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THE METAMORPHIC EVOLUTION OF THE AUSTRO-ALPINE NAPPES NORTH OF THE TAUERN WINDOW (INNSBRUCK QUARTZPHYLLITE COMPLEX - PATSCHERKOFEL CRYSTALLINE COMPLEX - KELLERJOCHGNEIS AND WILDSCHÖNAU SCHIST)

by

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The thesis submitted is closely related to the international geophysical ÖKORP-project which intends to provide a seismic reflection-profile through the Eastern Alps in the transect Bad Tölz Venice. Based on an agreement amongst the ÖKORP-coworkers petrological investigations along the Achensee - Zillertal - transect, located to the north of the Tauern-Window, will be carried out by the Institute of Mineralogy and Petrography at the University of Innsbruck.
Since there are only very few petrological and geochronological data available from this part of the Alps, it is the aim of this project to provide a set of these data especially from the nappes north of the Tauern Window, namely the Innsbruck Quartzphyllite, the Wildschönau Schist and the Schwazer Augengneiss (Kellerjochgneiss). This will help to correlate these Austroalpine units with other Austroalpine units, west of the Tauern Window (Ötztal-Stubai Crystalline Basement Complex, Patscherkofel Crystalline Complex) and will thus provide the basis of a geotectonic reconstruction of this part of the Eastern Alps.
The Eastern Alps are comprised of a complicated stack of imbricated nappes, which formed during the Alpine Orogeny. Within this nappe stack, the Austroalpine nappe complex forms the most dominant element, containing a multitude of geological units, with different geological histories. The scientific results of this project fill therefore a large data gap, since they provide important quantitative (structural, metamorphic) data from a number of geological units from the western part of the Eastern Alps (Innsbruck Quartzphyllite, Schwaz Augengneiss, Wildschönau Schists, Patscherkofel Crystalline Complex) where previously almost none of these data existed. The Innsbruck Quartzphyllite for instance has been treated as an undifferentiated mass for the last fifty years in terms of structural geology and metamorphic evolution.
Our data show that its structural and metamorphic evolution are much more complex than previously expected. The data also allow a direct comparison of the western Austroalpine nappes in terms of their metamorphic and structural history and this showed that the Schwaz Augengneiss couldn't be linked with the Ötztal-Stubai Crystalline Complex as previously thought.

Most likely, the Schwaz Augengneiss unit shows a strong similarity with the upper Austroalpine units (Greywacke Zone), which also contain meta-magmatic rocks of similar chemical composition and age of formation. Therefore the data contradict the long-standing hypothesis that the Schwaz Augengneiss is part of the so-called middle Austroalpine nappes of the Austroalpine nappe stack. The results of this study therefore allow to draw conclusions in terms of the paleogeographic distribution of the western Austroalpine nappes prior to the Eo-Alpine orogeny, because there has been a long-standing debate whether a so-called middle Austroalpine nappe system exists in the Eastern Alps. The attribution of the previously thought to be middle Austroalpine Schwaz Augengneiss to the upper Austroalpine nappe unit (Greywacke Zone) thus indicates, that in this part of the Eastern Alps, actually no middle Austroalpine nappes occur.
The dissertation was submitted as a paper-dissertation and was therefore divided into five separate chapters:

Chapter I
Structural evolution of the Austroalpine nappes in the northern Zillertal area (Tyrol, Eastern Alps)
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 (Schwazer Augengneiss), the Innsbruck Quartzphyllites and the Wildschönau Schists. Six stages of deformation could be distinguished. The first stage (D_1) is present only as a relic foliation, observed only in thin sections. In the Innsbruck Quartzphyllite the first deformation stage is also represented by isoclinal folds. The dominant foliation was formed in the second stage (D_2), which is the result of NW-SE oriented compression. This main ductile deformation event also is expressed by the formation of isoclinal folds. Associated shear bands indicate W-NW transport and thus D_2 is related to Cretaceous nappe stacking. The third ductile deformation stage (D_3) leads to the formation of open folds showing a vergence to the NE, indicating 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 semiductile 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 geochronological framework already available for this area, suggesting that nappe stacking of the Innsbruck Quartzphyllite, the Kellerjochgneiss and the Wildschönau Schist took place during the Late Cretaceous under middle to upper greenschist-facies conditions. Although the structural succession is similar in all three units, the available T-t paths of the units indicate that the Wildschönauer Schists underwent a slightly different Alpine evolution than the Kellerjochgneiss and the Innsbruck Quartzphyllite.

Chapter II
The metamorphic evolution of the Austroalpine nappes north of the Tauern Window (Tyrol, Eastern Alps) - Part I: Thermobarometry of the quartzphyllite basement units (Innsbruck Quartzphyllite Complex, Wildschönau Schists)
The Innsbruck Quartzphyllite Complex (IQP) and the Wildschönau Schists are part of the Austroalpine basement nappes north of the Tauern Window. The quartzphyllites from the westernmost IQP contain the mineral assemblage muscovite + plagioclase + quartz ± chlorite ± biotite ± garnet ± clinozoisite.

In the central part of the western IQP garnet-mica-schists with the mineral assemblage muscovite + chlorite + garnet + plagioclase occur. In contrast, the quartzphyllites of the eastern IQP, located in the Zillertal area, contain the mineral assemblage muscovite + albite + quartz + chlorite ± biotite, which is also the same mineral assemblage in the Wildschönau Schists.
Application of the garnet - biotite thermometer and the garnet - plagioclase - muscovite - quartz barometer, yields temperatures between 470°C and 525°C at pressures ranging from 6.6 to 8.9 kbar for samples from the western IQP underneath the Patscherkofel Crystalline Complex (PCC). Thermobarometric calculations with multi-equilibrium thermobarometry yield pressures of 8.2 - 10.5 kbar and temperatures of 458 - 523°C for the same samples. Based on phengite-chlorite-quartz thermobarometry (VIDAL, 2004, written comm.) P-T calculations resulted in 500 ± 50°C and 4.5 ± 2 kbar for the garnet mica schist of the central part of the western IQP. P-T estimates obtained with multi-equilibrium thermobarometry of a biotite-bearing quartzphyllite sample from the eastern IQP range from 3.8 - 5.9 kbar and 296 - 325°C. Lack of biotite in most of the samples of the eastern IQP prohibits calculations of invariant intersections. Consequently, only limiting pressure estimates of 3.5 to 6 kbar in a temperature range of 300 - 400°C, based on the reaction paragonite + celadonite = muscovite + albite + clinochlore + quartz + H_2O, can be obtained. Greenschist intercalations of the eastern IQP contain the mineral assemblage amphibole + biotite + clinozoisite + plagioclase + quartz. P-T conditions of 360 ± 45°C and 5.4 ± 2.0 kbar, based on the application of multi-equilibrium thermobarometry, were obtained. Lack of biotite in most of the samples of the Wildschönau Schist also prohibits calculations of invariant intersections. Thermobarometry results therefore were only available from one sample. Constraints performed with THERMOCALC v.3.1 (HOLLAND & POWELL, 1998) in the system KNFMASH yield pressures of 4.4 to 4.6 kbar and temperatures ranging from 316 to 336°C. P-T results performed by calculating intersections in the system KNFMASH and KFMASH with the program TWQ v.1.02 (BERMAN, 1992; MASSONNE, 1997) resulted in pressures of 4.8 and 5.1 kbar at temperatures between 295 and 300°C.
Geochronological constraints are indicative for the polymetamorphic nature of the IQP, namely a Permian and an Eo-Alpine metamorphic overprint, which is also in agreement with discontinuous chemical zoning in minerals such as plagioclase from the western IQP. In the eastern IQP, geochronological data also point to a pervasive Permian metamorphic event and local Eo-Alpine re-juvination. Based on microstructural evidence and the low temperature nature of the Eo-Alpine metamorphic overprint, it is thought that the P-T data from the eastern IQP therefore represent the Eo-Alpine metamorphic overprint. In contrast, geochronological data and thermobarometric data indicate that the Permian event is mainly manifested in the garnet-mica-schists in the central parts of the western IQP. Due to similar structural development and in consequence of also similar time temperature - evolution the thermobarometric data of the Wildschönau Schist exhibit the same Eo-Alpine tectonometamorphic origin as the Innsbruck Quartzphyllite and the Kellerjochgneiss.

Chapter III

The metamorphic evolution of the Austroalpine nappes north of the Tauern Window (Tyrol, Eastern Alps) - Part II: Thermobarometry of the orthogneiss and paragneiss basement units (Patscherkofel Crystalline Complex, Kellerjochgneiss)

The Kellerjochgneiss and the Patscherkofel Crystalline Complex are part of the Austroalpine basement nappes north of the Tauern Window. The Kellerjochgneiss contains the mineral

assemblage muscovite + plagioclase + chlorite + quartz ± biotite ± clinozoisite. It tectonically overlies the Innsbruck Quartzphyllite. The Patscher kofel Crystalline is mainly composed of mica schists with the mineral assemblage albite + plagioclase + muscovite + biotite + chlorite + quartz ± cloritoid ± garnet$_1$ ± garnet2 ± ilmenite ± clinozoisite ± staurolite ± margarite. Garnet$_1$ + staurolite represent Pre-Alpine relics, all other minerals are part of the Eo-Alpine mineral assemblage.

Multiequilibrium calculations of samples of the Kellerjochgneiss based on the programs TWQ v.1.02 (BERMAN, 1992; MASSONNE, 1997) and THERMOCALC v.3.01 (HOLLAND & POWELL, 1998) yield pressures in the systems KNFMASH and KFMASH yield pressures ranging from 3.2 to 6.8 kbar at temperatures in a range of 285 to 345°C. Average pressure of best fitted intersections performed with TWQ v.1.02 (BERMAN, 1992; MASSONNE, 1997) lie at pressures of 5.7 ± 0.4 kbar at temperatures of 297 ± 10°C. Best P-T constraints performed with THERMOCALC v.3.01 (HOLLAND & POWELL, 1998) yield average pressures in a range of 5.0 ± 1.0 kbar at temperatures of 311 ± 29°C. Furthermore calculations performed with the program stilp.mod2 (CURRIE & VAN STAAL, 1999) on the base of reactions between stilpnomelane + muscovite + chlorite + quartz yield average pressures in a range of 4.5 to 6.2 kbar at temperatures of 296 to 393°C.

Application of the garnet - biotite thermometer and the garnet - plagioclase - muscovite - quartz barometer, yields temperatures between 510°C and 570°C at pressures ranging from 9.5 to 12.2 kbar for most of the samples from the Patscherkofel Crystalline Complex (PCC). Thermobarometric calculations with multi-equilibrium programs such as TWQ v.1.02 and THERMOCALC v.3.02 (HOLLAND & POWELL, 1998) in the H2O present system KCNFMASH and the two H_2O absent systems KCNFMAS and KCFMAS yield pressures in a range of 7.3 - 11.5 kbar and temperatures of 454 - 585°C for the same samples. Based on calculations with the hbl-plag thermometer by HOLLAND & BLUNDY (1994) Variscan temperature estimates were performed. These temperatures are in a range of 563 to 650°C at presumed pressures of 5 klbar. Microstructural evidence and the low temperature nature of the Eo-Alpine metamorphic overprint probably indicate that the P-T data from the Kellerjochgneiss represent the Eo-Alpine metamorphic overprint. In contrast the PCC exhibits definitely higher metamorphic conditions, but due to similar structural development of the Innsbruck Quartzphyllite and the PCC and based on geochronological evidence the thermobarometric data are thought to represent Eo-Alpine metamorphic conditions. The P-T data and the mineral paragenesis from the PCC are in good correlation to southern parts of the Ötztal-Stubai Crystalline Complex.

Chapter IV

Thermobarometry in a stilpnomelane-garnet-bearing metapegmatite - constraints on the Eo - Alpine metamorphic evolution of the Austroalpine nappes north of the Tauern Window

The Kellerjochgneiss (Schwazer Augengneiss) is a polymetamorphic orthogneiss and is part of the Austroalpine basement nappes in the north of the Tauern Window. Within the Kellerjochgneiss a small, crosscutting, strongly deformed Ordovician meta-pegmatite dike occurs. The pegmatite crosscuts the gneiss discordantly and contains the mineral assemblage muscovite + plagioclase + chlorite + quartz + garnet$_1$ (Alm_{68} Sps_{27} Prp_3 Grs_2) + garnet$_2$ (Grs_{52} Alm_{33} Sps_{15}) ± stilpnomelane ± biotite. The magmatic protolith assemblage is comprised of relict K-feldspar, quartz and garnet1. Thermobarometry of the meta-pegmatite was performed with the Eo-Alpine assemblage garnet$_2$ + muscovite + chlorite + stilpnomelane + plagioclase + quartz.

Calculations of H_2O-absent intersections in the system [KCNFMAS] performed with the multi-equilibrium program THERMOCALC v. 3.1 (HOLLAND & POWELL, 1998) yield the best constrained P-T estimates of 5.7 ± 0.6 kbar and 314 ± 28°C. The application of TWQ v. 1.02 (BERMAN, 1992) for the H_2O-absent system [KCFMAS] and [CFMAS] using the paragenesis $garnet_2$ + biotite + chlorite + plagioclase + quartz ± clinozoisite yield pressures in a range of 5.9 to 6.6 kbar at temperatures between 314 and 325°C. Calculations of the P-T conditions by using the assemblage muscovite + chlorite + stilpnomelane + quartz yield slightly higher pressures of 6.4 to 7.3 kbar at temperatures of 300 - 325°C. Garnet - chlorite thermometry results in a large spread of temperatures ranging from 280 - 400°C. These rocks therefore provide additional – important information on the Eo-Alpine P-T conditions since most samples studied from the investigated nappes rarely show mineral assemblages suitable for thermobarometry.

Chapter V

Ba-Ti metasomatism in rodingites from the Austroalpine quartzphyllite units north of the Tauern Window (Eastern Alps, Schwaz, Tyrol)

At the southern border of the city of Schwaz (Tyrol, Austria) fine grained metarodingite bodies are tectonically embedded within quartzphyllites (Innsbruck Quartzphyllite or Wildschönau Schists). Lower-Ordovician ultramafic rocks have so far been only described in the Austroalpine nappes north of the Tauern Window from the Greywacke Zone and not from the Innsbruck Quartzphyllites. The mineral assemblage of the metarodingites is garnet + clinopyroxene + feldspar + biotite + titanite + clinozoisite + spinel + chlorite + calcite. Cr-bearing spinel is thought to represent a remnant of the protolith, pre-Alpine magmatic, ultramafic assemblage. BSE images and X-ray distribution images of biotites reveal a complex chemical zoning pattern with up to three different growth zones based on different TiO_2 and BaO contents. The TiO_2 contents range from 0.14 to 0.67 wt.%, the Ba contents range from 0.07 to 6.49 wt.%. Based upon thermobarometric data from biotite-bearing quartzphyllites and phase equilibrium constraints, this chemical zonation is thought to be a monitor for restricted, low $a(H_2O)$ fluids, leading to episodic minor element (Ti, Ba) transport during pre-Eo-Alpine and Eo-Alpine low-grade metamorphism/metasomatism.

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