 1971, "Gaaler Schuppenzone") mainly composed of the Speik Complex and overlying Permian to Lower Triassic metasediments is tectonically overlying the northwesternmost part of the Seckau Nappe in the Bösenstein area.

As mentioned before the pre-Alpine basement of the Seckau-Complex is formed by orthogneisses, paragneisses and migmatic paragneisses. The partly porphyric orthogneisses derived from tonalites, granodiorites as well as granites. In general these units form a coherent suite of I-type granitoids (Schermaier et al., 1997; Pfingstl, 2013). A-type, and transitional S- and I- type granitoids are represented to minor extent. Based on Rb-Sr whole rock (~ 350 Ma) and white mica ages (~330 Ma) and the low grade Eo-Alpine metomorphic overprint of the Permomesozoic metasediments above, the orthogneisses are thought to have formed during the Variscan tectonometamorphic event (Scharbert, 1981). An additional Rb-Sr whole rock age of 432 +/- 16 Ma argues for a pre-Variscan, possibly Ordovician intrusion age. To clarify the ages of the individual intrusive bodies, however, modern zircon ages are necessary.

The metamorphic conditions in the Seckau Nappe show a slight increase towards the south. In the northwest the transgressive Permian to Lower Triassic metasediments (Rannach-Formation) are characterised by the assemblage muscovite + chloritioid + chlorite + quartz, indicating upper greenschist facies conditions (520°C at 0.9 Gpa) (Faryad and Hoinkes, 2001). In the Gleinalm area in the south lower amphibolite facies conditions are expected from amphibolite assemblages including garnet + amphibole + plagioclase and intercalated micaschists with garnet, staurolite and kyanite. For the eastern

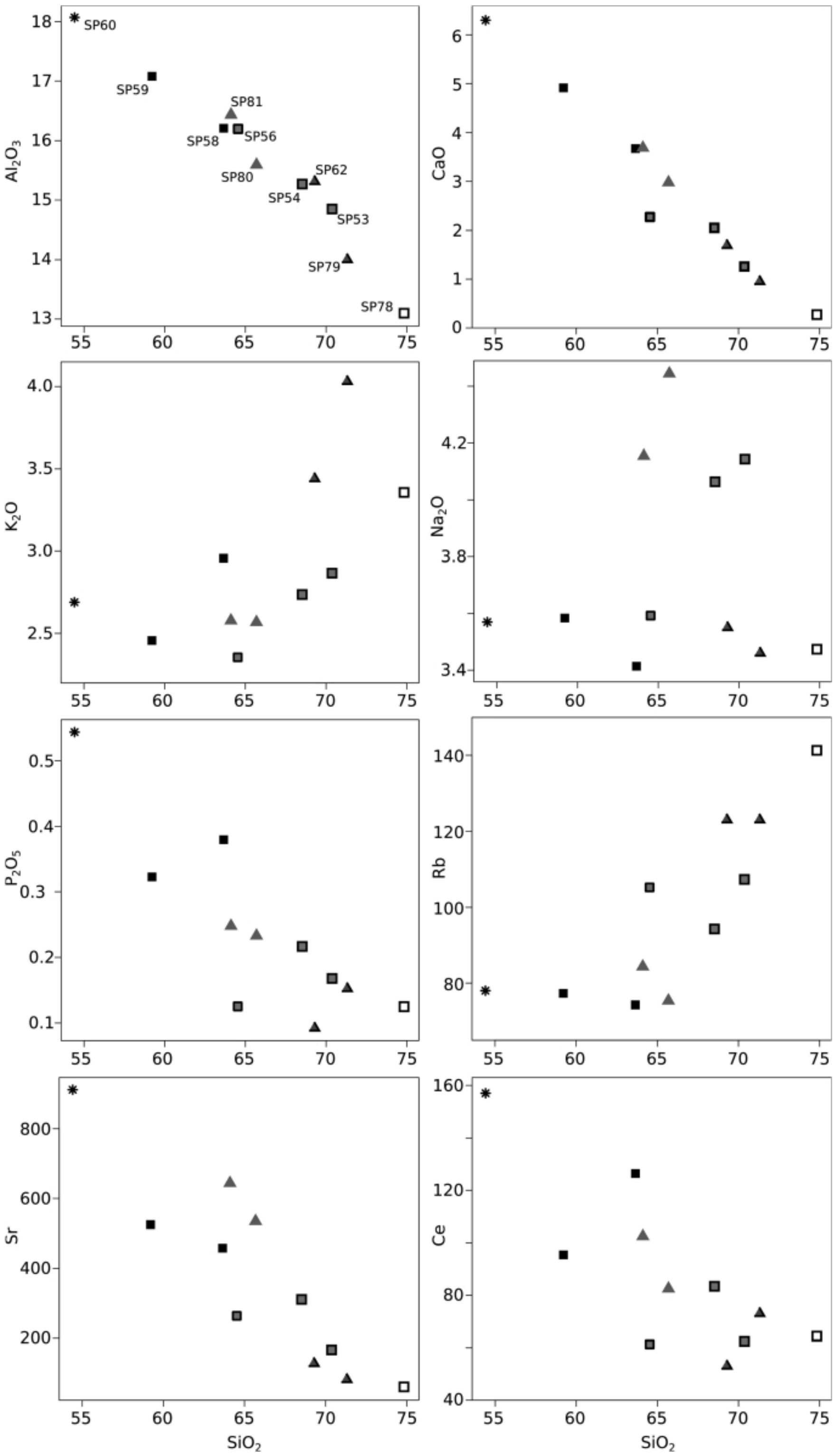


Figure 3: Harker diagrams with selected major and trace elements. The porhphyric samples (black squares) have low SiO_2 values but are high in CaO, P_2O_5, Sr and Ce. The S-type orthogneiss samples SP62 and SP79 (gray triangles with black outline) are relatively enriched in SiO_2, K_2O and Rb, while low in CaO, Na_2O, P_2O_5, Sr and Ce.

part no data are available, but as in the eastern continuation of the unit, represented by the Troiseck Floning Nappe, pre-Alpine Ar-Ar muscovite ages are preserved, decreasing conditions can be expected (Dallmeyer et al., 1998).

Timing of the peak of Eo-Alpine metamorphism in the Seckau Nappe is not constrained with age data and also for the cooling through greenschist facies conditions the data are scarce. Three Rb-Sr biotite ages are in the range of 70 to 77 Ma (Scharbert, 1981). Unexpected high fission track ages were described by Hejl (1997). Orthogneiss samples from the summit and valley areas of the Seckau Tauern yielded apatite fission track ages of ca. 60 Ma and 44 Ma, respectively. These fission track data indicate that after fast cooling during Late Cretaceous times the Seckau Nappe stayed at nearly constant temperature in the order of 80°C until the late Oligocene, followed by a phase of faster cooling, and a phase of slow cooling during Miocene times. The fission track data exclude any post-Cretaceous metamorphic overprint within the Seckau Nappe. During the whole Cenozoic the highest portions of the Seckau Nappe therefore resided at a depth of less than 3000 meters at temperatures much cooler than the conditions of anchimetamorphism (Hejl, 1997).

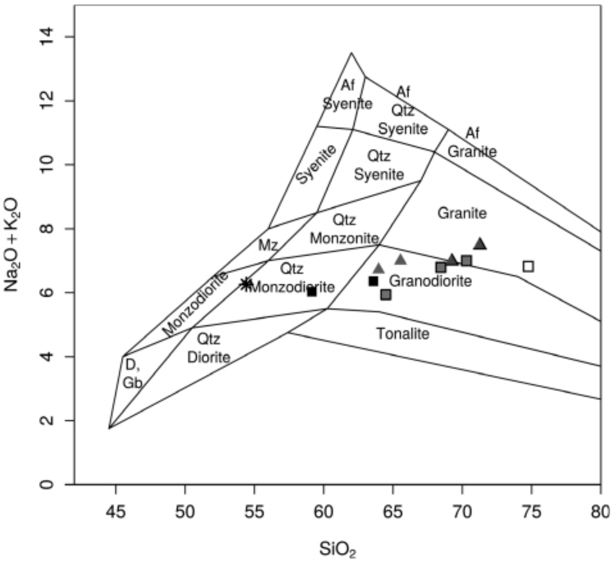


Figure 4: Total alkali ($Na_2O + K_2O$) against SiO_2 classification diagram after Middlemost (1994). Square and star symbols indicate samples from the "Untere Bodenhuette", samples with triangular symbols are from the "Ingering Gaal" area.

4. Analytical techniques

Mechanical and chemical sample preparation for Rb and Sr isotope analyses were performed at the Geological Survey of Austria in Vienna. Minerals were separated by standard methods of crushing, grinding, sieving and magnetic separations. Weights of samples used for dissolution were about 100 mg for whole rock powder and about 200 mg for biotite. Chemical sample preparation follows the procedure described by Sölva et al. (2005). Isotopic measurements were done at the Department of Lithospheric Research at the University of Vienna. Rb and Sr concentrations were determined by isotope dilution using mixed Rb-Sr spikes. Rb ratios were measured with a Finnigan® MAT 262 MC-TIMS, whereas Sr ratios were analysed with a ThermoFinnigan® Triton MC-TIMS. Sr was run from Re double filaments, whereas Rb was evaporated from a Ta filament. Total procedural blanks are < 1ng for Rb and Sr. During the periods of measurements the NBS987 standard yielded $^{86}Sr/^{87}Sr$ = 0.710248±4 (n=17; 2σ standard deviation) on the Triton TI. Isochron ages were calculated with the software ISOPLOT/Ex (Ludwig, 2001, 2003) assuming an error of 1% on the $^{87}Rb/^{86}Sr$ ratio.

The chemical composition of whole rock samples was determined by XRF. The finely powdered samples were dried at least 2 hours at 105 °C prior to further treatment. About 1g of sample was used for LOI determination at 1030 °C. For determination of major and selected trace elements a fused bead was prepared by using 1g of dried powder and 7g of dilithiumtetraborate. The glass bead was fused at ~1300°C with a semi-automatic VAA-2 fusion machine from HD-Electronic. About 60 international reference materials were used to calibrate the Bruker Pioneer S4 XRF, located at the Institute of Earth Sciences, Karl-Franzens-University Graz. The USGS reference material GSP-2 is analysed routinely as monitor standard which can be reproduced within the given errors.

5. Analytical data

The mainly foliated orthogneisses are from two localities, namely in the Untere Bodenhütte (square and star symbols in Fig. 3) and Ingering Gaal area (triangles in Fig. 4). The geographic location of the samples and their lithological / geochemical

Sample	Latitute	Longitude	Altitude (m)	type	Lithology
SP53	47°21.383'	14°47.201'	1455	S-type	granite gneiss; slightly foliated
SP54	47°21.383'	14°47.201'	1455	S-type	Orthogneiss, coarse grained
SP56	47°21.450'	14°47.429'	1443	S-type	granodiorite
SP58	47°20.940'	14°48.544'	1482	I-type	granodiorite
SP59	47°20.940'	14°48.544'	1482	I-type	monzodiorite
SP60	47°21.093'	14°48.143'	1447		basic dike
SP62	47°18.016'	14°41.856'	1145	S-type	granite gneiss, coarse grained; migmatic
SP79	47°21.811'	14°40.899'	2416	S-type	granite gneiss
SP80	47°19.695'	14°37.436'	1989	I-type	granodiorite gneiss
SP81	47°19.571'	14°37.657'	2038	I-type	granodiorite gneiss

Table 1: Sites of samples analysed for Rb-Sr geochronology on biotite.

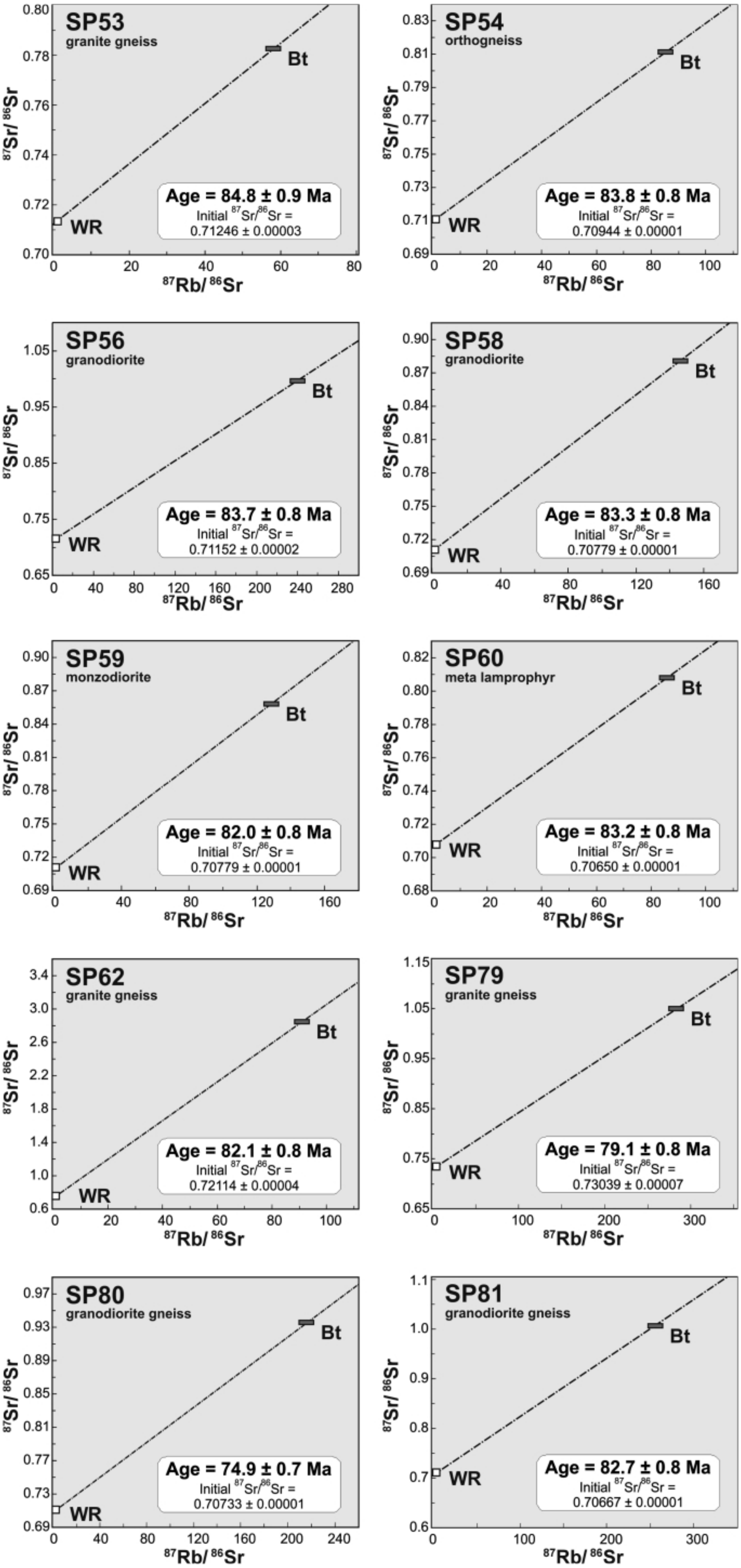


Figure 5: Selected Rb-Sr biotite – whole rock ages from orthogneisses of the Seckau Complex.

classification are given in Table 1, analytical data in Table 3.

Samples from the Untere Bodenhütte area include two porhphyric and only weakly foliated samples (SP58, SP59). Compared to the other samples described below, SP58 and SP59 show lower SiO_2, Na_2O and Rb concentrations but show the highest CaO, P_2O_5, Sr, and Ce contents. One sample (SP78), which did not contain biotite and thus was not dated, contains muscovite and geochemical data are plotted for comparison in Figure 4. This sample shows slightly different chemical features and contains the highest SiO_2 values of all samples with 74.8 wt.%. From the Ingering Gaal area four samples were taken. Two samples display higher SiO_2, K_2O and Rb while CaO, P_2O_5, Sr, and Ce values are very low. Based on geochemical and Sr isotope data both sample were identified to belong to a granitic suite with S-type affinity. However, most analyzed samples can be geochemically classified as I-type granites with respect to Chappell and White (1974, 2001) (Pfingstl, 2013) (Table 1). Sample SP60 from the Feistritz valley has been identified as metamorphosed mafic dike. Following the classification by Middlemost (1994) by application of the TAS diagram for plutonic rocks samples SP53, SP62, SP79, and SP78 can be classified as granites, and SP54, SP56, SP58, SP80 and SP81 as granodiorites (Figure 4). Only sample SP59 falls into the quartz monzodiorite field. The metamorphosed mafic dike SP 60 has a basaltic trachyandesite/ quartz-monzodiorite composition.

The results of geochronological analysis are summarized in Table 2, related Rb-Sr biotite ages and isochrons are displayed in Figure 5. The investigated biotites show brown to yellowish-brown pleochroism. Some separated from orthogneisses show typical rutile exsolutions ("Sagenitgitter"), indicating higher Ti-contents of the primary magmatic biotites. Within the eastern part of the investigated area near to Bodenhütte ages range from 83.3±0.8 Ma to 84.8±0.9 Ma (SP53, SP54, SP56, SP58, SP59, SP60). Taking into account the standard deviations (Table 2), these ages are more or less identical within error. A similar age of 83.2±0.8 Ma (SP62) has also been observed from the southern part of the investigated area. An age from the Hochreichart (Fig. 2) yielding 79.1±0.8 Ma (SP79) is significantly younger. In the western part of the area of investigation, west of the Ingering valley, two different ages were observed. An age of 82.7±0.8 Ma (SP81) is widely identical to the bulk of ages yielded in the eastern part, whereas an age of 74.9±0.7 Ma (SP80) is significantly younger.

Calculation of a regression line including all whole rocks analyses of granitic and granodioritic rocks results in an age value of 507±60 Ma with an initial isotopic ratio of 0.7045±0.0016.

6. Microstructures

Within the deeper levels of the Seckau Complex quartz is characterized by partly annealed fabrics. Equigranular grains generally show a polygonal shape (Fig. 6a). Quartz grains show grain sizes of 0.2 - 0.4 mm, the average grain size equals about 0.3 mm. Irregular and lobate grain boundaries are weakly developed; generally the grain boundaries are straight or slightly curved and form 120°- triple junctions. In places, the grains were subsequently affected by low-temperature deformation, and, therefore, show undulatory extinction.

Along the contact to the Rannach-Formation quartz grains are slightly elongated (Fig. 6b). Ribbon grains formed along shear bands. The quartz grains are characterized by undulatory extinction, the formation of subgrains, deformation lamellae and deformation bands, and by sutured, lobate, and bulged grain boundaries. Aggregates of fine-grained dynamically recrystallized grains (grain size ~ 0.05 - 0.1 mm) developed along shear bands due to secondary grain size reduction; bulging is assumed to be the main deformation mechanism.

Along the contact between the Seckau Complex and the Rannach-Formation both K-feldspar and plagioclase show high undulatory extinction, and, within domains along shear bands, curved twins. The feldspars are characterized by cataclastic deformation mechanisms, documented by the formation of extensional fractures and shear fractures (Fig. 6c). Extensional fractures are filled with quartz and calcite. Fragments confined by shear fractures were rotated towards the direction of shear that is accommodated by single and/or conjugate sets of shear bands. Along these shear bands (Fig. 6b) quartz is characterized by grain size reduction due to dynamic recrystallization. Biotite is aligned along these shear bands; within distinct domains biotite recrystallized and was newly formed. Additionally biotite is transformed to chlorite. In case of the occurrence of single sets the shear bands indicate a top-to-the WNW sense of shear. Antithetic sets with top-to-the ESE kinematics can be observed as well.

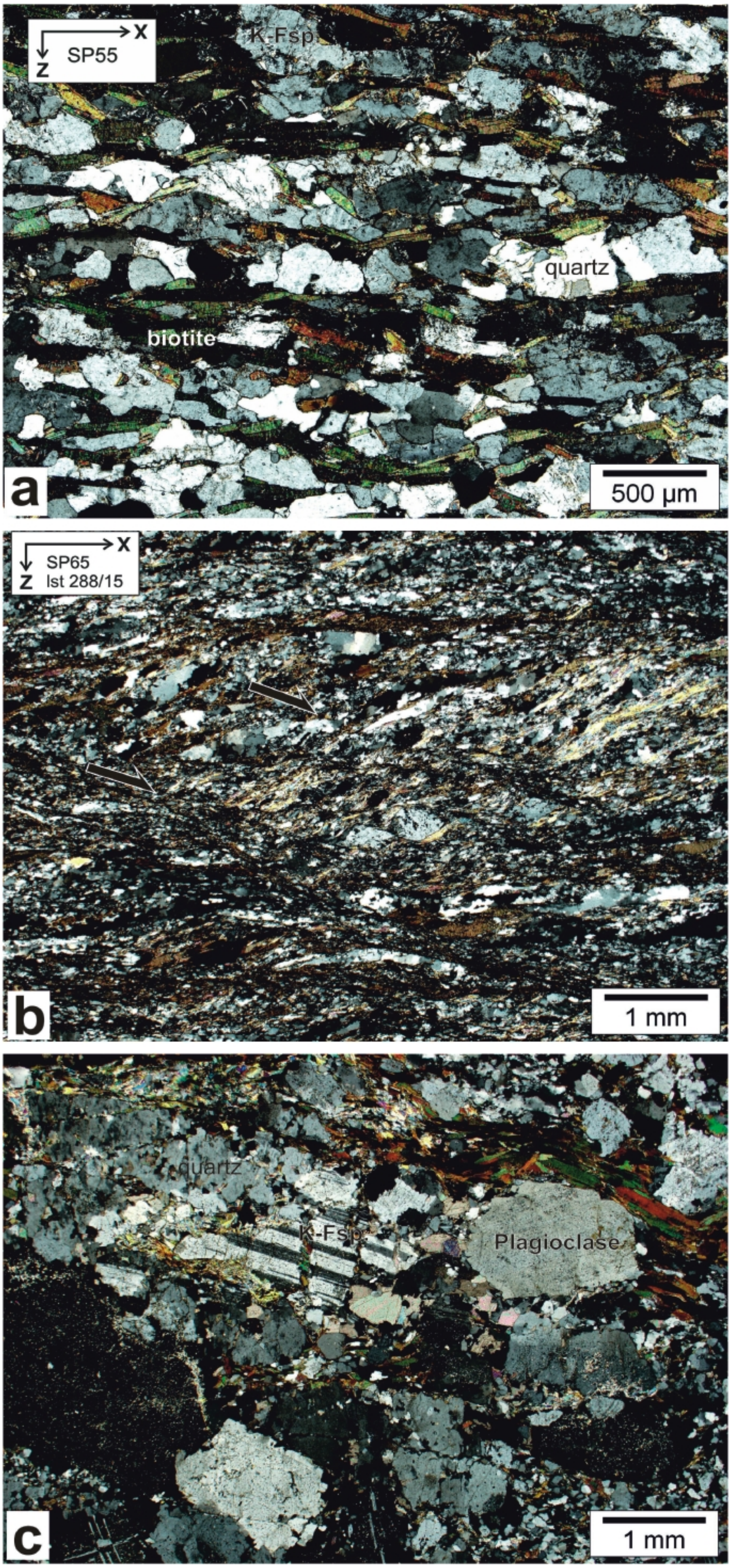
As feldspar is deformed by cataclastic deformation mechanisms, whereas quartz shows deformation mechanisms of dislocation creep and bulging dynamic recrystallization, we assume that the conditions of deformation along the higher part of the Seckau Complex and within the Rannach-Formation are in the range of 300°C to 400°C.

7. Discussion

The Rb-Sr biotite age data presented in this study range from 74.9±0.8 to 84±0.9 Ma, with eight samples showing ages

Sample	Material	Rb [ppm]	Sr [ppm]	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$	$\pm 2s_m$	age
SP53	WR	108.1	168.3	1.8612	0.714706	0.000004	84.8 ± 0.9
	Bt	628.2	31.48	58.163	0.782542	0.000005	
SP54	WR	90.93	317.5	0.8290	0.710423	0.000004	83.8 ± 0.8
	Bt	535.0	18.40	84.986	0.810618	0.000005	
SP56	WR	100.8	267.3	1.0924	0.712816	0.000004	83.7 ± 0.8
	Bt	438.5	5.442	239.79	0.996507	0.000006	
SP58	WR	72.97	470.4	0.4490	0.708325	0.000004	83.3 ± 0.8
	Bt	356.1	7.182	145.92	0.880531	0.000005	
SP59	WR	74.66	539.5	0.4005	0.708124	0.000004	82.0 ± 0.8
	Bt	287.1	6.571	128.27	0.857332	0.000004	
SP60	WR	78.78	945.7	0.2411	0.706782	0.000004	83.2 ± 0.8
	Bt	298.9	10.19	85.705	0.807810	0.000008	
SP62	WR	118.8	130.4	2.6421	0.724216	0.000004	82.1 ± 0.8
	Bt	619.9	1.194	1815.0	2.837138	0.000015	
SP79	WR	121.9	86.14	4.1077	0.735010	0.000004	79.1 ± 0.8
	Bt	680.1	7.168	283.76	1.049251	0.000006	
SP80	WR	74.69	549.5	0.3934	0.707748	0.000004	74.9 ± 0.7
	Bt	401.5	5.531	214.73	0.935750	0.000005	
SP81	WR	89.93	647.0	0.4022	0.707143	0.000004	82.7 ± 0.8
	Bt	452.5	5.280	255.25	1.006528	0.000006	

Table 2: Rb-Sr isotopic data on biotite and whole rock from the Seckau Nappe. Analytical techniques are described in text. Isochron ages were calculated from biotite and corresponding whole rock assuming an error of ±1% on the $^{87}Rb/^{86}Sr$ ratio.



around 82 to 84 Ma (Fig. 5) (Table 2). A sample from Hochreichart mountain has an age of 79.1±0.8 Ma, another sample (SP80) west of the Ingering valley yielded only 76.3±0.8 Ma. The latter seems to be exceptional as it is sampled only about 250 meters from sample SP81, which has an age of 82.7±0.8 Ma and as both samples show a nearly identical mineralogical and chemical composition. It is obvious that both samples underwent the same cooling history and we attribute the difference in age to a slight contamination by chlorite, grain size and/or weathering effects. According to Jäger (1979) Rb-Sr biotite-ages are interpreted to date cooling below 300±50°C. Therefore the investigated part of the Seckau Complex cooled down below ~300°C at about 85 Ma in the Santonian.

A regression line calculated from all whole rock analyses of granites, granodiortites and the quartz monzodiorite yielded an age value of 507±60 Ma. As obtained from the geochemical data the rocks show both I-type and S-type affinities, and therefore most probably not all of the investigated rocks belong to a co-genetic magmatic suite. However, except the granite SP53 all data points fit well to a regression line defining an age value of 517±16 Ma with an initial $^{87}Sr/^{86}Sr$ ratio of 0.7047±6. I-

Figure 6: (a) Microstructure (crossed polarizing filters) of a granitic orthogneiss from the Seckau basement, not affected by extensional shear. Quartz is characterized by equigranular grain shape, nearly straight grain boundaries and only subordinate undulatory extinction. (b) Microstructure characteristic for the contact domain between the Seckau basement and the Rannach-Formation. Shear bands indicate top-to-the west sense of shear. Quartz along shear bands is characterized by highly reduced grain size. Arrows indicate the sense of shear. (c) Microstructure of a granitic orthogneiss from the Seckau basement, immediately beneath the contact to the Rannach-Formation. Quartz is characterized by undulatory extinction and formation of multiple subgrains, Feldspar is characterized by undulatory extinction, bent twins, and fracturing.

Type and S-Type rocks are aligned on the regression line without any special systematics and therefore it might represent a geological meaningful errorchrone indicating crystallization of these rocks during Early Paleozoic times. Based on Rb-Sr data also Scharbert (1981) and Schermaier et al. (1997) argued for an early Paleozoic age of some igneous rock associations in the Seckau Complex.

Referring to microstructural observations, the contact between the Seckau Complex and the Rannach-Formation was strongly overprinted by the formation of distinct shear zones that are characterised by extensional fabrics. Kinematics is characterized by conjugate sets of top-to-the-WNW and top-to-the-ESE.

A comprehensive view of the ages and structural observations presented in this study shows that deformation temperatures overlap with the range of Rb-Sr biotite closure temperature. Therefore we assume that top-to-the WNW extensional shearing is related to exhumation of the Seckau Nappe and caused cooling below 300±50°C at 85 Ma in the Late Cretaceous. This coincides with the formation of the Gosau sedimentary basins in the central Eastern Alps (Neubauer et al., 1995; Dallmeyer et al., 1998; Faupl and Wagreich, 2000).

The Rb-Sr biotite ages by Scharbert (1981), which are slightly younger, were measured on samples taken from the more southern part of the Seckauer Tauern. They may indicate a trend to later cooling towards the south.

Geochronological data from the Seckau Complex collected from literature give additional information. An $^{40}Ar/^{39}Ar$ amphibole age measured on an eclogite amphibolite of the Speik Complex of the Gaal Zone in the Bösenstein massif yielded about 390 Ma (Faryad et al., 2002). This pre-Alpine age had been preserved as metamorphic conditions determined for the northern part of the Silvretta-Seckau Nappe System are around 500°C and are therefore in the range of the closure temperature of the K-Ar isotopic system in amphibole (von Blanckenburg and Villa, 1988; von Blanckenburg et al., 1989).

Sample Petrology	SP53 Orthogneiss	SP54 Orthogneiss	SP56 Orthogneiss	SP58 Porph.Granitoide	SP59 Porph.Granitoide	SP78 Ms-orthogneiss	SP62 Bt-orthogneiss*	SP79 Bt-orthogneiss*	SP80 Bt-orthogneiss	SP81 Bt-orthogneiss	SP60 Mafic dike
SiO_2	70.30	68.45	64.48	63.58	59.14	74.76	69.22	71.24	65.54	63.96	54.41
TiO_2	0.38	0.50	0.73	0.84	1.01	0.21	0.45	0.39	0.66	0.70	1.20
Al_2O_3	14.83	15.25	16.18	16.19	17.06	13.08	15.31	14.00	15.57	16.41	18.07
Fe_2O_3	2.40	3.27	5.55	5.04	6.47	2.12	3.24	2.85	4.13	4.34	7.52
MnO	0.038	0.055	0.111	0.074	0.127	0.026	0.058	0.047	0.085	0.072	0.139
MgO	0.98	1.04	2.11	1.38	2.58	0.36	0.97	0.72	1.60	1.66	3.40
CaO	1.24	2.03	2.25	3.65	4.89	0.25	1.69	0.95	2.95	3.66	6.30
Na_2O	4.14	4.06	3.59	3.41	3.58	3.47	3.55	3.46	4.44	4.15	3.57
K_2O	2.86	2.73	2.35	2.95	2.45	3.35	3.44	4.03	2.56	2.57	2.69
P_2O_5	0.166	0.215	0.124	0.378	0.321	0.123	0.092	0.152	0.231	0.246	0.544
LOI	1.61	1.10	1.60	1.23	1.13	1.04	0.73	1.13	0.82	1.03	0.87
Sum	99.09	98.95	99.28	99.05	99.02	98.93	98.94	99.14	98.85	99.03	99.03
Ba	650	902	478	1454	852	349	558	706	1108	925	1187
Ce	62	83	61	126	95	64	53	73	82	102	157
Cr	<20	<20	48	<20	<20	<20	<20	<20	<20	<20	<20
Cu	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20
Ga	20	21	20	25	21	15	21	19	18	23	23
Nb	<20	<20	<20	<20	<20	<20	<20	26	<20	<20	<20
Nd	50	34	25	54	58	25	35	47	48	41	60
Ni	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20
Pb	<20	<20	32	<20	<20	<20	<20	<20	<20	<20	26
Rb	107	94	105	74	77	141	123	123	75	84	78
Sr	164	308	262	455	522	58	128	82	531	640	911
V	37	49	98	85	139	<20	41	35	73	75	155
Y	20	19	24	18	27	32	33	50	25	25	33
Zn	28	53	109	71	82	23	54	30	84	77	105
Zr	166	209	160	308	224	110	166	262	216	223	271

* S-type affinity

Table 3: Chemical composition of selected rocks from Untere Bodenhütte area (SP53-SP78), Ingering Gaal (SP62-SP81), and a mafic dike from Feistritz valley.

Also Rb-Sr muscovite ages from the area around Bodenhütte yielded Variscan ages of about 330 Ma Scharbert (1981). With respect to the closure temperature of the Rb-Sr isotopic system in muscovite (Jäger, 1979) Alpine peak metamorphic conditions of less than, or about 500 °C are indicated. In contrast an $^{40}Ar/^{39}Ar$ age from the Speik Complex in the Gleinalm area yielded 95.4±1.2 Ma (Neubauer et al., 1995). This age reflects total resetting of the K-Ar isotopic system in hornblende during eo-Alpine epidote-amphibolite facies metamorphism at 550-600°C at 0.9-1.0 GPa (Faryad and Hoinkes, 2003).

In the Gleinalm mountain range the Speik Complex is overlain by the Wölz and Rappold Complexes being parts of the Koralpe-Wölz Nappe System. $^{40}Ar/^{39}Ar$ muscovite ages from there are in the range of 84 to 87 Ma (Neubauer et al., 1995). These muscovite ages are in the range of the new Rb-Sr cooling ages presented in this study. In the eastern part of the Eastern Alps, $^{40}Ar/^{39}Ar$ muscovite ages from the Silvretta-Seckau Nappe System (the so-called Troiseck-Floning Zug) indicate cooling of this unit between ca. 88 and 82 Ma (Dallmeyer et al., 1998). Despite the fact that the closure temperature of the Ar-isotopic system in white mica has been reported to be within a rather wider temperature range from ca. 350°C (Lips et al., 1998) to 425 ± 25 °C (Harrison et al., 2009), ca. 450 °C (Hames and Bowring, 1994; Kirschner et al., 1996) and ca. 500°C (Hammerschmidt and Frank, 1991; Hames and Cheney, 1997) and depends on grain-size, chemical composition and cooling rate (Villa, 1998; Warren et al., 2012), it is higher than those for Rb-Sr in biotite (300±50°C) (Jäger, 1979). This indicates earlier cooling of the Seckau Nappe below 350°C within the Seckauer Tauern than in the Gleinalm mountain range. Moreover, this evolution can be reconstructed for the eastward continuation of the Seckau Nappe System as well.

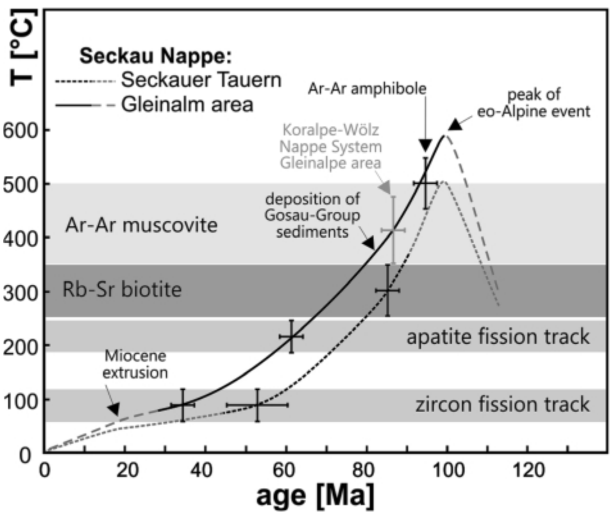


Figure 7: T-t paths for the different parts of the Seckau Nappe: Prior to the Eo-Alpine metamorphic peak the Seckau Complex and the overlying Permotriassic sediments were heated. The Eo-Alpine metamorphic peak was reached at 90-100 Ma. Rocks from the Seckauer Tauern experienced lower peak conditions as those in the Gleinalm area (about 500 °C) and cooled earlier than the latter. Diagram based on data from Dunkl et al. (2005), Faryad and Hoinkes (2001, 2003), Hejl (1997), Neubauer et al. (1995) and Scharbert (1981). Greyish lines inticate expected parts of T-t path. For explanation see text.

Fission track data from the Gleinalm mountain range measured on sphene, zircon and apatite yielded ages of ca. 69 Ma, 65 Ma, and 34 Ma, respectively (Neubauer et al., 1995; Dunkl et al., 2005). The fission track ages therefore support the trend with earlier cooling in the Seckauer Tauern with respect to the Gleinalm mountain range: The zircon fission track age of 65 Ma representing cooling below the partial annealing zone (< 240°C) (e.g., Wölfler et al., 2010) is just slightly older than the apatite fission track ages from the Seckauer Tauern yielding 60-44 Ma (Hejl, 1997). The latter indicates that the northern part of the Seckau Complex cooled below the apatite fission track partial retention zone (120° - 60°C; Green et al., 1986; Wolf et al., 1996) in Oligocene times. The apatite fission track age from the Gleinalm is 34 Ma (Dunkl et al., 2005) and indicates cooling 25-30 Ma later than in the north.

Compared to the cooling path of the basement rocks in the Seckau Tauern described above, cooling of the adjacent Gleinalm mountain range southeast of the Seckau Tauern appears to be more continuous (Fig. 7). The data set from the Gleinalm mountain range, however, is also more complete than those from the Seckauer Tauern. The question arises whether the Seckau and the Gleinalm domains of the Silvretta-Seckau Nappe System represent a continuous nappe sheet or two independent parts with a prominent shear zone in between which decoupled them during their exhumation. Based on mapping no major fault is known yet which could have caused the decoupling, until the sinistral Mur-Mürz fault developed during lateral extrusion of the Eastern Alps (Ratschbacher et al., 1991) during Miocene times. If this is the case, the Seckau Complex was a south dipping element from Cretaceous until Paleogene time when extensional tectonics and/or pronounced erosion in the south caused a tilting in a more horizontal position.

8. Concluding remarks

According to the new Rb-Sr biotite cooling ages presented in this study, the Seckau Complex cooled below~300°C at about 85 Ma in the Santonian. The contact of the Seckau Complex to the overlying Permotriassic metasediments of the Rannach-Formation is characterized by lower greenschist facies shear zones with top-to-the WNW displacement. As these shear zones developed at temperatures in the range of the Rb-Sr isotopic system in biotite we assume that cooling of the northern part of the Seckau Nappe is due to extensional shearing within the higher structural levels of the Seckau Nappe. Cooling ages indicate earlier cooling in the northern than in the southern part of the Seckau Nappe.

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References

Becker, L.P., 1979. Geologische Karte der Republik Österreich 1:50.000, Blatt 162 Köflach. Geologische Bundesanstalt, Wien.

Becker, L.P., 1980. Erläuterungen zu Blatt 162 Köflach. Geologische Karte der Republik 1:50.000, Geologische Bundesanstalt, Wien.

Chappell, B. W. and White, A. J. R., 1974. Two contrasting granite types. Pacific Geology, 8, 173-174.

Chappell, B. W. and White, A. J. R., 2001. Two contrasting granite types: 25 years later. Australian Journal of Earth Sciences, 48, 489-499. http://dx.doi.org/10.1046/j.1440-0952.2001.00882.x

Dal Piaz, G. V., Martin, S., Villa, I. M., Gosso, G. and Marschalko, R., 1995. Late Jurassic blueschist facies pebbles from the Western Carpathian orogenic wedge and paleostructural implications for western Tethys evolution. Tectonics, 14, 874-885.

Dallmeyer, R.D., Handler, R., Neubauer, F. and Fritz, H., 1998. Sequence of thrusting within a thick-skinned tectonic wedge: evidence from 40Ar/39Ar and Rb-Sr ages from the Austroalpine nappe complex of the Eastern Alps. Journal of Geology, 106, 71-86.

Dallmeyer, R. D., Neubauer, F. and Fritz, H., 2008. The Meliata suture in the Carpathians: regional significance and implications for the evolution of high-pressure wedges within collisional orogens. Geological Societyof London Special Publications, 298, 101-115. http://dx.doi.org/10.1144/SP298.6

Dunkl, I., Kuhlemann, J., Reinecker, J. and Frisch, W., 2005. Cenozoic relief evolution of the Eastern Alps - Contraints from apatite fission track age-provenance of Neogene intramontane sediments. Austrian Journal of Earth Sciences, 98, 92-105.

Faupl, P. and Wagreich, M., 2000. Late Jurassic to Eocene Palaeogeography and Geodynamic Evolution of the Eastern Alps. Mitteilungen der Österreichischen Geologischen Gesellschaft, 92, 79-94.

Faryad, S. W. and Hoinkes, G., 2001. Alpine Chloritoid and Garnet from the Hochgrössen Massif (Speik Complex, Eastern Alps). Mitteilungen der Österreichischen Geologischen Gesellschaft, 146, 387-396.

Faryad, S. W. and Hoinkes, G., 2003. P-T gradient of Eo-Alpine metamorphism within the Austroalpine basement units east of the Tauern Window (Austria). Mineralogy and Petrology, 77, 129-159. http://dx.doi.org/10.1007/s00710-002-0196-1

Faryad, S.W., Melcher, F.; Hoinkes, G., Puhl, J., Meisel, T. and Frank, W., 2002. Relics of eclogite facies metamorphism in the Austroalpine basement, Hochgrössen (Speik complex), Austria. Mineralogy and Petrology, 74, 49-73. http://dx.doi.org/10.1007/s710-002-8215-9

Flügel, H. W., 2000. Die lithostratigraphische Gliederung des Paläozoikums von Graz (Österreich). Österreichische Akademie der Wissenschaften / Schriftenreihe der Erdwissenschaftlichen Kommissionen, 13, 7-59.

Flügel, H. W. and Neubauer, F. R., 1984. Geologische Karte der Steiermark 1:200.000. Geologische Bundesanstalt, Wien.

Frank, W., 1987. Evolution of the Austroalpine elements in the Cretaceous. In: H. W. Flügel and P. Faupl (eds.), Geodynamics of the Eastern Alps, 379-406. Vienna, Deuticke.

Frisch, W. and Gawlick, H.-J., 2003. The nappe structure of the central Northern Calcareous Alps and its disintegration during Miocene tectonic extrusion - a contribution to understanding the orogenic evolution of the Eastern Alps. International Journal of Earth Sciences, 92, 712-727.

Froitzheim, N., Plasienka, D. and Schuster, R., 2008. Alpine tectonics of the Alps and Western Carpathians. In: T. McCann (ed.) The Geology of Central Europe, Volume 2: Mesozoic and Cenozoic. 1141-1232. Geological Society of London.

Froitzheim, N., Schmid, S. M. and Frey, M., 1996. Mesozoic paleogeography and the timing of eclogite facies metamorphism in the Alps: A working hypothesis. Eclogae geologicae Helvetiae, 89, 81-110.

Green, P. F., Duddy, I. R., Gleadow, A. J. W., Tingate, P. R. and Laslett, G. M., 1986. Thermal annealing of fission tracks in apatite 1. A qualitative description. Chemical Geology, 59, 237-253.

Hames, W. E. and Browning, S. A., 1994. An empirical evaluation of the argon diffusion geometry in muscovite. Earth and Planetary Science Letters, 124, 161-167.

Hames, W.E. and Cheney, J.T., 1997. On the loss of $^{40}Ar^*$ from muscovite during polymetamorphism. Geochimica et Cosmochimica Acta, 61, 3863-3872.

Hammerschmidt, K. and Frank, E., 1991. Relics of high pressure metamorphism in the Lepontine Alps (Switzerland) - $^{40}Ar/^{39}Ar$ and microprobe analyses on K-micas. Schweizerische mineralogische und petrographische Mitteilungen, 71, 261-274.

Handy, M. R. and Oberhänsli, R., 2004. Explanatory notes to the map: metamorphic structure of the Alps: age map of the metamorphic structure of the Alps - tectonic interpretation and outstanding problems. Mitteilungen der Österreichischen Mineralogischen Gesellschaft, 149, 201-225.

Harrison, T. M., Célélier, J., Aikman, A. B., Hermann, J. and Heizler, M.T., 2009. Diffusion of ^{40}Ar in muscovite. Geochimica et Cosmochimica Acta, 73, 1039-1051. http://dx.doi.org/10.1016/j.gca.2008.09.038

Hejl, E., 1997. 'Cold spots' during the Cenozoic evolution of the Eastern Alps: thermochronological interpretation of apatite fission-track data. Tectonophysics, 272, 159-173.

Hoinkes, G., Koller, F., Demeny, A., Miller, CH., Schuster, R., Thöni, M., Kurz, W., Krenn, K. and Walter, F., 2010. Metamorphism in the Eastern Alps. Acta Mineralogica-Petrographica, Field Guide Series, 1, 1-47.

Jäger, E., 1979. Introduction to Geochronology. In: E. Jäger and J.C. Hunziger (eds). Lectures in Isotope Geology, 1-12, Springer, Berlin Heidelberg New York.

Kirschner, D. L., Cosca, M. A., Masson, H. and Hunziker, J. C., 1996. Staircase 40Ar/39Ar of fine-grained white mica: Timing and duration of deformation and empirical constraints on Argon diffusion. Geology, 24, 747-750.

Ludwig, K.R., 2001. Isoplot/Ex version 2.49. A Geochronological Toolkit for Microsoft Excel. Berkeley Geochronology Center Special Publication N0. 1a.

Ludwig, K.R., 2003. Isoplot/Ex version 3.0. A geochronological toolkit for Microsoft Excel. Berkeley Geochronological Centre Special Publication, Berkeley, 70 p.

Lips, A. L. W., White, S. H. and Wijbrans, J. R., 1998. $^{40}Ar/^{39}Ar$ laserprobe direct dating of discrete deformational events: a continous record of early Alpine tectonics in the Pelagonian Zone, NW Aegean area, Greece. Tectonophysics, 298, 133-153.

Metz, K., 1967. Geologische Karte der Republik Österreich 1:50.000, Blatt 130-131 Oberzeiring-Kalwang. Geologische Bundesanstalt, Wien.

Metz, K., 1971. Das Problem der Grenzzone zwischen den Wölzer Glimmerschiefern und Ennstaler Phylliten. Carinthia II, Sonderheft 28, 159-166.

Metz, K., 1976. Der geologische Bau der Seckauer und Rottenmanner Tauern. Jahrbuch der Geologischen Bundesanstalt, 119, 151-205.

Metz, K., 1976. Der geologische Bau der Wölzer Tauern. Mitteilungen des Naturwissenschaftlichen Vereins für Steiermark, 106, 51-75.

Metz, K., 1979. Geologische Karte der Republik Österreich 1:50.000, Blatt 129 Donnersbach. Geologische Bundesanstalt, Wien.

Metz, K., 1980. Erläuterungen zu Blatt 129 Donnersbach. Geologische Bundesanstalt Wien, 35 pp.

Middlemost, E. A. K., 1994. Naming materials in magma/igneous rock system. Earth Science Reviews, 37, 215-224.

Missoni, S. and Gawlick, H.-J., 2010. Evidence for Jurassic subduction from the Northern Calcareous Alps (Berchtesgaden; Austroalpine, Germany). International Journal of Earth Sciences, http://dx.doi.org/10.1007/s00531-010-0552-z.

Nagel, T., 2006. Structure of Austroalpine and Penninic units in the Tilisuna area (Eastern Rhätikon, Austria): Implications for the paleogeographic position of the Allgäu and Lechtal nappes. Eclogae Geologicae Helvetiae, 99, 223-235. http://dx.doi.org/10.1007/s00015-006-1192-y

Neubauer, F., 1988. Bau und Entwicklungsgeschichte des Rennfeld-Mugel- und des Gleinalm-Kristallins (Ostalpen). Abhandlungen der Geologischen Bundesanstalt, 42, 1-137.

Neubauer, F., 1994. Kontinentkollision in den Ostalpen. Geowissenschaften, 12, 136-140.

Neubauer, F., 2002. Evolution of late Neoproterozoic to early Paleozoic tectonic elements in Central and Southeast European Alpine mountain belts: review and synthesis. Tectonophysics, 352, 87-103. http://dx.doi.org/10.1016/S0040-1951(02)00190-7

Neubauer, F., Dallmeyer, R. D., Dunkl, I. and Schirnik, D., 1995. Late Cretaceous exhumation of the metamorphic Gleinalm dome, Eastern Alps: kinematics, cooling history and sedimentary response in a sinistral wrench corridor. Tectonophysics, 242, 79-98.

Neubauer, F. and Frisch, W., 1993. The Austroalpine metamorphic basement east of the Tauern Window. In: J. von Raumer and F. Neubauer (eds.), Pre-Mesozoic Geology in the Alps, pp. 515-536. Springer (Berlin).

Neubauer, F., Genser, J. and Handler, R., 2000. The Eastern Alps: Result of a two-stage collision process. Mitteilungen der Österreichischen Geologischen Gesellschaft, 92, 117-134.

Neubauer, F., Hoinkes, G., Sassi, F.P., Handler, R., Höck, V., Koller, F. and Frank, W., 1999. Pre-Alpine metamorphism in the Eastern Alps. Schweizerische mineralalogische und petrographische Mitteilungen, 79, 41-62.

Nowotny, A., Pestal, G. and Rockenschaub, M.J., 1993. Die Landecker Quarzphyllit- und Phyllitgneiszone als schwächer metamorpher Anteil des Silvrettakristallins. Jahrbuch der Geologischen Bundesanstalt, 135, 867-872.

Pfingstl, S., 2013. Tektonische und metamorphe Entwicklung des Seckauer Kristallins.- Masterarbeit, Naturwisenschaftliche Fakultät, Universität Graz, 121 pp.

Plasienka, D., 1995. Passive and active margin history of the northern Tatricum (Western Carpathians, Slovakia). Geologische Rundschau, 84, 746-760.

Rantitsch, G. and Russegger, B., 2000. Thrust-Related Very Low Grade Metamorphism Within the Gurktal Nappe Complex (Eastern Alps). Jahrbuch der Geologischen Bundesanstalt, 142, 219-225.

Ratschbacher, L., Frisch, W., Neubauer, F., Schmid, S. M. and Neugebauer, J., 1989. Extension in compressional orogenic belts. The eastern Alps. Geology, 17, 404-407.

Ratschbacher, L., Frisch, W., Linzer, H.-G. and Merle, O., 1991. Lateral Extrusion in the Eastern Alps. Part 2: Structural Analysis. Tectonics, 10, 257-271.

Scharbert, S., 1981. Untersuchungen zum Alter des Seckauer Kristallins. Mitteilungen der Gesellschaftder Geologie- und Bergbaustudenten Österreichs, 27, 173-188.

Schermaier, A., Haunschmid, B. and Finger, F., 1997. Distribution of Variscan I- and S-type granites in the Eastern Alps. a possible clue to unravel pre-Alpine basement structures. Tectonophysics, 272, 315-333.

Schmid, S. M., Fügenschuh, B., Kissling, E. and Schuster, R., 2004. Tectonic map and overall architecture of the Alpine orogen. Eclogae geologicae Helvetiae, 97, 93-117. http://dx.doi.org/10.1007/s00015-004-1113-x

Schmidt, W., 1921. Grauwackenzone und Tauernfenster. Jahrbuch der Geologischen Staatsanstalt, 71, 101-116.

Schubert, G., Berka, R. and Philippitsch, R. 2009. Karte der trinkbaren Tiefengrundwässer Österreichs 1:500.000 In: Arbeitstagung 2007 der Geologischen Bundesanstalt Blatt 67 Grünau im Almtal und Blatt 47 Ried im Innkreis: Linz, 7. - 11. Mai 2007.

Schwinner, R., 1929. Geröllführende Schiefer und andere Trümmergesteine aus der Zentralzone der Ostalpen. Geologische Rundschau, 20, 211-244.

Schwinner, R., 1951. Die Zentralzone der Ostalpen. In: X.F. Schaffer (ed.), Geologie von Osterreich, 2nd ed., pp. 105-232.

Schuster, R., Koller, F., Hoeck, V., Hoinkes, G. and Bousquet, R., 2004. Explanatory notes to the map: Metamorphic structure of the Alps - Metamorphic evolution of the Eastern Alps. Mitteilungen der Österreichischen Mineralogischen Gesellschaft, 149, 175-199.

Sölva, H., Grasemann, B., Thöni, M., Thiede, R. and Habler, G., 2005. The Schneeberg Normal Fault Zone: Normal faulting associated with Cretaceous SE- directed extrusion in the Eastern Alps (Italy/Austria). Tectonophysics, 401, 143-166. http://dx.doi.org/10.1016/j.tecto.2005.02.005

Stüwe, K. and Schuster, R., 2010. Initiation of Subduction in the Alps: Continent or Ocean? Geology 38, 175-178, http://dx.doi.org/10.1130/G30528.

Thöni, M. and Jagoutz, E., 1992. Some new aspects of dating eclogites in orogenic belts: Sm-Nd, Rb-Sr and Pb-Pb isotopic results from the Austroalpine Saualpe and Koralpe type-locality (Carinthia/Styria, SE Austria). Geochimica et Cosmochimica Acta, 56, 347-368.

Thöni, M. and Jagoutz, E., 1993. Isotopic constraints for eo-Alpine high-P metamorphism in the Austroalpine nappes of the Eastern alps: bearing on Alpine orogenesis. Schweize-rische mineralogische und petrograpische Mitteilungen, 73, 177-189.

Thöni, M., Miller, C., Blichert-Toft, J., Whitehouse, M. J., Konzett, J. and Zanetti, A., 2008. Timing of high-pressure metamorphism and exhumation of the eclogite type-locality (Kupplerbrunn-Prickler Halt, Saualpe, south-eastern Austria): constraints from correlations of the Sm-Nd, Lu-Hf, U-Pb and Rb-Sr isotopic systems. Journal of Metamorphic Geology, 26, 561-581. http://dx.doi.org/10.1111/j.1525-1314.2008.00778.x

Tollmann, A., 1977. Geologie von Österreich. Band 1. Die Zentralalpen. 766 pp, Deuticke, Wien.

Villa, I.M., 1998. Isotopic closure. Terra Nova, 10, 42-47.

von Blanckenburg, F. and Villa, I.M., 1988. Argon retentivity and argon excess in amphiboles from the garbenschists of the Western Tauern Window, Eastern Alps. Contributions to Mineralogy and Petrology, 100, 1-11.

von Blanckenburg, F., Villa, I.M., Baur, H., Morteani, G. and Steiger, R.H., 1989. Time Calibration of a PT-path from the Western Tauern Window, Eastern Alps: the problem of closure temperatures. Contributions to Mineralogy and Petrology, 101, 1-11.

Warren, C. J., Smye, A. J., Kelley, S. P. and Sherlock, S. C., 2012. Using white mica 40Ar/39Ar data as a tracer for fluid flow and permeability under high-P conditions: Tauern Window, Eastern Alps. Journal of Metamorphic Geology, 30, 63-80. http://dx.doi.org/10.1111/j.1525-1314.2011.00956.x

Wölfler, A., Kurz, W., Danisik, M. and Rabitsch, R., 2010. Dating of fault zone activity by apatite fission track and apatite (U-Th)/He thermochronometry: a case study from the Lavanttal fault system (Eastern Alps). Terra Nova, 22, 274-282.

Wolf, R. A., Farley, K. A. and Silver, L. T., 1996. Helium diffusion and low temperature thermochronometry of apatite. Geochimica et Cosmochimica Acta, 60, 4231-4240.

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Stefan PFINGSTL[1)], Walter KURZ[1)*)], Ralf SCHUSTER[2)] & Christoph HAUZENBERGER[1)]

[1)] Institut für Erdwissenschaften, Universität Graz, Heinrichstrasse 26 / Universitätsplatz 2, A- 8010 Graz; Member of NAWI Graz (an Inter University cooperation between the University of Graz and the Graz University of Technology), Austria;

[2)] Geologische Bundesanstalt, Neulinggasse 38, 1030 Wien, Austria;

[*)] Corresponding author, walter.kurz@uni-graz.at