

# New insights into the Cambrian to Permian evolution of the Austroalpine basement units of the Schladming Crystalline by U-Pb zircon geochronology and granitoid geochemistry

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## KEYWORDS:

Eastern Alps; pre-Alpine basement; Austroalpine unit; Silvretta-Seckau Nappe System; plutonic suite; tectono-magmatic evolution; paleogeographic situation

## Abstract

The Austroalpine unit comprises, among others, pre-Variscan and Variscan crustal fragments that were incorporated into several nappe systems during Alpine orogeny. These fragments therefore provide important insights that help fill in gaps in our knowledge regarding pre-Alpine paleogeography, tectonics and related magmatism. U-Pb zircon dating in combination with geochemical whole rock and zircon isotope data of meta-granitoids revealed three distinct pre-Alpine plutonic suites within the Austroalpine Schladming crystalline: (1) the Lignitz Plutonic Suite, (2) the Untertal Plutonic Suite and (3) the Eisenhut Plutonic Suite.

The mostly fine grained, highly fractionated meta-granitoids of the Lignitz Plutonic Suite have U-Pb ages ranging from  $480.1 \pm 6.4$  to  $501.2 \pm 6.6$  Ma and mean  $\varepsilon_{\text{Hf}}(t)$  values between 6.8 and 11.2. The Hf-isotopes partly hint to a mantle source with different degrees of crustal material assimilation during magma ascent. This suite is highly differentiated showing met- to peraluminous, calc-alkalic character. A suitable setting for this suite is an active margin along northern Gondwana during the Ceneric orogeny. The meta-granitoids to meta-granodiorites of the Untertal Plutonic Suite have U-Pb zircon ages between  $350.4 \pm 4.8$  Ma and  $370.4 \pm 4.9$  Ma and  $\varepsilon_{\text{Hf}}(t)$  values between 2.6 and 3.9. Ordovician ages and high  $\varepsilon_{\text{Hf}}(t)$  values of zircon cores indicate remelting of parts of the Lignitz Plutonic Suite. The Untertal Plutonic Suite is poorly fractionated having comparatively low  $\text{SiO}_2$  and high  $\text{Al}_2\text{O}_3$  contents. The rocks are strongly peraluminous, mostly magnesian and have calc-alkalic to alkali-calcic affinities. Emplacement of the Untertal Plutonic Suite can be related to a Devonian/early Carboniferous continental arc setting that formed during the early phases of the Variscan orogeny. The Eisenhut Plutonic Suite contains highly fractionated meta-granitoids with ages between  $261.0 \pm 3.5$  Ma and  $271.2 \pm 5.7$  Ma and  $\varepsilon_{\text{Hf}}(t)$  values of 2.7 to 5.2. Its more juvenile  $\varepsilon_{\text{Hf}}(t)$  values probably indicate renewed input of mantle-derived melts. This suite is peraluminous, ferroan and has a calc-alkalic to alkali-calcic character. It likely intruded during Permian lithospheric extension, following late Variscan orogeny that was accompanied by formation of horst-graben structures that finally resulted in the disintegration of Pangea.

## 1. Introduction

In the Earth's history, mountain building processes can be generally reconstructed by magmatic, metamorphic, and sedimentary records, even though large parts of an-

cient mountain belts are reworked within younger, more recent orogens. The Alps, for instance, incorporate various crustal fragments that derived from the earlier Variscan orogen, and even pre-Variscan elements are part

of the pre-Alpine basement within the Alpine orogenic edifice (e.g., 1998; Hoinkes et al., 1997, 1999; Siegesmund et al., 2007; Neubauer et al., 2002; Neubauer et al., 2022; Schulz et al. 2004; Nilius et al., 2016; Mandl et al., 2018; Huang et al., 2021; Kurz et al., 2024). The Austroalpine unit, for instance, comprises distinct Variscan intrusives as well as fragments that derived from the Ceneric orogen (e.g., Zurbriegen, 2017; Burda et al., 2021; Finger and Riegler 2023), and Late Cambrian and Early Ordovician crustal fragments that are attributed to the closure of the proto-Rheic -Quaidam ocean (e.g., von Raumer et al., 2002; von Raumer et al., 2003; Stampfli et al., 2002).

While many aspects of the pre-Alpine evolution, especially of the extra-Alpine European Variscan belt, are well studied (e.g., the Bohemian Massif: Finger et al., 2007; Schulmann et al., 2009, 2022; Žák et al., 2014), the overall structure and the plate tectonic evolution of the Variscan orogen still are ambiguously discussed. Several microcontinents/terrane (Franke, 2000; Nance et al., 1991; von Raumer et al., 2002, 2003, 2013; Stampfli et al., 2002; Franke et al., 2017; Neubauer et al., 2022; Finger and Riegler, 2023, 2025), which rifted off along distinct sectors of the northern Gondwana margin, were later incorporated and reworked by subsequent orogenic events, in particular during the Variscan and Alpine orogenies. Hence, their evolution, formation ages and deformation history are important for the paleogeographic and tectonic reconstruction of Variscan and Alpine tectonics.

In this study, we provide new geochronological and geochemical data from the basement of the Schladming crystalline as part of the Silvretta-Seckau Nappe System of the Eastern Alps to reconstruct its pre-Alpine magmatic and tectonic evolution. The meta-granitoids of the Schladming crystalline as well as the Seckau Complex were considered to be of Variscan origin for a long time. This assumption was mainly based on a few Rb-Sr whole rock (~350 Ma) and white mica ages (~330 Ma) (Scharbert, 1981; Frank et al., 1987; Schermaier et al., 1997). Recent studies of the Seckau Complex by Mandl et al. (2018) and of the Schladming crystalline by Huang et al. (2021, 2022), however, revealed that granitoid emplacement occurred during distinct tectonic phases and in distinct tectonic settings during Cambrian/Ordovician, Devonian, and Permian times. Hence, a re-evaluation of the pre-Alpine evolution of this part of the Eastern Alps and its magmatic and geochemical development is needed, since the distinct granitoids represent distinct magmatic events. While the paleogeographic and tectonic position of these basement complexes during the Alpine evolution is ascertained, their plate tectonic arrangement during Cambrian and Late Devonian to early Carboniferous times has so far remained unclear and also is the focus of this study.

Our new major, trace and rare earth element analyses together with U-Pb zircon dates and new Hf isotope data allow to better constrain three different granitoid suites and to explain their tectonothermal and magmatic evolution during the Ceneric and Variscan orogenies, and

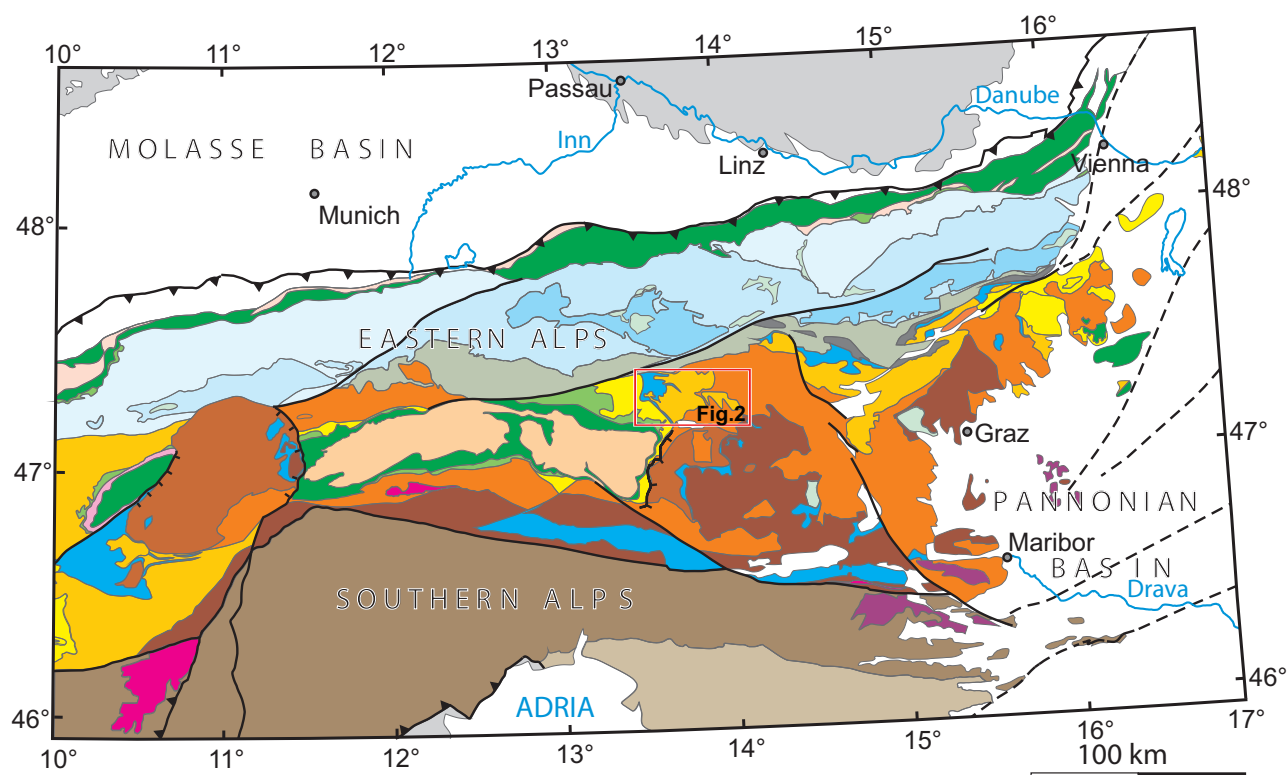
the subsequent Permian evolution. Moreover, the data allows us to correlate the Schladming crystalline with other pre-Alpine basement units and to reconstruct its pre-Alpine paleogeographic position.

## 2. Geological Overview

The Alpine-Carpathian orocline, and the Eastern Alps in particular (Fig. 1), expose nappe systems resulting from two orogenies. The Austroalpine and Southalpine units basically originated from the (south-) eastern Adriatic continental margin and incorporate pre-Alpine and pre-Variscan crust into several nappe stacks. The Austroalpine formed during the closure of the Meliata ocean as part of the Neotethys from Late Jurassic times onwards, which was followed by Eo-Alpine (Cretaceous) continental collision. In contrast, the Penninic and Sub-Penninic nappe systems formed by the closure of the Penninic (Piemont-Ligurian and Valais) ocean(s) between the Adriatic plate and Europe. The latter also affected the north(-western) Adriatic continental margin (Lower Austroalpine unit) (for summary, see Froitzheim et al., 2008; Schmid et al., 2004; Kurz et al., 2024).

The Austroalpine unit (Fig. 1) represents an Eo-Alpine nappe pile. Within that assembly, the Silvretta-Seckau Nappe System (Fig. 1) is dominated by a crystalline basement of pre-Alpine and (pre-) Variscan plutonic rocks, paragneisses, amphibolites, and remnants of Carboniferous to Triassic cover sequences. The crystalline basement formed during rifting and subduction processes from Precambrian to Carboniferous times encompassing the Variscan orogeny and the culmination of Pangea (e.g., Neubauer, 2002; von Raumer et al., 2013; von Raumer and Neubauer, 1993). Pre-Variscan units were in part affected by Variscan medium- to high-grade metamorphism (Neubauer et al., 1999). Parts of the basement units were subsequently intruded by Permian pegmatites, granitoids and gabbros (e.g., Thöni and Jagoutz, 1992; Thöni and Miller, 1997; Neubauer et al., 2022). During the Eo-Alpine evolution, these units were overprinted by low grade (sub-greenschist to greenschist facies) metamorphism (Schuster et al., 2013; Pfingstl et al., 2015).

The Schladming crystalline, the target of this study, is part of the Silvretta-Seckau Nappe System and is exposed along an approximately 50 km east-west trending mountain range (Fig. 2). It overlies the Lower Austroalpine Radstadt Nappe System, which is exposed along the northeastern margin of the Tauern Window (Fig. 1), to the southwest. It underlies the Tirolic-Noric Nappe System to the north, and phyllites and micaschists of the Koralpe-Wölz Nappe System in the east. It is further sub-divided into the Riesach Complex and the Golling Complex (Fig. 2). These comprise amphibolites within paragneisses, the latter being locally migmatized, as well as micaschists. These lithologies are collectively intruded by large volumes of met- to peraluminous granitoids (Mandl and Matura, 1995; Mandl et al., 2014). The Permian to Mesozoic cover includes quartz-phyllites, quartzites



#### Foreland of the Alps

- Foreland basins (Eocene-Quaternary sediments)
- European/Adriatic foreland (undifferentiated)

#### Alpine Orogen

- Intramontane basins and Quaternary sediments
- Pannonian magmatic rocks (Miocene-Quaternary)
- Periadriatic magmatic rocks (Eocene-Oligocene)
- Southalpine Unit/Dinarides

#### Austroalpine Unit

- Gosau Group sediments (Cretaceous-Paleogene)
- Upper Austroalpine Unit**
- Drauzug-Gurktal Nappe System
- Ötztal-Bundschuh Nappe System
- Juvavic Nappe System
- Tirolic-Noric Nappe System

- Bajuvaric Nappe System
- Veitsch-Silbersberg Nappe System
- Koralpe-Wölz Nappe System
- Silvretta-Seckau Nappe System
- Lower Austroalpine Unit**
- Lower Austroalpine Nappes

#### Penninic Unit

- Lower/Middle/Upper Penninic nappes

#### European Plate

- Helvetic and Ultrahelvetic nappes
- Subpenninic nappes

#### Tectonic Boundaries

- Alpine Frontal Thrust
- Normal faults
- Fault, Shear Zone (ap. located)

**Figure 1:** Geological map of the Eastern Alps showing the main tectonic subdivision based on Schmid et al. (2004) and Froitzheim et al. (2008). The red square refers to the area shown in Figure 2. The horizontally divided boxes show basement (below) and overlying cover rock (above) of a unit.

and meta-conglomerates that are mainly exposed in the northwestern part of the Schladming crystalline (Slapansky and Frank, 1987). These Permian to Lower Triassic meta-clastics are partly overlain by Middle to Upper Triassic dolomitic and calcitic marbles (Mandl et al., 2014). During Cretaceous (Eo-Alpine) times, these units were affected

by polyphase deformation including internal thrusting and folding (Neubauer and Frisch, 1993; Slapansky and Frank, 1987) that finally resulted in the formation of a frontal fold system (Slapansky and Frank, 1987; Mandl and Matura, 1995; Mandl et al., 2014 and references therein).

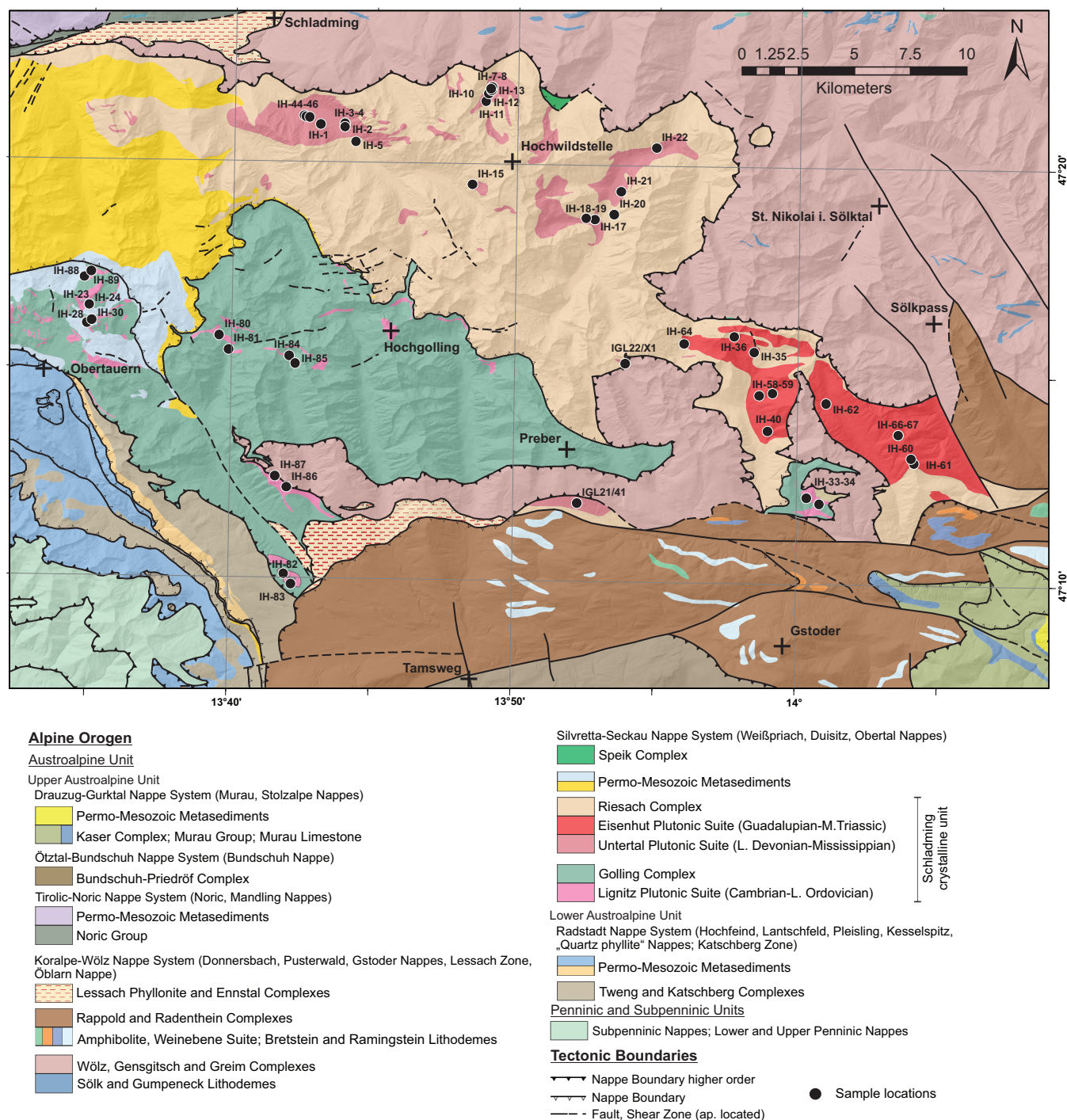


**Figure 2:** Tectonic map of the Schladming crystalline and adjacent Austroalpine units, based on Mandl et al. (2014); sample locations are indicated.

Schermaier et al. (1997) described late to post-Variscan granite and granodiorite intrusives from that part of the Eastern Alps and distinguished two geochemical groups of granitoids in the Schladming crystalline: I-type granitoids and A-type granitoids. Carboniferous K-Ar ages of muscovite (340 and 347 Ma) were interpreted as Carboniferous intrusion ages of pegmatites during a thermal peak of mid-Variscan metamorphism, whereas Permian K-Ar ages of 265 and 282 Ma were interpreted as cool-

ing ages (Hejl, 1984). More recent Ar-Ar muscovite data confirm Permian ages between 250 and 288 Ma and an Eo-Alpine age of 83 Ma in the Weißpriach Nappe of the Silvretta-Seckau Nappe System (Liu et al., 2001). These Ar-Ar ages are presumably related to crustal extension resulting in cooling due to exhumation.

Recent studies by Huang et al. (2021, 2022) identified Cambrian granodioritic gneisses of lower crustal origin (538 and 539 Ma) and Ordovician magmatic ages of pla-

gioclase gneisses (464 and 487 Ma). The magmatic protoliths of amphibolites of the western Schladming crystalline were dated to 531 and 495 Ma and presumably formed concomitantly with the plagioclase gneiss protolith as part of a bimodal magmatic event (Huang et al., 2021). U-Pb zircon ages of ca. 356–308 Ma were interpreted as metamorphic ages associated with Variscan crustal thickening (Huang et al., 2021). Another suite of amphibolites showed U-Pb zircon ages of ca. 480–490 Ma and ca. 380–390 Ma, while a suite of granitic orthogneisses yielded ages of 280–300 Ma (Chang et al., 2021). Huang et al. (2022) attributed granitic gneisses of Permian and Triassic magmatic age (261 and 244 Ma, respectively) to a back-arc setting related to the subduction of the Paleotethys Ocean.

### 3. Analytical methods

Major and trace element whole rock and zircon U-Pb, Hf isotope and trace element analyses were conducted at the Department of Earth Sciences – NAWI Graz Geocenter (NAWI Graz Central Lab for Water, Minerals and Rocks, University of Graz, Austria). Whole-rock chemistry of two samples was conducted by Activation Laboratories Ltd. (Ancaster, Ontario, Canada) following the analytical procedure termed ‘Code 4LITHO’ as described in detail in Reiser et al. (2024).

A total of 51 samples were collected from meta-granitic bodies occurring in the Schladming crystalline. All samples were studied petrographically with optical microscopy of thin sections. Major and selected trace element compositions were analyzed by X-ray fluorescence spectrometry. The samples were powdered and dried at 105 °C, followed by loss on ignition determination by igniting the powders at 1000 °C for one hour. One gram of each sample was mixed with 7g of Di-Lithium Tetraborate powder and fused to glass discs using a semi-automatic VAA-2 fusion machine from HD Electronics. The fused glass discs were analyzed with a Bruker® Tiger S8-II spectrometer with a Rh target X-ray tube, using a calibration with ca. 100 certified reference materials. The geochemical data were plotted using the software package GCDkit (Janoušek et al., 2006).

Rare earth element (REE) and trace element contents of the whole rock powders were acquired by dissolution of approximately 40mg sample powder in a mixture of 1 ml double distilled HNO<sub>3</sub> (15N) and 2 ml suprapure HF (28N) in closed Teflon beakers on a hot plate at 200 °C for 48 hours. This was followed by evaporation and consecutive re-dissolution in 1 ml HNO<sub>3</sub> (15N) and 1 ml HCL (12N). Each sample was taken up with 2%(v/v) HNO<sub>3</sub> to achieve a ~1500x dilution for analysis with an Agilent 7700 quadrupole ICP-MS at the Department of Chemistry, University of Graz. Solutions of BHVO-2 (USGS) and IV-ICPMS-71A (Inorganic Venture) were used for calibration and the reference materials JR-2, BCR-2, GS-N, MRH1 and MTA-1 were used for monitoring accuracy. The detection limit was ca. 0.01 µg/g for most trace element measurements.

Zircon rare earth element (REE) and selected trace elements were determined in 6 samples for 15 zircons each, using a quadrupole Agilent 7500 CX mass-spectrometer connected to an ESI NWR 193nm laser ablation system at the NAWI Graz Central Lab for Water, Minerals and Rocks (NAWI Graz Geocenter, Graz University of Technology). The element analysis was done with a 25 µm beam diameter, a ~4 J/cm<sup>2</sup> fluence, 8 Hz repetition rate, a helium flow of 0.75 l/min and a laser warm-up time of 25 s and 45 s of ablation. NIST 612 glass (Jochum et al., 2011) was used for standardization and NIST 610 (Jochum et al., 2011), zircon 91500 (Wiedenbeck et al., 1995) and GZ8 (Nasdala et al., 2018) were used for quality control and to assess reproducibility. For data reduction we used the “GLITTER” software package (Griffin, 2008). The software package GCDkit (Janoušek et al., 2006) was used to display the geochemical data set. The Ce anomaly ( $Ce/Ce^* = Ce_N / (\sqrt{La_N \cdot Pr_N})$ ) and the Eu anomaly ( $Eu/Eu^* = Eu_N / (\sqrt{Sm_N \cdot Gd_N})$ ) were calculated using the chondrite values of Cesare et al. (2002) and Sun and McDonough (1989).

Thirty of the investigated samples were selected for U-Pb zircon dating based on spatial distribution, major element variation and petrography of the meta-granitoids. U-Pb zircon dating was conducted with an ESI NWR 193nm laser ablation system connected to a Nu Plasma II multi-collector inductively coupled plasma mass spectrometer (LA-MC-ICP-MS) or an Agilent 7900 quadrupole ICP-MS (LA-ICP-MS). The samples were crushed and sieved to a grain size smaller than 2 mm. This was followed by heavy mineral separation through gold panning and random hand picking of zircons under a binocular microscope. The zircons were embedded in epoxy resin and polished to expose the grain centers. Cathodoluminescence (CL) pictures of the single zircon grains were taken with a ZEISS DSM 982 (Gemini) scanning electron microscope (SEM), a JEOL JXA-8530F Plus field emission microprobe and a VEGA/TESCAN scanning electron microscope, equipped with an Oxford detector, to visualize the internal growth structures of the zircons. The conditions for the LA-MC-ICP-MS measurements can be found in Supplementary Table 1. Zircon GJ1 (Jackson et al., 2004) was used as primary reference material and the zircons 91500 (Wiedenbeck et al., 1995), M257 (Nasdala et al., 2008) and Plesovice (Sláma et al., 2008) were used as secondary reference materials to verify the reproducibility and accuracy of the measurements. For data reduction, the IOLITE v. 3.71 as well as v.4.10 software and the X\_U-Pb\_Geochron4 data reduction scheme (Paton et al., 2010, 2011) were used. No common lead correction was performed. Concordia diagrams and weighted mean age calculations were done with Isoplot R online (Vermeesch, 2018). Only zircons with less than 2% discordance were used for further age interpretations. Systematic uncertainties were propagated to the uncertainty of the calculated weighted mean ages (Horstwood et al., 2016). The U-Pb isotope data of the zircon reference materials and all samples are presented in Supplementary Tables 1 and 2A–B.

| Sample   | Lithology                 | N               | E               | Suite                   |
|----------|---------------------------|-----------------|-----------------|-------------------------|
| IH-23    | Plagioclase orthogneiss   | 47° 16' 29.496" | 13° 34' 57.612" | Lignitz Plutonic Suite  |
| IH-24    | Plagioclase orthogneiss   | 47° 16' 29.496" | 13° 34' 57.612" |                         |
| IH-28    | Plagioclase orthogneiss   | 47° 16' 03.324" | 13° 34' 53.220" |                         |
| IH-30    | Plagioclase orthogneiss   | 47° 16' 07.752" | 13° 35' 03.408" |                         |
| IH-33    | Granitic orthogneiss      | 47° 12' 05.400" | 14° 00' 21.204" |                         |
| IH-34    | Granitic orthogneiss      | 47° 11' 56.832" | 14° 00' 48.528" |                         |
| IH-80    | Granitic orthogneiss      | 47° 15' 49.032" | 13° 39' 34.092" |                         |
| IH-81    | Granitic orthogneiss      | 47° 15' 28.332" | 13° 39' 54.036" |                         |
| IH-82    | Granitic orthogneiss      | 47° 10' 06.420" | 13° 41' 58.308" |                         |
| IH-83    | Granodioritic orthogneiss | 47° 09' 51.696" | 13° 42' 13.212" |                         |
| IH-84    | Granitic orthogneiss      | 47° 15' 20.644" | 13° 42' 02.592" |                         |
| IH-85    | Granitic orthogneiss      | 47° 15' 09.540" | 13° 42' 15.480" |                         |
| IH-86    | Granitic orthogneiss      | 47° 12' 10.872" | 13° 42' 00.972" |                         |
| IH-87    | Granitic orthogneiss      | 47° 12' 26.928" | 13° 41' 36.672" |                         |
| IH-88    | Plagioclase orthogneiss   | 47° 17' 09.459" | 13° 34' 46.959" |                         |
| IH-89    | Plagioclase orthogneiss   | 47° 17' 18.049" | 13° 35' 00.769" |                         |
| IH-1     | Granodioritic orthogneiss | 47° 20' 56.428" | 13° 43' 53.385" | Untertal Plutonic Suite |
| IH-2     | Granitic orthogneiss      | 47° 20' 56.428" | 13° 43' 53.385" |                         |
| IH-3     | Granodioritic orthogneiss | 47° 20' 51.370" | 13° 43' 53.248" |                         |
| IH-4     | Granitic orthogneiss      | 47° 20' 51.370" | 13° 43' 53.248" |                         |
| IH-5     | Granitic orthogneiss      | 47° 20' 30.264" | 13° 44' 17.448" |                         |
| IH-7     | Granodioritic orthogneiss | 47° 21' 51.804" | 13° 49' 04.058" |                         |
| IH-8     | Granodioritic orthogneiss | 47° 21' 51.804" | 13° 49' 04.058" |                         |
| IH-10    | Granitic orthogneiss      | 47° 21' 31.507" | 13° 48' 51.994" |                         |
| IH-11    | Granodioritic orthogneiss | 47° 21' 42.530" | 13° 48' 56.800" |                         |
| IH-12    | Granodioritic orthogneiss | 47° 21' 46.566" | 13° 49' 03.230" |                         |
| IH-13    | Granodioritic orthogneiss | 47° 21' 49.399" | 13° 49' 01.682" |                         |
| IH-15    | Granodioritic orthogneiss | 47° 19' 30.864" | 13° 48' 25.380" |                         |
| IH-17    | Monzodioritic orthogneiss | 47° 18' 42.728" | 13° 52' 46.200" |                         |
| IH-18    | Granitic orthogneiss      | 47° 18' 42.728" | 13° 52' 46.200" |                         |
| IH-19    | Granitic orthogneiss      | 47° 18' 44.424" | 13° 52' 27.660" |                         |
| IH-20    | Granodioritic orthogneiss | 47° 18' 50.472" | 13° 53' 26.592" |                         |
| IH-21    | Granodioritic orthogneiss | 47° 19' 23.592" | 13° 53' 40.956" |                         |
| IH-22    | Granodioritic orthogneiss | 47° 20' 26.844" | 13° 54' 54.612" |                         |
| IH-43    | Granodioritic orthogneiss | 47° 21' 06.717" | 13° 42' 26.881" |                         |
| IH-44    | Granitic orthogneiss      | 47° 21' 05.400" | 13° 42' 30.960" |                         |
| IH-45    | Granodioritic orthogneiss | 47° 21' 04.896" | 13° 42' 38.052" |                         |
| IH-46    | Granitic orthogneiss      | 47° 20' 54.600" | 13° 43' 01.632" |                         |
| IGL22/X1 | Dioritic orthogneiss      | 47° 15' 14.400" | 13° 53' 58.600" |                         |
| IGL21/41 | Granitic orthogneiss      | 47° 11' 53.900" | 13° 52' 15.500" |                         |
| IH-35    | Granitic orthogneiss      | 47° 15' 34.164" | 13° 58' 27.048" | Eisenhut Plutonic Suite |
| IH-36    | Granitic orthogneiss      | 47° 15' 56.448" | 13° 57' 44.712" |                         |
| IH-40    | Granitic orthogneiss      | 47° 13' 40.584" | 13° 58' 57.252" |                         |
| IH-58    | Granitic orthogneiss      | 47° 14' 31.776" | 13° 58' 38.316" |                         |
| IH-59    | Granitic orthogneiss      | 47° 14' 35.848" | 13° 59' 07.332" |                         |
| IH-60    | Granitic orthogneiss      | 47° 12' 56.340" | 14° 04' 08.328" |                         |
| IH-61    | Granitic orthogneiss      | 47° 13' 03.324" | 14° 04' 01.776" |                         |
| IH-62    | Granitic orthogneiss      | 47° 14' 21.408" | 14° 01' 00.552" |                         |
| IH-64    | Granitic orthogneiss      | 47° 15' 45.288" | 13° 55' 58.152" |                         |
| IH-66    | Granitic orthogneiss      | 47° 13' 37.020" | 14° 03' 33.984" |                         |
| IH-67    | Granitic orthogneiss      | 47° 13' 37.020" | 14° 03' 33.984" |                         |

**Table 1:** Sample list and sample location coordinates.

In-situ Hf isotope analysis was performed with a Nu Plasma II MC-ICP-MS coupled to an ESI 193nm Laser. For the measurements, a 35 µm spot diameter, a 10 Hz repetition rate and a sample fluence of ~5.4 J/cm<sup>2</sup> were used. After 25 s of laser warm-up, the zircons were ablated for 60 s. Ablation and transport occurred in a 750 ml/min He gas flow that was mixed with 0.75 l/min Ar before introduction to the torch. All isotopes from mass 171 to mass 180 were measured simultaneously on Faraday cups. Hafnium mass bias was corrected by using an exponential law and a value of 0.7325 for <sup>179</sup>Hf/<sup>177</sup>Hf (e.g., Patchett and Tatsumoto, 1981). An Yb mass bias factor was determined using an exponential law and <sup>173</sup>Yb/<sup>171</sup>Yb = 1.132685 (Chu et al., 2002). The Lu mass bias factor was assumed to be the same as that of Yb. Interference correction on <sup>176</sup>Hf was done by measuring and subtracting Lu and Yb isotopes using <sup>173</sup>Yb/<sup>176</sup>Yb = 0.796218 and <sup>175</sup>Lu/<sup>176</sup>Lu = 0.02655 (Chu et al., 2002; Vervoort et al., 2004). Data reduction was done offline with Lolite v. 3.71 and a customized Hf isotope DRS (Paton et al., 2010). Data reporting follows the recommendations of Fisher et al. (2014). Approximately 30–50 s of the signal were selected for isotope ratio calculation. CL images were used to place the Hf spots within the same crystal domain as the U-Pb spots. More information on the method and quality control is presented in Gallhofer et al. (2023). A systematic offset between the measured and the true <sup>176</sup>Hf/<sup>177</sup>Hf of the reference zircons was corrected by normalizing to Mud Tank zircon. After offset correction, the mean <sup>176</sup>Hf/<sup>177</sup>Hf of the reference zircons were in good agreement with their published values (Supplementary Table 3).

Initial <sup>176</sup>Hf/<sup>177</sup>Hf and εHf were calculated with the <sup>176</sup>Lu decay constant λ = 1.867\*10<sup>-11</sup> yr<sup>-1</sup> of Söderlund et al. (2004), CHUR values (<sup>176</sup>Hf/<sup>177</sup>Hf = 0.282785 and <sup>176</sup>Lu/<sup>177</sup>Hf = 0.0336) of Bouvier et al. (2008) and the corresponding U-Pb zircon dates. The uncertainty in initial εHf was calculated with the algorithms of Ickert (2013). The εHf(t) values were calculated using the corresponding U-Pb zircon dates, and two stage Hf model ages (T<sub>DM</sub>) were calculated assuming an average continental crust <sup>176</sup>Lu/<sup>177</sup>Hf ratio of 0.012 (Spencer et al., 2020) and DM values (<sup>176</sup>Lu/<sup>177</sup>Hf = 0.03976 and <sup>176</sup>Hf/<sup>177</sup>Hf = 0.283238) of Vervoort et al. (2018). The Hafnium isotope data of all samples and zircon reference materials are presented in Supplementary Table 3.

#### 4. Lithological units and petrography

Metapelites, mainly paragneisses and (garnet-) micaschists form the crystalline basement of the Schlading crystalline. These were intruded by large volumes of granitoids, now observed as meta-granitoids. The meta-igneous rocks mostly have felsic compositions and granitic to granodioritic character. They commonly appear leucocratic in the field and vary from slightly to strongly deformed. Based on their petrographical, geochemical and geochronological characteristics, the meta-granitoids were subdivided into three plutonic suites

(Fig. 2): (1) the Lignitz Plutonic Suite, (2) the Untertal Plutonic Suite and (3) the Eisenhut Plutonic Suite. Fifty-one meta-granitoid samples were taken from several exposures within the Schlading crystalline. The related sample locations are shown in Figure 2 and Table 1.

##### 4.1. Lignitz Plutonic Suite

The meta-igneous rocks of the western part of the Schlading crystalline (from now on referred to as Lignitz Plutonic Suite) occur within the Golling Complex. They occur as small, dismembered slivers exclusively in the western part of the Schlading crystalline, except for two samples that were collected from its southeastern part. The slivers tend to be aligned in a west-east direction. The rocks are commonly leucocratic meta-granites and are beige to light greyish colored. Based on their appearance and geochemical characteristics, the meta-granitoids can be sub-divided into two sub-types: fine-grained plagioclase orthogneisses and porphyritic orthogneisses.

In the northern occurrences of the Lignitz Plutonic Suite, the fine-grained plagioclase orthogneisses appear strongly foliated and do not show a relict plutonic, but rather gneissose texture (IH23-IH30, IH88–89) (Fig. 3a). Plagioclase comprises about 30 to 40 vol% of the samples, is generally hypidiomorphic, shows polysynthetic twinning and ranges in size from 0.2 to 0.5 mm. The fine-grained groundmass is composed of quartz (~50 vol%) and white mica (up to 10 vol%). Potassium feldspar is less common. Biotite, if present, forms small flakes degrading mostly into chlorite. A distinct foliation and gneissose structure are common.

In the southern occurrences of the Lignitz Plutonic Suite (IH33–34, IH80-IH87) (Fig. 3b), the rocks are coarse-grained and have higher quartz contents of up to 65 vol%. Potassium feldspar is common in these samples (~10 vol%) and occurs together with larger biotite flakes which are often altered to chlorite. White mica is still present, however, in a low amount (~5 vol%). A foliation is not as clearly developed as in the samples from the northern occurrences and a porphyritic texture is more common. Both types contain opaque phases and accessory minerals like apatite and zircon.

##### 4.2. Untertal Plutonic Suite

The meta-igneous rocks of the northern part of the Schlading crystalline (from now on referred to as Untertal Plutonic Suite) occur within the Riesach Complex and comprise a wider variety in composition and texture compared to the other suites. This suite includes meta-granites to meta-granodiorites and one sample of monzodioritic character. The rocks appear greyish in the field and can be subdivided into two sub-types: an equigranular holocrystalline and a porphyritic variety.

The granitoids in the northwestern occurrences (IH1-IH5 and IH43–IH46) (Fig. 3c–d) are characterized by their

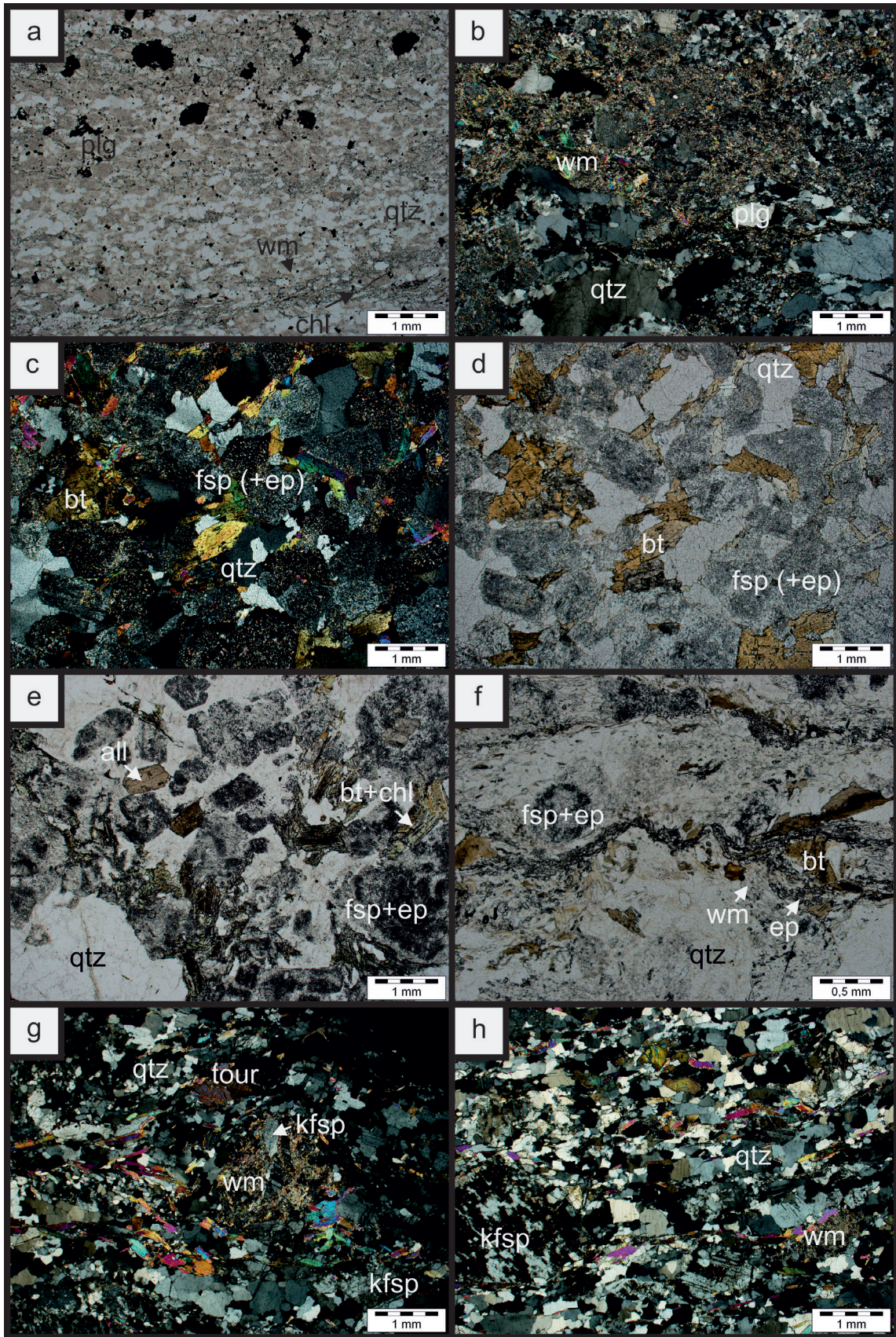


**Figure 3:** Thin section photomicrographs of representative samples. **(a)** and **(b)** Granitic gneiss IH89 and IH81 of the Lignitz Plutonic Suite. **(c)** and **(d)** Granitic gneiss IH3 of the Untertal Plutonic Suite. **(e)** and **(f)** Granodioritic gneiss IH8 and IH13 of the Untertal Plutonic Suite. **(g)** and **(h)** Granitic gneiss IH35 and IH67 of the Eisenhut Plutonic Suite. Abbreviations: wm: white mica, plg: plagioclase, qtz: quartz, chl: chlorite, ep: epidote, bt: biotite, fsp: feldspar, all: allanite, kfsp: potassium feldspar.

equigranular texture. The main constituents are quartz (40–50 vol%), potassium feldspar (15–20 vol%) and plagioclase (~30 vol%). K-feldspar, quartz, plagioclase and also biotite have an average size of 1 to 2 mm. Plagioclase shows typical polysynthetic twinning, and quartz shows mainly bulging recrystallization. The sagenitic biotite grains are subhedral and exhibit intense pleochroism. The feldspars of this sub-type are commonly altered and replaced by epidote and white mica. Less common phases are allanite and titanite. Secondary chlorite is frequently observed in all samples, as are the accessories apatite, zircon, rutile and opaque phases.

The samples of the eastern occurrences (IH15–IH22) (Fig. 3e–f) show a porphyritic texture and a well-developed foliation. In some cases, they are strongly sheared and may be described as augengneiss. Quartz (40–50 vol%), potassium feldspar (~15 vol%) and plagioclase (25–30 vol%) are the main minerals. The K-feldspar grains are mostly un-altered, the quartz and plagioclase grains are smaller and often elongated. Internal quartz microstructures indicate dynamic recrystallization, mainly subgrain rotation. White mica within the matrix, allanite, small biotite grains and secondary chlorite are common. These samples also comprise rare, small garnets.

Samples in the southern occurrences of the Riesach Complex (IGL22/X1, IGL21/41) show a porphyritic texture with hornblende (up to 10%) as an additional main phase. Sometimes a variation in grain-size from medium to fine grained is observed. Especially sample IGL21/41 has two generations of K-feldspar – an altered type replaced by white mica and big crystals with myrmekitic texture and twinning. Because of their general texture and geochemical characteristics, these granitoids fit to the samples from the northern occurrences.

#### 4.3. Eisenhut Plutonic Suite

The term Eisenhut Plutonic Suite is used for the granitoids from the southeastern part of the Schladming crystalline occurring within the Riesach Complex. These rocks have mainly leucocratic appearance in the field and are of granitic composition. They are fine- to medium grained with average grain sizes between 0.3 and 1 mm. The average composition is 40–50 vol% quartz, 30–35 vol% potassium feldspar and 15–20 vol% plagioclase. Some samples show equigranular texture, while others have an augengneiss fabric; both types are strongly foliated. The augengneisses are characterized by their large K-feldspar grains and smaller elongated grains of quartz and plagioclase (Fig. 3g). The feldspars sometimes show myrmekitic textures and growth twins. Quartz is often recrystallized, mostly showing subgrain rotation. Small flakes of biotite, frequently altered to chlorite, are common. Additional mineral phases are epidote, white mica, allanite and occasionally titanite, accessory apatite, magnetite and zircon, and distinct garnet grains of varying size (0.5 to 2 mm) as well as large tourmaline grains (up to 2 mm) (Fig. 3h).

### 5. U-Pb zircon ages and zircon geochemistry

The zircons of the three plutonic suites of the Schladming crystalline have distinct appearances (Fig. 4) and differ in their U-Pb ages. Thirty samples were dated by measuring 36 zircons of each sample. The zircon dates of each plutonic suite are shown in Concordia and weighted mean age diagrams (Figs. 5–7). Weighted mean  $^{206}\text{Pb}/^{238}\text{U}$  ages were calculated for every sample using only single zircon dates that are less than 2% discordant. Where possible, mean ages were calculated for groups of zircons forming more or less statistically robust plateaus (MSWD c. 1–2.5). However, few samples show a spread in ages along the Concordia curve. A spread towards younger dates may be due to lead loss during a later metamorphic overprint. In such cases, younger dates were excluded from mean age calculation. Zircon dates older than a main population (sample IH23; Fig. 5) may represent inherited cores or derive from a metamorphic overprint of precursor material slightly preceding partial melting and major magmatic activity. A summary of all weighted mean ages and their total 2SE uncertainties including systematic uncertainties is presented in Table 2. Elevated MSWD values (>2.5) may partly be explained by low uncertainties on single zircon dates and/or by a later metamorphic overprint resulting in lead loss and, hence, younging of dates and smearing along the Concordia curve. The Th/U ratio of most zircons is above 0.1 indicating a magmatic origin of these zircons (e.g., Rubatto, 2002).

#### 5.1. U-Pb zircon ages

##### 5.1.1. Lignitz Plutonic Suite

The zircons are small and grain sizes typically vary between 50 and 100  $\mu\text{m}$ , they show oscillatory zoning and contain only a few xenocrystic cores (Fig. 4). Their habitus is mostly euhedral with a compact, square and less elongated shape compared to zircons from the other suites. The aspect ratio lies between 1:2 and 1:3. The zircons are mostly colorless to slightly beige. The crystals are often cracked and contain many inclusions. They occasionally have a metamictic/dull appearance and are rarely affected by recrystallization.

The felsic meta-granitoids of the Lignitz Plutonic Suite yield Cambrian (Miaolingian to Furongian) U-Pb zircon ages between  $480.1 \pm 6.4$  and  $501.2 \pm 6.6$  Ma (Fig. 5). The samples from the westernmost occurrences of the Lignitz Plutonic Suite, north of Obertauern, have weighted mean  $^{206}\text{Pb}/^{238}\text{U}$  ages of  $501.0 \pm 6.7$  Ma (IH23),  $498.1 \pm 6.7$  Ma (IH24),  $494.7 \pm 6.6$  Ma (IH 28) and  $495.9 \pm 6.6$  Ma (IH 30). One sample of the Lignitz Plutonic Suite from the eastern part of the Schladming crystalline (IH34) has a weighted mean  $^{206}\text{Pb}/^{238}\text{U}$  age of  $498.6 \pm 6.7$  Ma. The samples located west of Hochgolling yield weighted mean ages of  $501.2 \pm 6.6$  Ma (IH81) and  $497.1 \pm 6.6$  Ma (IH84). Weighted mean ages of  $480.1 \pm 6.4$  Ma (IH83) and  $498.4 \pm 6.6$  Ma (IH87) were obtained from the southwestern occurrences of the Lignitz Plutonic Suite between Hochgolling and Tamsweg.



**Figure 4:** Representative CL images of zircons of the Lignitz Plutonic Suite, the Untertal Plutonic Suite and the Eisenhut Plutonic Suite. LA-MC-ICP-MS spots of Pb/U (white circles) and Hf (dashed white circles) isotope measurements and the corresponding  $^{206}\text{Pb}/^{238}\text{U}$  dates are indicated.

### 5.1.2. Untertal Plutonic Suite

Zircons of this suite have a mostly euhedral and long-prismatic habitus and show a complicated internal structure (Fig. 4). The aspect ratios lie between 1:3 and 1:4 and the zircons are mostly colorless to slightly pinkish. The grain size varies between 50 and 150  $\mu\text{m}$ . Some zircons are cracked and contain inclusions, while others appear metamictic. The CL images show oscillatory zoning and some zircons (IH02, IH 05) contain inherited cores and show late to post-magmatic recrystallization structures (cf. Corfu, 2003) (Fig. 4). If metamorphic rims are present, they are only a few  $\mu\text{m}$  thick, homogenous and too thin for in-situ analysis. The zircons from this suite tend to have very dark zones in CL images (Fig. 4) indicating enriched U contents.

The samples yield Late Devonian/Mississippian weighted mean  $^{206}\text{Pb}/^{238}\text{U}$  ages between  $350.4 \pm 4.8$  Ma and  $370.4 \pm 4.9$  Ma (Fig. 6). Samples from the western occurrences of the Untertal Plutonic Suite (Fig. 6) yield zircon ages of  $357.5 \pm 4.8$  Ma (IH1),  $354.3 \pm 4.7$  Ma (IH2),  $370.4 \pm 4.9$  Ma (IH3) and  $356.2 \pm 4.7$  Ma (IH5). In the northernmost occurrences of the Untertal Plutonic Suite, weighted mean ages are  $361.3 \pm 4.8$  Ma (IH7),  $366.6 \pm 4.9$  Ma (IH8),  $358.5 \pm 4.7$  Ma (IH11),  $358.5 \pm 4.8$  Ma (IH12) and  $359.4 \pm 4.8$  Ma (IH13). Sample IH15 yields a weighted mean  $^{206}\text{Pb}/^{238}\text{U}$  age of  $350.4 \pm 4.8$  Ma. In the easternmost occurrences of the Untertal Plutonic Suite, ages of  $354.6 \pm 4.7$  Ma (IH17),  $359.7 \pm 4.8$  Ma (IH19),  $355.7 \pm 4.9$  Ma (IH20),  $362.3 \pm 5.0$  Ma (IH21) and  $358.2 \pm 4.8$  Ma (IH22) were obtained. The samples from the southern occurrences of the Untertal Plutonic Suite show similar ages of  $358.3 \pm 4.8$  Ma (IGL22/X1). Zircon cores, if present, yield Cambrian dates (ca. 500 Ma) (Fig. 6) (Table 2) that are like the zircon ages of the Lignitz Plutonic Suite.

### 5.1.3. Eisenhut Plutonic Suite

The samples from the southeastern part of the Schladming crystalline contain zircon grains with sizes between 100 and 200  $\mu\text{m}$ . The zircons are euhedral with pronounced prismatic shapes and aspect ratios between 1:2 and 1:3. They are mostly colorless with a few slightly pinkish crystals and have fewer cracks and broken grains than the other two groups described above. The zircons commonly do not have a metamictic appearance and scarcely show xenocrystic cores. They are mostly oscillatory zoned with few internal recrystallization textures and no evidence of metamorphic overgrowth (Fig. 4). In one sample from the southern occurrences of the Riesach Complex (IGL21/41), two populations of zircons are obvious: elongated crystals with high aspect ratios, bright oscillatory zones and low Pb, Th, U contents as well as euhedral prismatic ones with low aspect ratios, U-rich dark zoning and high Pb, Th, U contents. The Th/U values are between 0.076–0.443 in the younger zircon generation and between 0.215–0.685 in the older one, interpreted as magmatic emplacement ages with inheritance of older grains. The dates from the older population yield  $357.2 \pm$

5.4 Ma (Fig. 6), indicating inheritance of zircons from the Untertal Plutonic Suite. The younger zircon population of sample IGL21/41 shows an age of  $271.2 \pm 5.7$  Ma (Fig. 7).

Four additional samples yield slightly younger Permian ages (Fig. 7). A sample from the western occurrence of the Eisenhut Plutonic Suite has a weighted mean  $^{206}\text{Pb}/^{238}\text{U}$  age of  $263.0 \pm 3.5$  Ma (IH58). Meta-granitoids from the eastern section of the Eisenhut plutonic Suite (IH61 and IH66) yield zircon mean ages of  $263.4 \pm 3.5$  Ma and  $262.3 \pm 3.5$  Ma, respectively. A sample from the northernmost occurrence yields an age of  $261.0 \pm 3.5$  Ma (IH64).

## 5.2. Zircon Hf isotope data

Seven samples were selected for zircon Hf isotope analysis: IH24 and IH81 from the Lignitz Plutonic Suite, IH1, IH5 and IH8 from the Untertal Plutonic Suite and IH58 and IH66 from the Eisenhut Plutonic Suite. A summary of the Hf isotope data is shown in Table 2, and the complete data set is presented in Supplementary Table 3.

In the  $\epsilon\text{Hf}(t)$  isotope evolution diagram (Fig. 8a), all zircons plot below the depleted mantle (DM) and above the Chondritic Uniform Reservoir (CHUR) evolution lines. When depleted mantle model ages ( $T_{\text{DM}}$  ages) are plotted against the U-Pb zircon ages, one sample of the Lignitz Plutonic Suite (IH24) falls close to the 1:1 line, while all other zircons have  $T_{\text{DM}}$  ages that are older than their U-Pb ages (Fig. 8b).

The Hf isotopes of the zircons from the two Lignitz Plutonic Suite samples (ca. 500 Ma) are slightly offset,  $^{176}\text{Hf}/^{177}\text{Hf}_i$  ranges from 0.282614 to 0.282751 in IH81, and from 0.282715 to 0.282845 in IH24. The mean  $\epsilon\text{Hf}(t)$  values are  $6.8 \pm 2.7$  (IH81) and  $11.2 \pm 2.6$  (IH24). The calculated  $T_{\text{DM}}$  ages of these Cambrian magmatic rocks range from 717 to 982 Ma in IH81 and from 548 to 781 Ma in IH24 (Fig. 8b). The  $^{176}\text{Hf}/^{177}\text{Hf}_i$  of the three samples of the Late Devonian / early Carboniferous Untertal Plutonic Suite overlap and range from 0.282650 to 0.282694 in IH1, from 0.282576 to 0.282698 in IH5 and from 0.282576 to 0.282696 in IH8. They also have overlapping mean  $\epsilon\text{Hf}(t)$  values of  $3.9 \pm 1.3$  (IH1),  $2.6 \pm 2.3$  (IH5) and  $3.0 \pm 2.7$  (IH8). Old cores of Cambrian age found in sample IH1 yield a mean  $\epsilon\text{Hf}(t)$  of  $6.2 \pm 1.7$ . The calculated  $T_{\text{DM}}$  ages are 887–977 Ma for IH1, 887–1116 Ma for IH5 and 883–1116 Ma for IH8 (Fig. 8b). In the Permian Eisenhut Plutonic Suite, zircons yielded a  $^{176}\text{Hf}/^{177}\text{Hf}_i$  range from 0.282642 to 0.282756 in IH58 and from 0.282727 to 0.282817 in IH66. The samples yield different mean  $\epsilon\text{Hf}(t)$  values of  $2.7 \pm 2.2$  (IH58) and  $5.2 \pm 1.0$  (IH66). The calculated  $T_{\text{DM}}$  ages partly overlap and range from 815 to 1031 Ma (IH58) and from 698 to 869 Ma (IH66) (Fig. 8b).

## 5.3. Rare earth element (REE) and Ti content of zircons

Zircons from six samples were analyzed for their REE and titanium contents: IH24 from the Lignitz Plutonic Suite, IH2, IH12, IH15 and IH17 from the Untertal Pluton-

| Sample   | Suite                   | Lithology                 | Age and 2 $\sigma$ error (Ma)                 | $\epsilon_{\text{Hf}}(t)$ |
|----------|-------------------------|---------------------------|-----------------------------------------------|---------------------------|
| IH23     | Lignitz Plutonic suite  | Plagioclase orthogneiss   | 501.0 $\pm$ 6.7                               | 11.2 $\pm$ 2.6            |
| IH24     |                         | Plagioclase orthogneiss   | 498.1 $\pm$ 6.7                               |                           |
| IH28     |                         | Plagioclase orthogneiss   | 494.7 $\pm$ 6.6                               |                           |
| IH30     |                         | Plagioclase orthogneiss   | 495.9 $\pm$ 6.6                               |                           |
| IH34     |                         | Granitic orthogneiss      | 498.6 $\pm$ 6.7                               | 6.8 $\pm$ 2.7             |
| IH81     |                         | Granitic orthogneiss      | 501.2 $\pm$ 6.6                               |                           |
| IH83     |                         | Granodioritic orthogneiss | 480.1 $\pm$ 6.4                               |                           |
| IH84     |                         | Granitic orthogneiss      | 497.1 $\pm$ 6.6                               |                           |
| IH87     |                         | Granitic orthogneiss      | 498.4 $\pm$ 6.6                               |                           |
| IH01     | Untertal Plutonic suite | Granodioritic orthogneiss | 357.5 $\pm$ 4.8<br>(core: 505.8 $\pm$ 6.8 Ma) | 3.9 $\pm$ 1.3             |
| IH02     |                         | Granitic orthogneiss      | 354.3 $\pm$ 4.7<br>(core: 481.0 $\pm$ 6.4 Ma) |                           |
| IH03     |                         | Granodioritic orthogneiss | 370.4 $\pm$ 4.9                               | 2.6 $\pm$ 2.3             |
| IH05     |                         | Granitic orthogneiss      | 356.2 $\pm$ 4.7                               |                           |
| IH07     |                         | Granodioritic orthogneiss | 361.3 $\pm$ 4.8                               | 3.0 $\pm$ 2.7             |
| IH08     |                         | Granodioritic orthogneiss | 366.6 $\pm$ 4.9                               |                           |
| IH11     |                         | Monzodioritic orthogneiss | 358.5 $\pm$ 4.7                               |                           |
| IH12     |                         | Granitic orthogneiss      | 358.5 $\pm$ 4.8                               |                           |
| IH13     |                         | Granitic orthogneiss      | 360.7 $\pm$ 4.8                               |                           |
| IH15     |                         | Granodioritic orthogneiss | 350.4 $\pm$ 4.8<br>(core: 488.6 $\pm$ 6.4 Ma) |                           |
| IH17     |                         | Granodioritic orthogneiss | 354.6 $\pm$ 4.7                               |                           |
| IH19     |                         | Granodioritic orthogneiss | 359.7 $\pm$ 4.8                               |                           |
| IH20     |                         | Granitic orthogneiss      | 355.7 $\pm$ 4.9                               |                           |
| IH21     |                         | Granodioritic orthogneiss | 362.3 $\pm$ 5.0                               |                           |
| IH22     |                         | Granitic orthogneiss      | 358.2 $\pm$ 4.8                               |                           |
| IGL22/X1 |                         | Dioritic orthogneiss      | 358.3 $\pm$ 4.8                               |                           |
| IGL21/41 |                         | Granitic orthogneiss      | 357.2 $\pm$ 5.4                               |                           |
| IH58     | Eisenhut Plutonic suite | Granitic orthogneiss      | 263.0 $\pm$ 3.5                               | 2.7 $\pm$ 2.2             |
| IH61     |                         | Granitic orthogneiss      | 263.4 $\pm$ 3.5                               |                           |
| IH64     |                         | Granitic orthogneiss      | 261.0 $\pm$ 3.5                               |                           |
| IH66     |                         | Granitic orthogneiss      | 262.3 $\pm$ 3.5                               | 5.2 $\pm$ 1.0             |
| IGL21/41 |                         | Granitic orthogneiss      | 271.2 $\pm$ 5.7                               |                           |

**Table 2:** Summary of the weighted mean  $^{206}\text{Pb}/^{238}\text{U}$  ages and the associated  $\epsilon_{\text{Hf}}(t)$  of the measured samples of the three plutonic suites.

ic Suite, and IH61 from the Eisenhut Plutonic Suite. The complete data set is presented in Supplementary Table 4, additional discrimination diagrams are provided in Supplementary Figures A1 and A2.

### 5.3.1. Rare earth elements (REE)

Zircons from the Lignitz Plutonic Suite (IH24) show moderate positive Ce anomalies ( $\text{Ce}/\text{Ce}^*=6.2\text{--}43.2$ ) and negative Eu anomalies ( $\text{Eu}/\text{Eu}^*=0.11\text{--}0.22$ ). These zircons are more enriched in light and middle REEs (LREE, MREE) than zircons of the other age groups (Fig. A1e). Zircons from the Untertal Plutonic Suite show similar overall

trends but are less enriched in light REEs (Fig. A1 a–d). Zircons of two samples from the northeastern occurrences of this suite (IH17 and IH12) have only mildly negative Eu anomalies ( $\text{Eu}/\text{Eu}^*=0.24\text{--}0.71$  and  $0.23\text{--}0.42$ ). Moreover, zircons of sample IH17 show the strongest positive Ce anomalies ( $\text{Ce}/\text{Ce}^*=44.6\text{--}257.0$ ). Zircon cores of the Untertal Plutonic Suite show patterns similar to the zircons of the Lignitz Plutonic suite with moderate negative Eu-anomalies and lower positive Ce anomalies (e.g.,  $\text{Ce}/\text{Ce}^*=9.2\text{--}31.4$  in IH15, Fig. A1c). Zircons from the Eisenhut Plutonic Suite have mildly positive Ce anomalies and the most pronounced negative Eu-anomalies ( $\text{Eu}/\text{Eu}^*=0.02\text{--}0.07$ ) of all suites (Fig. A1f). Overall, the zircon REE patterns

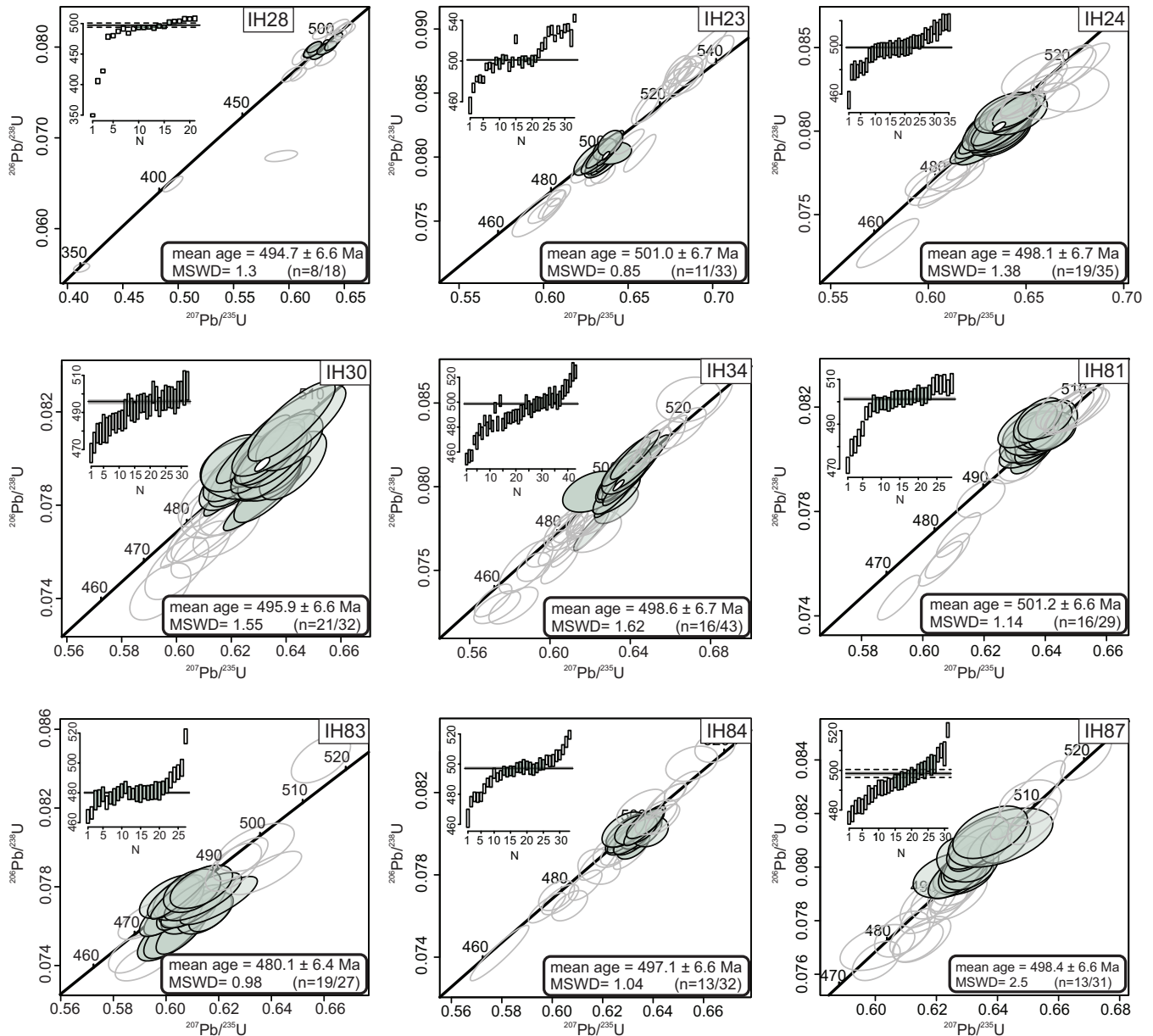


**Figure 5:** U-Pb Concordia plots and weighted mean plots (inserts) of the Lignitz Plutonic Suite. The ages given are weighted mean  $^{206}\text{Pb}/^{238}\text{U}$  ages  $\pm$  2SE uncertainty including external components. The error ellipses are at a  $2\sigma$  level. Sample IH23 has zircon dates older than a main population; this may represent inherited cores or derive from a metamorphic overprint of precursor material slightly preceding partial melting and major magmatic activity.

of all suites show positive Ce and negative Eu anomalies and high heavy REE (HREE) contents (Fig. A1), which is typical for igneous zircons (Hoskin, 2005; Hoskin and Schaltegger, 2003; Rubatto, 2017).

The zircons of the three plutonic suites overlap and show a decrease of Dy with increasing Yb/Dy and a decrease of Th/U with decreasing Zr/Hf (Fig. A2). A decrease in Dy with increasing Yb/Dy indicates that the zircons likely fractionated or co-crystallized with LREE and MREE scavenging minerals like apatite and titanite (Schaltegger and Davies, 2017). The linear trend observed in Th/U vs. Zr/Hf confirms titanite or apatite fractionation or co-crystallization (Schaltegger and Davies, 2017).

### 5.3.2. Titanium-in-zircon thermometry

Crystallization temperatures of the zircons were calculated using the Ti-in-zircon thermometer of Ferry and Watson (2007) applying an activity correction for  $\text{TiO}_2$  and  $\text{SiO}_2$  activities from Schiller and Finger (2019). The results for the individual zircons are shown in Table 3.

Zircons of the Lignitz Plutonic Suite (IH24) have Ti contents between 4.5 and 26.4  $\mu\text{g/g}$  and a mean content of 10.7  $\mu\text{g/g}$ . The calculated crystallization temperatures vary from approximately 730 to 925  $^\circ\text{C}$  and yield a mean temperature of 817  $^\circ\text{C}$ . Titanium contents of zircons from the northwestern Untertal Plutonic Suite (IH 2) have Ti contents ranging from 2.3 to 20.3  $\mu\text{g/g}$  (mean 9.6  $\mu\text{g/g}$ )

| Sample    |          | Ti<br>[mg/kg] | activity<br>TiO <sub>2</sub> | activity<br>SiO <sub>2</sub> | T [Ferry &<br>Watson<br>2007] | corr. T |
|-----------|----------|---------------|------------------------------|------------------------------|-------------------------------|---------|
| IH24-mean | LP       | 10.7          | 0.527                        | 1.000                        | 752                           | 817     |
| IH24-4    | LP       | 15.2          | 0.527                        | 1.000                        | 787                           | 856     |
| IH24-9    | LP       | 26.4          | 0.527                        | 1.000                        | 846                           | 923     |
| IH24-10   | LP       | 9.5           | 0.527                        | 1.000                        | 741                           | 805     |
| IH24-12   | LP       | 10.6          | 0.527                        | 1.000                        | 751                           | 816     |
| IH24-16   | LP       | 6.3           | 0.527                        | 1.000                        | 704                           | 762     |
| IH24-20   | LP       | 8.5           | 0.527                        | 1.000                        | 731                           | 793     |
| IH24-26   | LP       | 11.2          | 0.527                        | 1.000                        | 756                           | 822     |
| IH24-37   | LP       | 4.5           | 0.527                        | 1.000                        | 676                           | 731     |
| IH24-43   | LP       | 9.3           | 0.527                        | 1.000                        | 738                           | 802     |
| IH24-48   | LP       | 19.2          | 0.527                        | 1.000                        | 811                           | 884     |
| IH24-49   | LP       | 10.5          | 0.527                        | 1.000                        | 750                           | 814     |
| IH24-51   | LP       | 6.5           | 0.527                        | 1.000                        | 707                           | 766     |
| IH24-63   | LP       | 7.4           | 0.527                        | 1.000                        | 719                           | 779     |
| IH24-74   | LP       | 4.7           | 0.527                        | 1.000                        | 680                           | 736     |
| IH2-mean  | UP       | 9.6           | 0.507                        | 1.000                        | 742                           | 809     |
| IH2-19    | UP       | 5.6           | 0.507                        | 1.000                        | 694                           | 756     |
| IH2-27    | UP       | 2.4           | 0.507                        | 1.000                        | 627                           | 679     |
| IH2-38    | UP       | 20.3          | 0.507                        | 1.000                        | 817                           | 895     |
| IH2-63    | UP       | 10.6          | 0.507                        | 1.000                        | 751                           | 820     |
| IH2-65    | UP       | 11.6          | 0.507                        | 1.000                        | 760                           | 830     |
| IH2-68    | UP       | 7.3           | 0.507                        | 1.000                        | 717                           | 781     |
| IH12-mean | UP       | 4.9           | 0.510                        | 1.000                        | 683                           | 742     |
| IH12-11   | UP       | 5.6           | 0.510                        | 1.000                        | 694                           | 754     |
| IH12-17   | UP       | 1.6           | 0.510                        | 1.000                        | 596                           | 645     |
| IH12-18   | UP       | 1.6           | 0.510                        | 1.000                        | 598                           | 646     |
| IH12-22   | UP       | 20.8          | 0.510                        | 1.000                        | 819                           | 897     |
| IH12-25   | UP       | 2.8           | 0.510                        | 1.000                        | 638                           | 691     |
| IH12-41   | UP       | 2.3           | 0.510                        | 1.000                        | 623                           | 674     |
| IH12-51   | UP       | 2.6           | 0.510                        | 1.000                        | 633                           | 686     |
| IH12-55   | UP       | 2.0           | 0.510                        | 1.000                        | 615                           | 666     |
| IH12-69   | UP       | 5.0           | 0.510                        | 1.000                        | 684                           | 744     |
| IH15-mean | UP       | 6.9           | 0.529                        | 1.000                        | 712                           | 771     |
| IH15-Zr06 | UP       | 11.6          | 0.529                        | 1.000                        | 760                           | 825     |
| IH15-Zr25 | UP       | 4.8           | 0.529                        | 1.000                        | 681                           | 737     |
| IH15-Zr56 | UP       | 2.7           | 0.529                        | 1.000                        | 637                           | 688     |
| IH17-mean | UP       | 9.2           | 0.456                        | 0.874                        | 738                           | 802     |
| IH17-1    | UP       | 9.1           | 0.456                        | 0.874                        | 737                           | 801     |
| IH17-4    | UP       | 7.8           | 0.456                        | 0.874                        | 723                           | 785     |
| IH17-10   | UP       | 9.6           | 0.456                        | 0.874                        | 742                           | 806     |
| IH17-11   | UP       | 11.7          | 0.456                        | 0.874                        | 761                           | 827     |
| IH17-14   | UP       | 6.7           | 0.456                        | 0.874                        | 710                           | 770     |
| IH17-22   | UP       | 11.2          | 0.456                        | 0.874                        | 756                           | 823     |
| IH17-27   | UP       | 6.5           | 0.456                        | 0.874                        | 707                           | 767     |
| IH17-41   | UP       | 9.9           | 0.456                        | 0.874                        | 745                           | 810     |
| IH17-42   | UP       | 15.1          | 0.456                        | 0.874                        | 786                           | 857     |
| IH17-48   | UP       | 9.4           | 0.456                        | 0.874                        | 740                           | 804     |
| IH17-50   | UP       | 8.1           | 0.456                        | 0.874                        | 726                           | 789     |
| IH17-53   | UP       | 12.9          | 0.456                        | 0.874                        | 770                           | 839     |
| IH17-52   | UP       | 6.9           | 0.456                        | 0.874                        | 712                           | 772     |
| IH17-62   | UP       | 4.3           | 0.456                        | 0.874                        | 671                           | 727     |
| IH17-66   | UP       | 8.7           | 0.456                        | 0.874                        | 732                           | 795     |
| IH2-9     | UP-cores | 3.9           | 0.507                        | 1.000                        | 665                           | 722     |
| IH2-25    | UP-cores | 2.7           | 0.507                        | 1.000                        | 636                           | 690     |
| IH2-50    | UP-cores | 8.7           | 0.507                        | 1.000                        | 732                           | 799     |
|           |          |               |                              |                              | mean:                         | 737     |
| IH12-42   | UP-cores | 14.2          | 0.510                        | 1.000                        | 780                           | 852     |
| IH12-44   | UP-cores | 6.4           | 0.510                        | 1.000                        | 706                           | 768     |
| IH12-62   | UP-cores | 5.7           | 0.510                        | 1.000                        | 696                           | 756     |
|           |          |               |                              |                              | mean:                         | 792     |
| IH15-10   | UP-cores | 2.3           | 0.529                        | 1.000                        | 624                           | 672     |
| IH15-30   | UP-cores | 7.4           | 0.529                        | 1.000                        | 718                           | 778     |
| IH15-32   | UP-cores | 7.6           | 0.529                        | 1.000                        | 721                           | 781     |
| IH15-40   | UP-cores | 3.9           | 0.529                        | 1.000                        | 663                           | 717     |
|           |          |               |                              |                              | mean:                         | 737     |
| IH61-mean | EP       | 8.9           | 0.523                        | 1.000                        | 735                           | 798     |
| IH61-3    | EP       | 2.8           | 0.523                        | 1.000                        | 638                           | 690     |
| IH61-6    | EP       | 4.7           | 0.523                        | 1.000                        | 680                           | 736     |
| IH61-9    | EP       | 2.7           | 0.523                        | 1.000                        | 636                           | 687     |
| IH61-10   | EP       | 6.4           | 0.523                        | 1.000                        | 706                           | 765     |
| IH61-18   | EP       | 25.1          | 0.523                        | 1.000                        | 840                           | 918     |
| IH61-21   | EP       | 11.8          | 0.523                        | 1.000                        | 762                           | 828     |
| IH61-52   | EP       | 11.7          | 0.523                        | 1.000                        | 761                           | 827     |
| IH61-36   | EP       | 5.9           | 0.523                        | 1.000                        | 698                           | 757     |
| IH61-43   | EP       | 16.6          | 0.523                        | 1.000                        | 796                           | 867     |
| IH61-44   | EP       | 8.6           | 0.523                        | 1.000                        | 731                           | 794     |
| IH61-72   | EP       | 7.5           | 0.523                        | 1.000                        | 719                           | 780     |
| IH61-74   | EP       | 4.8           | 0.523                        | 1.000                        | 682                           | 738     |
| IH61-92   | EP       | 6.6           | 0.523                        | 1.000                        | 708                           | 768     |

yielding crystallization temperatures of approximately 680 to 895 °C (mean of 809 °C). Zircons of three samples from the northeastern occurrences (IH12, IH15 and IH17) have Ti contents between 1.6 and 20.8 µg/g (mean 4.9 µg/g), 2.8 and 11.6 µg/g (mean 6.9 µg/g), and 4.3 and 15.1 µg/g (mean 9.2 µg/g). This correlates to temperatures of approximately 645 to 900 °C for sample IH12 (mean of 742 °C), 690 to 825 °C for sample IH15 (mean of 771 °C), and 730 to -860 °C and a higher mean of 802°C for sample IH17. Zircon cores of the Untertal Plutonic Suite (IH2, IH12 and IH15) yield temperatures of approximately 740 °C to 790 °C. Titanium contents of zircons from the Eisenhut Plutonic Suite (IH61) range from 2.7 to 25.1 µg/g (mean 8.9 µg/g) and corresponding crystallization temperatures range from 680 to 920 °C (mean of 798 °C).

In order to confirm these temperature estimates, Zr saturation temperatures were additionally calculated following Watson and Harrison (1983) and Boehnke et al. (2013). For this, an intrusion temperature of 800 °C has been assumed. The analytical data used for the calculation can be retrieved from Supplementary Table 5. For the Lignitz Plutonic Suite, the Zr saturation temperatures range from approximately 725 to 840 °C, with a mean temperature of 790°C, and are in the range of the Ti-in-zircon crystallization temperatures. Like the Ti-in-zircon crystallization temperatures, the Zr saturation temperatures are lower in the Untertal Plutonic Suite; they range from approximately 595 to 790 °C, with a mean of 724 °C. For the Eisenhut Plutonic Suite, the Zr saturation temperatures range from ~640 to 800 °C, with a mean temperature of 738 °C.

## 6. Geochemistry

Samples from the Lignitz-, the Untertal- and the Eisenhut Plutonic Suites were analyzed for major, trace, and rare earth elements. Representative element compositions of selected samples are shown in Tables 4–6 and are displayed in Figures 9 and 10. Additional discrimination diagrams are provided in Supplementary Figures A3–A6. The major and trace element whole rock data of all Schladming crystalline samples of this study are presented in Supplementary Table 5. In order to correlate the tectono-magmatic evolution of the Schladming crystalline with that of the Seckau Complex, we included data of Mandl et al. (2018, 2022) and Mandl (2020). Additionally, two recently published geochemical data sets from the Schladming crystalline by Huang et al. (2021, 2022) were also considered for comparison.

**Table 3:** Ti-in-zircon thermometer calculations for samples of the three plutonic suites; LP: Lignitz Plutonic Suite; UP: Untertal Plutonic Suite; EP: Eisenhut Plutonic Suite; T: Temperature (°C); corr.: corrected.

| Sample                         | IH23  | IH24   | IH28   | IH30   | IH33  | IH34   | IH80   | IH81  | IH82  | IH83  | IH84  | IH85  | IH86  | IH87  | IH88  | IH89  |
|--------------------------------|-------|--------|--------|--------|-------|--------|--------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| SiO <sub>2</sub>               | 77.43 | 77.42  | 77.15  | 71.75  | 75.32 | 76.85  | 69.42  | 72.76 | 81.30 | 61.12 | 77.17 | 77.51 | 75.85 | 77.24 | 77.25 | 76.28 |
| TiO <sub>2</sub>               | 0.18  | 0.15   | 0.19   | 0.39   | 0.14  | 0.22   | 0.32   | 0.17  | 0.36  | 0.95  | 0.12  | 0.07  | 0.18  | 0.20  | 0.15  | 0.29  |
| Al <sub>2</sub> O <sub>3</sub> | 13.13 | 12.74  | 13.06  | 13.76  | 13.00 | 12.50  | 17.17  | 11.23 | 9.96  | 17.38 | 11.98 | 12.57 | 13.06 | 13.06 | 12.88 | 11.42 |
| Fe <sub>2</sub> O <sub>3</sub> | 1.02  | 1.55   | 1.07   | 2.85   | 1.42  | 2.17   | 1.39   | 1.25  | 1.24  | 6.52  | 1.12  | 0.79  | 1.21  | 0.34  | 1.03  | 2.05  |
| MnO                            | 0.003 | 0.01   | 0.03   | 0.05   | 0.02  | 0.03   | 0.03   | 0.01  | 0.01  | 0.10  | 0.02  | 0.01  | 0.02  | 0.01  | 0.02  | 0.02  |
| MgO                            | 0.15  | 0.10   | 0.30   | 0.58   | 0.34  | 0.90   | 0.53   | 0.29  | 0.94  | 2.59  | 0.10  | 0.03  | 0.43  | 0.30  | 0.19  | 0.26  |
| CaO                            | 0.48  | 0.78   | 0.31   | 1.85   | 0.26  | 0.83   | 0.15   | 0.03  | 0.10  | 1.56  | 0.38  | 0.42  | 0.07  | 0.22  | 0.32  | 0.31  |
| K <sub>2</sub> O               | 0.79  | 0.29   | 0.87   | 0.85   | 3.67  | 0.79   | 0.13   | 3.41  | 1.01  | 2.54  | 4.40  | 3.37  | 1.60  | 1.10  | 0.36  | 1.39  |
| Na <sub>2</sub> O              | 6.15  | 6.46   | 6.17   | 6.00   | 4.32  | 4.95   | 9.48   | 3.46  | 3.44  | 3.75  | 3.54  | 4.29  | 5.74  | 6.01  | 6.58  | 4.56  |
| P <sub>2</sub> O <sub>5</sub>  | 0.02  | 0.01   | 0.03   | 0.07   | 0.04  | 0.04   | 0.03   | 0.03  | 0.07  | 0.24  | 0.02  | 0.01  | 0.03  | 0.04  | 0.02  | 0.04  |
| LOI                            | 0.53  | 0.59   | 0.80   | 1.77   | 0.68  | 0.92   | 0.71   | 0.78  | 1.13  | 2.79  | 0.49  | 0.40  | 0.71  | 0.78  | 0.45  | 0.72  |
| Sum                            | 99.98 | 100.29 | 100.12 | 100.04 | 99.49 | 100.41 | 99.53  | 93.57 | 99.78 | 99.75 | 99.50 | 99.63 | 99.05 | 99.43 | 99.41 | 97.52 |
| Li                             | 8.32  | 5.26   | 8.52   | 10.16  | 8.32  | 16.0   | 9.65   | 6.65  | 15.43 | 42.88 | 5.35  | 1.93  | 9.34  | 9.01  | 5.09  | 8.92  |
| Sc                             | 2.24  | 1.73   | 3.31   | 8.75   | 8.44  | 5.60   | 10.63  | 4.33  | 4.24  | 18.07 | 3.79  | 1.85  | 5.82  | 4.60  | 3.18  | 4.49  |
| V                              | 3.86  | 3.10   | 4.35   | 14.01  | 4.33  | 29.2   | 16.92  | 7.09  | 27.54 | 94.72 | 4.10  | 0.26  | 7.14  | 10.06 | 1.97  | 19.98 |
| Cr                             | 2.82  | 3.38   | 2.45   | 3.54   | 7.36  | 15.0   | 7.43   | 1.84  | 24.48 | 60.49 | 1.21  | 0.86  | 1.97  | 2.22  | 1.18  | 1.51  |
| Ni                             | 1.33  | 2.23   | 0.96   | 1.00   | 5.38  | 10.9   | 14.56  | 0.86  | 15.62 | 27.29 | 0.41  | 0.42  | 0.87  | 0.91  | 0.83  | 1.54  |
| Cu                             | 1.07  | 0.75   | 4.22   | 0.81   | 4.98  | 13.0   | 3.94   | 2.37  | 0.39  | 3.60  | 1.47  | 1.83  | 0.38  | 0.66  | 0.90  | 1.21  |
| Zn                             | 13.28 | 4.2    | 4.46   | 26.92  | 14.7  | 19.2   | 11.26  | 7.83  | 12.20 | 114   | 13.70 | 4.07  | 13.88 | 5.28  | 7.20  | 6.71  |
| Ga                             | 18.10 | 5.7    | 22.0   | 18.10  | 19.9  | 13.1   | 17.6   | 18.09 | 10.2  | 19.4  | 17.54 | 19.35 | 16.94 | 18.34 | 21.0  | 18.44 |
| Rb                             | 23.80 | 6.50   | 29.10  | 28.50  | 58.30 | 29.10  | 3.00   | 98.00 | 35.00 | 110   | 142   | 111   | 58.00 | 44.00 | 11.00 | 45.00 |
| Sr                             | 76.70 | 96.70  | 63.10  | 125    | 70.50 | 64.50  | 138    | 29.00 | 66.00 | 155   | 73.00 | 67.00 | 24.00 | 31.00 | 77.00 | 91.00 |
| Y                              | 18.01 | 54.2   | 46.83  | 63.14  | 24.5  | 10.2   | 28.18  | 24.33 | 9.84  | 29.93 | 51.39 | 48.44 | 31.60 | 53.55 | 59.07 | 32.41 |
| Zr                             | 305   | 295    | 305    | 444    | 176   | 114    | 303    | 160   | 211   | 238   | 122   | 123   | 187   | 152   | 255   | 268   |
| Nb                             | 14.05 | 16.5   | 13.93  | 13.94  | 7.85  | 3.50   | 5.27   | 7.02  | 7.98  | 13.98 | 6.81  | 11.69 | 8.06  | 7.36  | 13.55 | 13.27 |
| Cs                             | 8.01  | 1.19   | 5.86   | 4.62   | 0.27  | 0.54   | 0.79   | 2.43  | 1.17  | 18.18 | 2.02  | 0.44  | 1.27  | 1.14  | 2.25  | 10.73 |
| Ba                             | 134   | 169    | 329    | 179    | 527   | 349    | 73.0   | 347   | 440   | 551   | 402   | 190   | 232   | 112   | 103   | 343   |
| La                             | 21.17 | 21.2   | 56.56  | 43.22  | 15.3  | 6.17   | 80.77  | 40.02 | 12.75 | 27.90 | 47.27 | 17.41 | 22.27 | 52.59 | 36.27 | 22.37 |
| Ce                             | 44.66 | 53.3   | 123    | 97.67  | 46.4  | 17.6   | 164.51 | 84.22 | 25.40 | 54.83 | 88.80 | 50.55 | 71.93 | 58.91 | 74.44 | 44.96 |
| Pr                             | 5.92  | 5.91   | 15.14  | 12.32  | 4.98  | 1.79   | 18.31  | 9.24  | 2.66  | 6.64  | 10.56 | 5.04  | 4.72  | 11.45 | 8.63  | 5.58  |
| Nd                             | 23.91 | 24.4   | 60.69  | 51.31  | 21.0  | 7.34   | 72.44  | 35.13 | 10.08 | 27.19 | 41.00 | 20.97 | 17.86 | 45.04 | 34.58 | 23.47 |
| Sm                             | 5.18  | 5.96   | 12.95  | 12.34  | 5.67  | 1.69   | 14.41  | 7.39  | 2.03  | 5.90  | 9.20  | 6.11  | 4.15  | 9.97  | 8.12  | 5.69  |
| Eu                             | 0.57  | 0.67   | 1.55   | 1.94   | 0.71  | 0.39   | 1.53   | 0.37  | 0.43  | 1.51  | 0.36  | 0.07  | 0.39  | 0.59  | 0.76  | 0.82  |
| Gd                             | 4.63  | 7.12   | 10.33  | 12.27  | 5.92  | 1.76   | 11.04  | 6.73  | 1.91  | 5.84  | 9.03  | 6.97  | 4.37  | 9.78  | 8.59  | 5.91  |
| Tb                             | 0.64  | 1.39   | 1.33   | 1.82   | 1.02  | 0.29   | 1.30   | 0.99  | 0.29  | 0.93  | 1.46  | 1.33  | 0.78  | 1.61  | 1.55  | 1.02  |
| Dy                             | 3.58  | 9.10   | 7.89   | 11.05  | 5.66  | 1.71   | 6.30   | 5.43  | 1.80  | 5.69  | 8.77  | 8.83  | 5.38  | 9.64  | 9.96  | 6.38  |
| Ho                             | 0.71  | 2.00   | 1.73   | 2.31   | 1.07  | 0.36   | 1.12   | 0.96  | 0.36  | 1.13  | 1.70  | 1.79  | 1.14  | 1.87  | 2.03  | 1.27  |
| Er                             | 2.01  | 6.25   | 5.22   | 6.36   | 3.06  | 1.14   | 3.01   | 2.59  | 1.11  | 3.33  | 5.03  | 5.35  | 3.77  | 5.48  | 6.06  | 3.77  |
| Tm                             | 0.29  | 0.95   | 0.74   | 0.86   | 0.45  | 0.18   | 0.36   | 0.33  | 0.16  | 0.47  | 0.70  | 0.77  | 0.59  | 0.75  | 0.87  | 0.54  |
| Yb                             | 2.15  | 6.31   | 5.56   | 6.22   | 3.01  | 1.16   | 2.06   | 2.01  | 1.07  | 3.10  | 4.54  | 5.15  | 4.24  | 4.90  | 5.70  | 3.54  |
| Lu                             | 0.34  | 0.97   | 0.83   | 0.93   | 0.46  | 0.19   | 0.27   | 0.30  | 0.16  | 0.48  | 0.67  | 0.75  | 0.63  | 0.72  | 0.85  | 0.50  |
| Hf                             | 11.77 | 11.39  | 10.38  | 13.42  | 6.81  | 4.23   | 9.29   | 7.13  | 6.28  | 7.67  | 5.81  | 6.54  | 8.03  | 6.18  | 9.38  | 9.65  |
| Ta                             | 4.28  | 4.08   | 2.69   | 2.95   | 3.65  | 3.48   | 2.16   | 1.84  | 3.35  | 1.63  | 1.88  | 2.34  | 2.66  | 2.44  | 3.20  | 3.13  |
| Pb                             | 4.89  | 4.71   | 5.49   | 5.31   | 10.8  | 2.44   | 4.63   | 11.20 | 2.79  | 4.32  | 11.22 | 8.36  | 2.01  | 1.26  | 4.51  | 4.50  |
| Th                             | 12.49 | 12.5   | 12.04  | 11.41  | 11.0  | 2.06   | 26.10  | 19.96 | 7.07  | 8.06  | 20.89 | 19.38 | 18.44 | 17.00 | 11.50 | 10.58 |
| U                              | 1.40  | 1.98   | 3.01   | 1.85   | 0.44  | 1.65   | 1.41   | 2.33  | 1.26  | 2.38  | 2.26  | 9.00  | 2.18  | 4.28  | 2.24  | 1.38  |
| A/CNK                          | 1.11  | 1.03   | 1.12   | 0.97   | 1.13  | 1.19   | 1.07   | 1.19  | 1.44  | 1.48  | 1.06  | 1.10  | 1.16  | 1.14  | 1.09  | 1.19  |
| A/NK                           | 1.20  | 1.16   | 1.18   | 1.28   | 1.17  | 1.39   | 1.09   | 1.20  | 1.48  | 1.95  | 1.13  | 1.17  | 1.17  | 1.18  | 1.15  | 1.27  |
| K/Rb                           | 276   | 370    | 248    | 248    | 523   | 225    | 360    | 289   | 240   | 192   | 257   | 252   | 229   | 208   | 272   | 256   |
| Rb/Sr                          | 0.31  | 0.07   | 0.46   | 0.23   | 0.83  | 0.45   | 0.02   | 3.38  | 0.53  | 0.71  | 1.95  | 1.66  | 2.42  | 1.42  | 0.14  | 0.49  |
| (Eu/Eu*)N                      | 0.36  | 0.32   | 0.41   | 0.48   | 0.37  | 0.69   | 0.37   | 0.16  | 0.66  | 0.79  | 0.12  | 0.03  | 0.28  | 0.18  | 0.28  | 0.43  |
| (La/Yb*)N                      | 6.64  | 2.27   | 6.87   | 4.69   | 3.43  | 3.58   | 26.54  | 13.45 | 8.02  | 6.08  | 7.03  | 2.28  | 3.55  | 7.26  | 4.30  | 4.27  |
| Nb/Ta                          | 3.28  | 4.06   | 5.18   | 4.72   | 2.15  | 1.01   | 2.44   | 3.82  | 2.38  | 8.56  | 3.62  | 4.99  | 3.03  | 3.01  | 4.23  | 4.24  |

**Table 4:** Major element oxides, selected trace element and rare earth element data of the meta-granitoids of the Lignitz Plutonic Suite. Major oxides are given in weight percent, Rb and Sr contents are given in parts per million [ppm, i.e., µg/g].

### 6.1. General geochemical discrimination

In a TAS diagram (Middlemost, 1994), most of the plutonic rocks show granitic to granodioritic compositions (Fig. 9a). The Lignitz Plutonic Suite and the Eisenhut Plutonic Suite are SiO<sub>2</sub>-rich (>72 wt% SiO<sub>2</sub>) and widely fall in the granite, in parts in the granodiorite field, while the

Untertal Plutonic Suite has partly lower SiO<sub>2</sub> values and comprises monzodioritic, granodioritic, and granitic varieties.

The data distribution within the A/CNK (molar proportion of Al<sub>2</sub>O<sub>3</sub>/(CaO+Na<sub>2</sub>O+K<sub>2</sub>O)) versus A/NK (molar proportions of Al<sub>2</sub>O<sub>3</sub>/(Na<sub>2</sub>O+K<sub>2</sub>O)) diagram by Shand (1943)

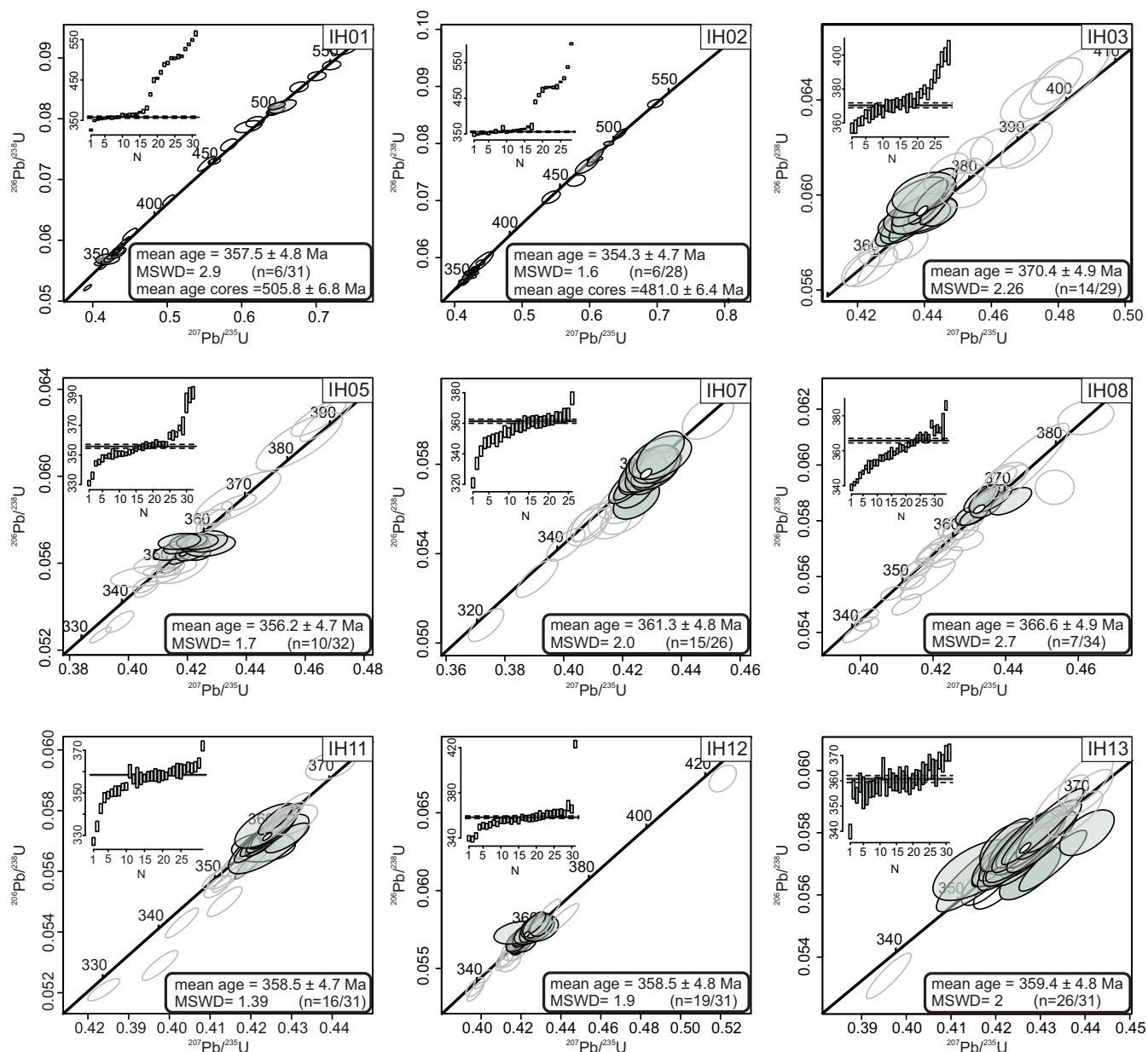


**Figure 6:** U-Pb Concordia plots and weighted mean plots (inserts) of the Untertal Plutonic Suite. The ages given are weighted mean  $^{206}\text{Pb}/^{238}\text{U}$  ages  $\pm$  2SE uncertainty including external components. The error ellipses are at a 2 $\sigma$  level. Sample IGL21/41 contains two zircon populations; the older ages in the range of  $357.2 \pm 5.4$  Ma indicate inheritance of zircons from the Untertal Plutonic Suite. The younger zircon population of sample IGL21/41 shows an age of  $271.2 \pm 5.7$  Ma.

indicates a predominantly peraluminous character of the granitoids; only one sample of the Lignitz Plutonic Suite falls into the metaluminous field (Fig. 9b). In general, the Untertal Plutonic Suite shows higher A/NK ratios than the other two suites; the Eisenhut Suite, however, shows a wider range in composition. A distinction between I- and S-type granitoids (I-type: A/CNK <1.1 and S-type: A/CNK >1.1; Chappell and White, 2001) is not conclusive for some of the igneous suites. In general, the Lignitz Plutonic Suite can be separated into an I-type and a S-type subgroup, whereas the Untertal Plutonic Suite widely shows I-type character.

The Lignitz Plutonic Suite shows a magnesian and a ferroan subgroup (Fig. 9c) in the  $\text{SiO}_2$  versus FeOt/

(FeOt+MgO) diagram, and mostly calc-alkaline character in the  $\text{SiO}_2$  versus  $\text{Na}_2\text{O}+\text{K}_2\text{O}-\text{CaO}$  diagram (Fig. 9d) (Frost et al., 2001). The Untertal Plutonic Suite falls exclusively in the magnesian field and shows alkali-calcic to calc-alkaline composition. The Eisenhut Plutonic Suite plots in the ferroan field showing compositions from alkali-calcic to calc-alkaline.

Rb/Sr ratios and  $\text{Al}_2\text{O}_3$  contents further allow to discriminate the three suites. In particular the high  $\text{Al}_2\text{O}_3$  content of the Untertal Plutonic Suite (13.84–17.07 wt%) and the Eisenhut Plutonic Suite (approximately 9–15 wt%) discriminates these suites from the Lignitz Plutonic Suite. Rb/Sr ratios are higher in the granitoids of the Eisenhut Plutonic Suite (0.11 up to 133.7) than in the Lignitz

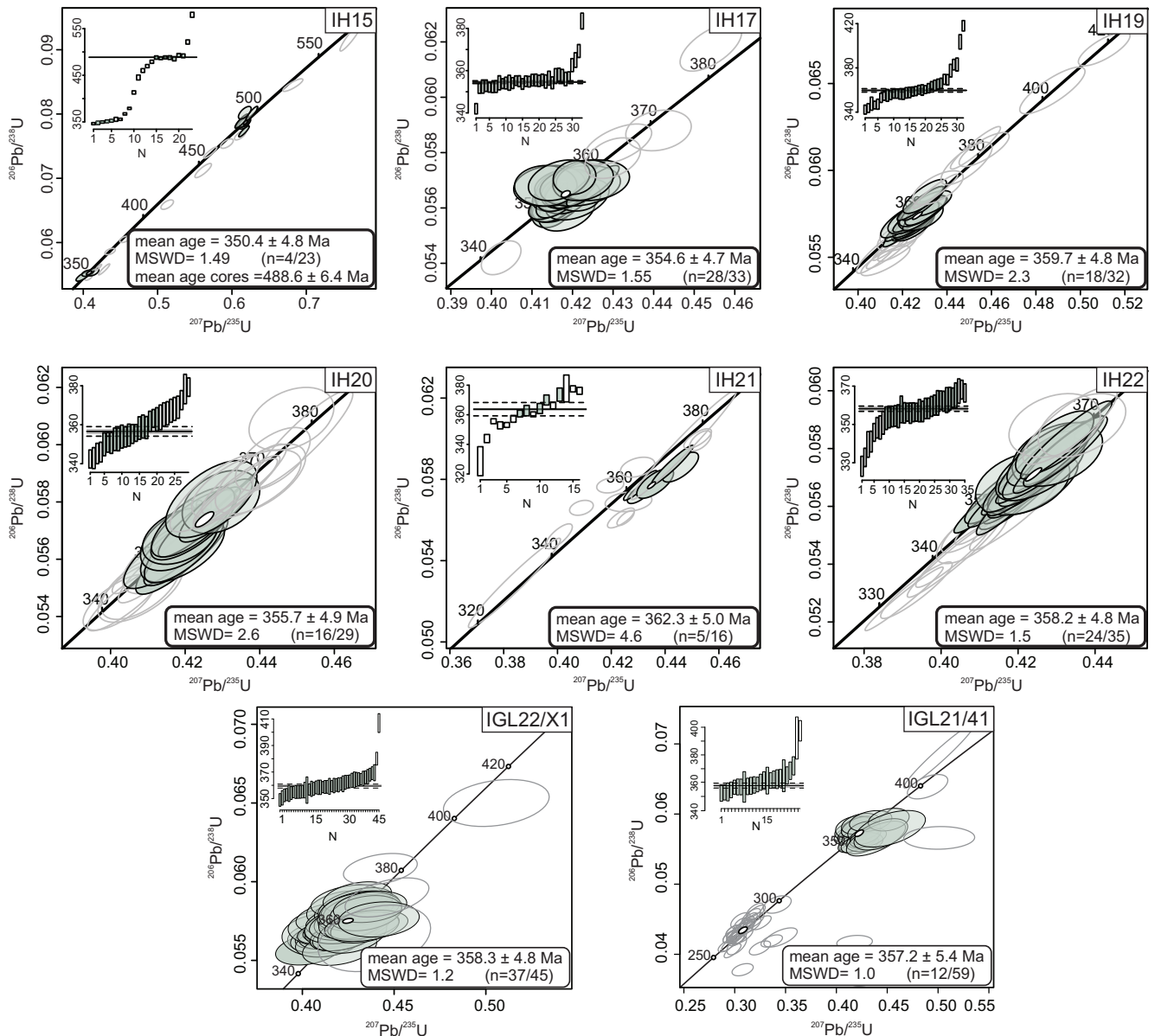


Figure 6 continued

(0.02–3.38) and the Untertal Plutonic Suites (0.07–2.10) (Tables 4 to 6 and Figures A3–A5).

The Rb vs Y+Nb and Nb vs Y diagrams of Pearce et al. (1984) (Fig. 10) were used for tentative discrimination between potential tectonic settings of granitoid emplacement. The Lignitz Plutonic Suite has the lowest Rb contents (mainly <60  $\mu\text{g/g}$ ) and in both diagrams it plots within the volcanic arc granite (VAG) and within-plate granite (WPG) fields (Fig. 10). The Untertal Plutonic Suite exclusively plots in the VAG field in both diagrams. The Eisenhut Plutonic Suite shows the highest Rb contents and, therefore, can clearly be distinguished from the Lignitz and the Untertal Plutonic Suites in the Rb vs Y+Nb diagram (Fig. 10a). It plots mainly in the syn-collision granite (syn-COLG) and the within plate granite (WPG) fields and might therefore be categorized as S- to A-type granite.

## 6.2. Major, trace and rare earth elements

The meta-granitoids of the Lignitz Plutonic Suite have particularly high  $\text{SiO}_2$  (71.15 to 81.30 wt%) (Fig. A3) and relatively high  $\text{Na}_2\text{O}$  (3.54 to 6.58 wt%) contents. They show low contents of  $\text{K}_2\text{O}$ , Rb, Sc and V, high contents of Zr and Y, and high variations of Rb/Sr (0.02–2.42) and K/Rb (192–370) (Table 4). A negative correlation of V/Ti and Ti/Zr with  $\text{SiO}_2$  can be correlated with Fe-Ti oxide fractionation (Fig. A6) (Nielsen et al., 1994; Pearce and Norry 1997). Two samples of this suite deviate from the overall trends (IH80 and IH83) and show lower  $\text{SiO}_2$  contents but higher  $\text{TiO}_2$  and  $\text{Al}_2\text{O}_3$ , which is likely related to contamination by the surrounding lithologies and secondary alteration; IH80 and IH83 were, therefore, not considered for interpretation of the overall geochemical trends. In major oxide and trace element versus  $\text{SiO}_2$  variation dia-

| Sample                         | IH01  | IH02  | IH03  | IH04   | IH05   | IH43   | IH44   | IH45   | IH46  | IH07  | IH08  | IH10   | IH11  | IH12    | IH13   | IH15  | IH17   | IH18   | IH19   | IH20  | IH21  | IH22  | IGL22/X1 | IGL21/41 |
|--------------------------------|-------|-------|-------|--------|--------|--------|--------|--------|-------|-------|-------|--------|-------|---------|--------|-------|--------|--------|--------|-------|-------|-------|----------|----------|
| SiO <sub>2</sub>               | 68.33 | 71.14 | 68.82 | 71.62  | 70.97  | 69.23  | 69.16  | 67.86  | 71.03 | 68.07 | 65.92 | 75.22  | 68.40 | 69.55   | 66.78  | 67.56 | 52.63  | 74.71  | 72.94  | 63.07 | 64.42 | 66.33 | 59.35    | 74.97    |
| TiO <sub>2</sub>               | 0.37  | 0.27  | 0.37  | 0.30   | 0.21   | 0.37   | 0.29   | 0.29   | 0.29  | 0.46  | 0.57  | 0.07   | 0.49  | 0.39    | 0.57   | 0.51  | 0.64   | 0.06   | 0.24   | 0.45  | 0.66  | 0.54  | 0.82     | 0.19     |
| Al <sub>2</sub> O <sub>3</sub> | 16.42 | 15.25 | 15.54 | 14.61  | 16.35  | 15.89  | 16.00  | 15.68  | 15.22 | 15.67 | 16.40 | 13.84  | 15.55 | 15.78   | 16.41  | 16.22 | 20.33  | 14.63  | 14.49  | 17.03 | 17.07 | 16.28 | 16.50    | 13.33    |
| Fe <sub>2</sub> O <sub>3</sub> | 2.35  | 1.74  | 2.71  | 1.77   | 1.42   | 3.09   | 2.13   | 2.05   | 1.93  | 3.30  | 4.04  | 0.41   | 3.50  | 2.75    | 3.96   | 3.53  | 7.74   | 0.67   | 1.92   | 4.71  | 4.75  | 3.88  | 7.02     | 1.46     |
| MnO                            | 0.04  | 0.03  | 0.05  | 0.03   | 0.03   | 0.07   | 0.04   | 0.05   | 0.04  | 0.07  | 0.07  | 0.02   | 0.07  | 0.06    | 0.07   | 0.05  | 0.10   | 0.02   | 0.08   | 0.12  | 0.05  | 0.07  | 0.12     | 0.03     |
| MgO                            | 0.87  | 0.67  | 0.98  | 0.90   | 0.47   | 0.90   | 1.36   | 1.68   | 0.89  | 0.97  | 1.18  | 0.02   | 1.02  | 0.79    | 1.19   | 0.97  | 4.88   | 0.12   | 0.47   | 2.41  | 1.67  | 1.13  | 3.02     | 0.19     |
| CaO                            | 3.11  | 1.73  | 2.10  | 1.10   | 1.07   | 2.23   | 1.64   | 1.75   | 1.62  | 2.68  | 3.21  | 0.44   | 2.36  | 1.72    | 2.44   | 2.99  | 4.17   | 1.01   | 1.47   | 4.01  | 2.18  | 2.93  | 6.13     | 0.19     |
| K <sub>2</sub> O               | 2.43  | 2.78  | 4.22  | 3.55   | 2.32   | 2.49   | 2.50   | 2.80   | 2.41  | 3.05  | 2.98  | 5.47   | 3.14  | 2.45    | 2.95   | 1.65  | 1.29   | 1.44   | 2.06   | 2.20  | 2.44  | 3.16  | 1.15     | 4.41     |
| Na <sub>2</sub> O              | 4.22  | 4.91  | 3.73  | 4.45   | 5.79   | 4.13   | 4.81   | 4.81   | 4.70  | 3.85  | 3.94  | 3.70   | 3.77  | 4.95    | 4.05   | 4.76  | 4.50   | 6.18   | 4.89   | 4.30  | 4.39  | 3.74  | 3.24     | 4.06     |
| P <sub>2</sub> O <sub>5</sub>  | 0.12  | 0.09  | 0.15  | 0.08   | 0.12   | 0.14   | 0.09   | 0.09   | 0.09  | 0.16  | 0.20  | 0.02   | 0.17  | 0.16    | 0.21   | 0.26  | 0.58   | 0.07   | 0.04   | 0.17  | 0.32  | 0.19  | 0.21     | 0.04     |
| LOI                            | 1.19  | 1.07  | 0.90  | 1.55   | 1.12   | 0.91   | 1.83   | 2.78   | 1.21  | 1.28  | 1.08  | 0.59   | 1.21  | 1.27    | 1.39   | 1.00  | 3.04   | 1.25   | 1.47   | 1.04  | 1.54  | 1.28  | 1.86     | 1.06     |
| Sum                            | 99.70 | 99.88 | 99.81 | 100.13 | 100.01 | 100.15 | 100.48 | 100.51 | 99.71 | 99.76 | 99.80 | 100.04 | 99.89 | 100.17  | 100.29 | 99.71 | 100.12 | 100.31 | 100.26 | 99.72 | 99.65 | 99.74 | 99.42    | 99.93    |
| Li                             | 28.75 | 15.25 | 25.17 | 22.09  | 13.70  | 22.68  | 16.06  | 15.86  | 15.65 | 36.72 | 24.70 | 4.68   | 23.68 | 27.33   | 36.13  | 16.90 | 34.81  | 3.30   | 16.04  | 23.52 | 24.58 | 34.31 | n.d.     | n.d.     |
| Sc                             | 5.45  | 4.61  | 7.20  | 5.68   | 4.72   | 6.69   | 4.28   | 4.30   | 3.67  | 11.17 | 9.34  | 1.26   | 8.62  | 4.15    | 7.53   | 10.41 | 35.11  | 1.39   | 4.55   | 21.37 | 15.05 | 10.71 | 18.00    | 5.00     |
| V                              | 28.50 | 18.93 | 32.12 | 22.66  | 14.82  | 34.56  | 24.87  | 23.16  | 25.86 | 48.84 | 37.43 | 3.75   | 34.47 | 33.72   | 49.77  | 38.64 | 120    | 1.91   | 20.20  | 81.41 | 58.34 | 44.02 | 147.00   | 9.00     |
| Cr                             | 11.53 | 11.48 | 13.61 | 14.71  | 4.69   | 6.97   | 16.12  | 15.91  | 15.96 | 10.85 | 8.94  | 3.96   | 6.40  | 6.98    | 8.71   | 6.38  | 9.05   | 2.45   | 4.30   | 18.34 | 13.21 | 7.84  | < 20     | < 20     |
| Ni                             | 3.97  | 5.54  | 4.68  | 3.67   | 1.56   | 3.72   | 9.55   | 8.25   | 8.45  | 2.87  | 2.01  | 2.45   | 1.80  | 3.11    | 3.69   | 2.87  | 11.04  | 1.38   | 2.21   | 10.47 | 6.59  | 2.50  | < 20     | < 20     |
| Cu                             | 1.11  | 2.20  | 2.29  | 0.64   | 2.51   | 0.77   | 0.38   | 0.29   | 1.77  | 5.07  | 2.68  | 2.24   | 1.46  | 4.28    | 3.29   | 6.10  | 14.92  | 1.47   | 0.56   | 9.37  | 3.59  | 2.10  | 20.00    | < 10     |
| Zn                             | 60.60 | 34.60 | 54.50 | 33.90  | 30.90  | 59.27  | 30.18  | 33.01  | 37.69 | 45.90 | 61.70 | 9.42   | 68.00 | 41.33   | 54.84  | 34.00 | 85.80  | 7.56   | 38.93  | 69.28 | 53.50 | 60.80 | 70.00    | < 30     |
| Ga                             | 17.70 | 10.80 | 14.90 | 18.70  | 12.90  | 17.70  | 15.30  | 15.50  | 13.50 | 16.80 | 18.90 | 9.10   | 16.80 | 13.00   | 18.40  | 18.90 | 22.00  | 17.80  | 14.20  | 18.50 | 17.60 | 18.40 | 16.00    | 21.00    |
| Rb                             | 64.90 | 53.10 | 95.80 | 112    | 62.70  | 72.00  | 61.40  | 78.80  | 58.10 | 93.70 | 103   | 179    | 101   | 83.50   | 107    | 50.30 | 49.50  | 37.80  | 68.10  | 73.30 | 93.80 | 115   | 34       | 432      |
| Sr                             | 954   | 550   | 451   | 222    | 250    | 552    | 544    | 282    | 552   | 369   | 394   | 85.00  | 349   | 236     | 375    | 455   | 629    | 155    | 215    | 456   | 240   | 404   | 365      | 39       |
| Y                              | 10.75 | 9.53  | 14.60 | 16.82  | 13.38  | 19.72  | 8.91   | 9.57   | 8.33  | 23.15 | 22.72 | 39.87  | 21.29 | 14.66   | 21.18  | 24.76 | 52.33  | 11.72  | 42.59  | 32.29 | 22.61 | 24.94 | 22.00    | 13.00    |
| Zr                             | 145   | 97.70 | 134   | 115    | 90.90  | 125    | 111    | 120    | 115   | 200   | 235   | 27.80  | 217   | 208     | 242    | 269   | 87.80  | 29.20  | 116    | 247   | 233   | 221   | 189      | 121      |
| Nb                             | 4.39  | 5.11  | 7.14  | 5.50   | 7.32   | 10.87  | 5.00   | 4.83   | 6.25  | 13.44 | 11.21 | 5.33   | 10.22 | 11.57   | 13.28  | 12.07 | 13.67  | 7.69   | 13.38  | 5.71  | 12.69 | 12.13 | 6.00     | 16.00    |
| Cs                             | 1.62  | 0.66  | 3.18  | 3.07   | 0.81   | 1.51   | 1.80   | 2.76   | 1.27  | 3.18  | 1.23  | 1.97   | 2.30  | 1.18    | 2.15   | 1.44  | 0.78   | 0.43   | 0.75   | 1.73  | 5.45  | 4.79  | 0.70     | 22.90    |
| Ba                             | 1002  | 959   | 1267  | 934    | 746    | 839    | 873    | 673    | 1122  | 888   | 1004  | 111    | 914   | 684     | 869    | 700   | 221    | 327    | 424    | 798   | 537   | 850   | 427      | 149      |
| La                             | 24.58 | 13.23 | 21.96 | 15.68  | 18.61  | 17.37  | 12.75  | 12.82  | 14.13 | 56.54 | 39.92 | 5.40   | 40.68 | 21.86   | 32.59  | 54.75 | 88.50  | 5.57   | 22.94  | 1.86  | 39.89 | 52.28 | 26.00    | 6.50     |
| Ce                             | 51.40 | 27.59 | 46.75 | 31.46  | 42.54  | 40.91  | 33.54  | 28.67  | 37.25 | 117   | 81.24 | 12.80  | 79.27 | 89.67   | 100    | 113   | 190    | 15.60  | 54.51  | 6.14  | 89.85 | 107   | 54       | 22       |
| Pr                             | 5.82  | 3.23  | 5.46  | 3.60   | 4.65   | 4.34   | 3.06   | 3.18   | 3.33  | 12.52 | 9.23  | 1.77   | 9.47  | 5.68    | 7.78   | 12.63 | 19.88  | 1.46   | 5.57   | 1.28  | 9.96  | 11.94 | 5.85     | 1.62     |
| Nd                             | 22.00 | 12.40 | 20.21 | 13.82  | 18.01  | 17.34  | 12.04  | 12.57  | 12.83 | 46.76 | 34.69 | 7.88   | 35.50 | 21.93   | 29.93  | 49.06 | 76.02  | 5.65   | 21.43  | 8.38  | 38.21 | 45.08 | 23.20    | 6.10     |
| Sm                             | 3.64  | 2.43  | 3.77  | 3.03   | 3.78   | 3.83   | 2.49   | 2.66   | 2.51  | 8.33  | 6.64  | 2.95   | 6.67  | 4.39    | 6.19   | 9.15  | 14.63  | 1.61   | 4.84   | 4.05  | 7.26  | 8.37  | 4.60     | 1.50     |
| Eu                             | 1.06  | 0.81  | 0.96  | 0.80   | 1.03   | 1.06   | 0.68   | 0.77   | 0.74  | 1.57  | 1.33  | 0.48   | 1.32  | 0.95    | 1.31   | 1.73  | 2.70   | 0.26   | 0.81   | 1.31  | 1.44  | 1.58  | 1.12     | 0.11     |
| Gd                             | 2.89  | 2.18  | 3.24  | 2.93   | 3.38   | 3.79   | 2.22   | 2.37   | 2.26  | 6.98  | 5.82  | 3.81   | 5.73  | 3.94    | 5.67   | 7.87  | 13.08  | 1.78   | 5.13   | 5.34  | 6.37  | 7.10  | 4.10     | 1.30     |
| Tb                             | 0.35  | 0.31  | 0.46  | 0.46   | 0.47   | 0.62   | 0.32   | 0.34   | 0.32  | 0.87  | 0.76  | 0.82   | 0.76  | 0.54    | 0.79   | 1.00  | 1.91   | 0.34   | 0.94   | 0.96  | 0.87  | 0.90  | 0.70     | 0.30     |
| Dy                             | 2.00  | 1.80  | 2.72  | 2.95   | 2.66   | 3.58   | 1.65   | 1.78   | 1.66  | 4.60  | 4.28  | 5.67   | 4.12  | 2.72    | 3.99   | 5.25  | 9.99   | 2.10   | 6.22   | 6.03  | 4.76  | 4.79  | 4.00     | 2.00     |
| Ho                             | 0.40  | 0.36  | 0.53  | 0.62   | 0.49   | 0.70   | 0.32   | 0.34   | 0.32  | 0.87  | 0.83  | 1.23   | 0.78  | 0.51    | 0.75   | 0.95  | 1.82   | 0.40   | 1.38   | 1.18  | 0.86  | 0.92  | 0.80     | 0.40     |
| Er                             | 1.09  | 0.93  | 1.41  | 1.67   | 1.24   | 2.06   | 0.91   | 0.97   | 0.90  | 2.22  | 2.18  | 3.83   | 2.03  | 1.47    | 2.20   | 2.35  | 5.10   | 1.18   | 4.25   | 3.28  | 2.12  | 2.39  | 2.30     | 1.60     |
| Tm                             | 0.15  | 0.13  | 0.19  | 0.20   | 0.15   | 0.30   | 0.12   | 0.13   | 0.12  | 0.26  | 0.28  | 0.58   | 0.25  | 0.20    | 0.29   | 0.27  | 0.69   | 0.18   | 0.60   | 0.45  | 0.25  | 0.29  | 0.34     | 0.30     |
| Yb                             | 1.09  | 0.89  | 1.36  | 1.31   | 1.08   | 2.05   | 0.83   | 0.82   | 0.73  | 1.80  | 1.96  | 3.73   | 1.72  | 1.23    | 1.88   | 1.73  | 4.29   | 1.21   | 3.82   | 2.79  | 1.74  | 2.00  | 2.20     | 2.50     |
| Lu                             | 0.17  | 0.14  | 0.20  | 0.18   | 0.16   | 0.32   | 0.12   | 0.12   | 0.11  | 0.28  | 0.31  | 0.55   | 0.26  | 0.19    | 0.29   | 0.25  | 0.59   | 0.19   | 0.59   | 0.41  | 0.26  | 0.31  | 0.34     | 0.42     |
| Hf                             | 4.01  | 3.30  | 3.83  | 3.87   | 3.00   | 3.69   | 5.75   | 3.43   | 3.41  | 5.15  | 6.59  | 1.94   | 6.23  | 5.72    | 6.37   | 8.42  | 3.46   | 1.43   | 4.06   | 10.29 | 5.47  | 5.94  | 4.20     | 3.20     |
| Ta                             | 1.91  | 3.88  | 1.97  | 1.86   | 2.79   | 2.87   | 1.49   | 1.45   | 2.33  | 2.12  | 2.30  | 3.85   | 1.64  | 3.83    | 2.43   | 2.31  | 1.79   | 2.19   | 2.38   | 1.21  | 2.61  | 2.20  | 0.30     | 6.20     |
| Pb                             | 33.13 | 23.74 | 18.45 | 6.54   | 19.66  | 15.24  | 9.27   | 5.55   | 10.18 | 19.91 | 23.94 | 33.95  | 20.57 | 8.50    | 21.04  | 18.21 | 13.27  | 3.66   | 51.39  | 21.12 | 10.54 | 19.10 | 7.00     | 18.00    |
| Th                             | 6.04  | 3.61  | 5.21  | 12.86  | 9.28   | 4.48   | 5.05   | 5.37   | 4.43  | 18.44 | 14.95 | 11.00  | 14.67 | 11.61   | 17.26  | 16.35 | 18.99  | 3.52   | 17.11  | 0.30  | 15.61 | 19.05 | 6.60     | 18.50    |
| U                              | 2.17  | 2.39  | 1.63  | 4.35   | 2.24   | 1.20   | 2.94   | 1.96   | 1.71  | 2.92  | 3.84  | 8.07   | 3.08  | 1.28    | 2.87   | 3.01  | 2.52   | 7.17   | 4.44   | 0.84  | 4.05  | 2.46  | 0.40     | 6.70     |
| A/CNK                          | 1.08  | 1.07  | 1.07  | 1.11   | 1.17   | 1.17   | 1.18   | 1.11   | 1.15  | 1.08  | 1.06  | 1.08   | 1.12  | 1.13    | 1.15   | 1.08  | 1.24   | 1.08   | 1.12   | 1.02  | 1.23  | 1.09  | 0.93     | 1.13     |
| A/NK                           | 1.72  | 1.38  | 1.45  | 1.31   | 1.36   | 1.68   | 1.51   | 1.43   | 1.47  | 1.63  | 1.69  | 1.15   | 1.62  | 1.46    | 1.67   | 1.69  | 2.31   | 1.25   | 1.41   | 1.80  | 1.73  | 1.70  | 2.51     | 1.16     |
| K/Rb                           | 311   | 435   | 366   | 263    | 307    | 287    | 338    | 295    | 344   | 270   | 239   | 254    | 257   | 244     | 229    | 272   | 216    | 316    | 251    | 249   | 216   | 227   | 281      | 85       |
| Rb/Sr                          | 0.07  | 0.10  | 0.21  | 0.50   | 0.25   | 0.13   | 0.11   | 0.28   | 0.11  | 0.25  | 0.26  | 2.10   | 0.29  | 0.35    | 0.29   | 0.11  | 0.08   | 0.24   | 0.32   | 0.16  | 0.39  | 0.29  | 0.09     | 11.08    |
| (Eu/Eu*)N                      | 0.99  | 1.08  | 0.84  | 0.82   | 0.88   | 0.85   | 0.88   | 0.94   | 0.95  | 0.63  | 0.66  | 0.44   | 0.66  | 0.69    | 0.68   | 0.62  | 0.60   | 0.47   | 0.49   | 0.86  | 0.65  | 0.63  | 0.79     | 0.24     |
| (La/Yb) <sub>N</sub>           | 15.18 | 10.08 | 10.92 | 8.10   | 11.69  | 5.73   | 10.43  | 10.58  | 13.09 | 21.18 | 13.77 | 0.98   | 15.95 | 12.04</ |        |       |        |        |        |       |       |       |          |          |

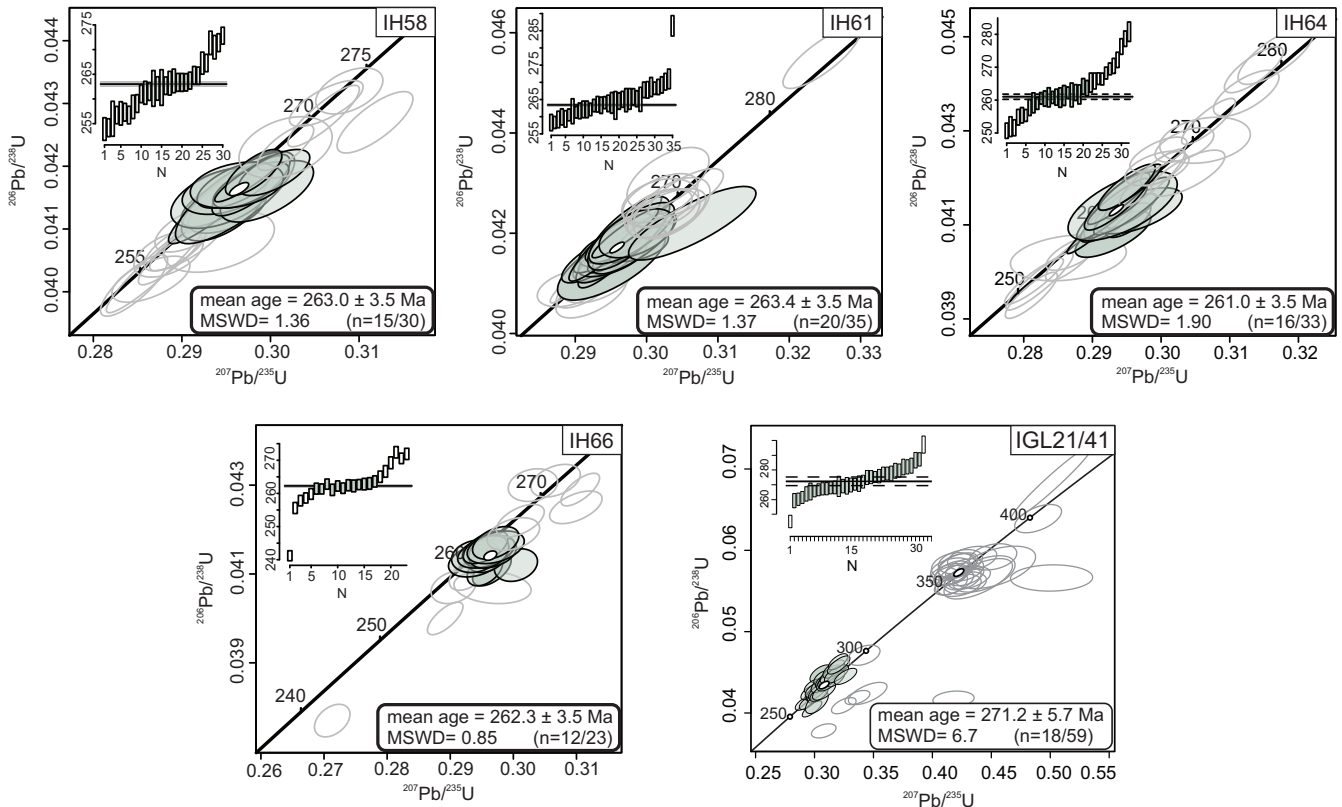


**Figure 7:** U-Pb Concordia plots and weighted mean plots (inserts) of the Eisenhut Plutonic Suite. The ages given are weighted mean  $^{206}\text{Pb}/^{238}\text{U}$  ages  $\pm$  2SE uncertainty including external components. The error ellipses are at a  $2\sigma$  level. Sample IGL21/41 contains two zircon populations; the older ages in the range of  $357.2 \pm 5.4$  Ma indicate inheritance of zircons from the Untertal Plutonic Suite.

lower  $\text{SiO}_2$  content (52.63 wt%; monzodioritic composition) is not shown on the diagrams. The meta-granitoids have high contents of  $\text{Al}_2\text{O}_3$ ,  $\text{MgO}$  and  $\text{CaO}$  (Table 5). They show clear trends for most major elements with increasing  $\text{SiO}_2$  content (Fig. A5). The trace elements Sr, Sc and V decrease with increasing  $\text{SiO}_2$  content and faint trends of decreasing Rb, Ba, Zr and Cr are visible. Sr/Y decreases and Ba/Sr increases with increasing  $\text{SiO}_2$  (Fig. A6). Samples of this suite are characterized by low to moderate Rb/Sr (0.07 to 0.39) and high K/Rb (216 to 435). Additionally, their contents of Sr, Pb, Ba and V are comparatively high. The Untertal Plutonic Suite (Fig. 11c) shows depletions in Nb, P and Ti for most samples, as well as positive anomalies in Pb, U and to some extent in Sr. It also shows slightly negative Eu-anomalies in some samples (Fig. 11d) and a pronounced decrease from LREE to HREE ( $(\text{La}/\text{Yb})_N = 3.11$  to 21.36).

The Eisenhut Plutonic Suite is characterized by high contents of  $\text{SiO}_2$  (70.27 to 81.53 wt%) and  $\text{K}_2\text{O}$  (3.79 to 4.83 wt%) (Table 6). However, a few samples (IH40, IH60 and IH64) have comparatively low  $\text{K}_2\text{O}$  contents (0.86–1.70 wt%). The latter samples tend to deviate from the other samples of this suite, probably due to assimilation of the surrounding host rocks, and were excluded from further interpretations. This Plutonic suite shows high contents of Rb (26.6 to 762  $\mu\text{g/g}$ ), Nb (6.5 to 20.2  $\mu\text{g/g}$ ) and vary-

ing Y (12.8 to 63.9  $\mu\text{g/g}$ ). Rubidium and Sc are positively correlated with  $\text{SiO}_2$ , while Ba, V, Nb and Zr are negatively correlated with  $\text{SiO}_2$  (Fig. A5). The samples have high Rb/Sr (0.1 to 133.7) and moderate K/Rb (53 to 268). A negative correlation of V/Ti and Ti/Zr with  $\text{SiO}_2$  may be linked to Fe-Ti oxide fractionation (Fig. A6). The Eisenhut Suite shows depletions in Ba, Nb, Sr, P, Eu and Ti (Fig. 11e). The REE patterns are flat with high HREE contents [ $(\text{La}/\text{Yb})_N = 0.85$ –9.38] and strong negative Eu-anomalies (0.04 to 0.32) (Fig. 11f).

## 7. Discussion

### 7.1. Subdivision of the plutonic suites and their magma sources

Schermaier et al. (1997) distinguished an I-type and an A-type granitoid group in the Schladming crystalline. Based on the petrographic and geochemical differences and the different plutonic emplacement ages, these groups can now be differentiated more precisely and we therefore propose a revised, new subdivision of the meta-granitoids of the Schladming crystalline: (1) the Lignitz Plutonic Suite as part of the Golling Complex, (2) the Untertal Plutonic Suite and (3) the Eisenhut Plutonic Suite. The latter two are part of the Riesach Complex.

The classification follows the scheme of the North

| Sample                         | IH35   | IH36   | IH40   | IH58  | IH59  | IH60   | IH61  | IH62  | IH64  | IH66  | IH67  | IGL21/41 |
|--------------------------------|--------|--------|--------|-------|-------|--------|-------|-------|-------|-------|-------|----------|
| SiO <sub>2</sub>               | 77.15  | 77.57  | 72.05  | 72.67 | 73.23 | 70.27  | 81.53 | 74.12 | 75.70 | 73.89 | 76.18 | 74.97    |
| TiO <sub>2</sub>               | 0.07   | 0.10   | 0.32   | 0.29  | 0.32  | 0.37   | 0.18  | 0.19  | 0.24  | 0.20  | 0.05  | 0.19     |
| Al <sub>2</sub> O <sub>3</sub> | 12.67  | 13.17  | 15.11  | 13.49 | 13.25 | 15.23  | 9.11  | 13.36 | 13.29 | 13.03 | 12.58 | 13.33    |
| Fe <sub>2</sub> O <sub>3</sub> | 1.03   | 0.87   | 2.77   | 2.49  | 2.56  | 3.07   | 1.26  | 1.69  | 1.46  | 1.70  | 0.96  | 1.46     |
| MnO                            | 0.06   | 0.05   | 0.06   | 0.04  | 0.04  | 0.07   | 0.02  | 0.04  | 0.02  | 0.05  | 0.03  | 0.03     |
| MgO                            | 0.04   | 0.21   | 0.71   | 0.45  | 0.46  | 0.92   | 0.26  | 0.25  | 0.36  | 0.23  | 0.04  | 0.19     |
| CaO                            | 0.06   | 0.04   | 2.57   | 0.67  | 0.78  | 2.95   | 0.18  | 0.73  | 0.30  | 0.69  | 0.11  | 0.19     |
| K <sub>2</sub> O               | 4.83   | 3.94   | 0.89   | 4.53  | 4.27  | 0.86   | 3.79  | 4.70  | 1.70  | 4.66  | 4.35  | 4.41     |
| Na <sub>2</sub> O              | 3.50   | 4.22   | 4.65   | 4.00  | 3.89  | 4.84   | 2.27  | 3.74  | 5.37  | 3.58  | 3.37  | 4.06     |
| P <sub>2</sub> O <sub>5</sub>  | 0.04   | 0.05   | 0.11   | 0.07  | 0.08  | 0.12   | 0.05  | 0.05  | 0.07  | 0.07  | 0.06  | 0.04     |
| LOI                            | 0.53   | 0.41   | 0.59   | 0.55  | 0.56  | 0.71   | 0.46  | 0.47  | 0.81  | 0.75  | 0.88  | 1.06     |
| Sum                            | 100.24 | 100.91 | 100.51 | 99.47 | 99.63 | 99.58  | 99.31 | 99.56 | 99.50 | 99.10 | 98.87 | 99.93    |
| Li                             | 128    | 365    | 6.66   | 16.1  | 24.3  | 12.6   | 8.10  | 17.1  | 36.5  | 29.00 | 104   | n.d.     |
| Sc                             | 3.81   | 4.82   | 5.99   | 5.92  | 6.58  | 5.94   | 1.74  | 3.83  | 6.58  | 3.99  | 3.03  | 5.00     |
| V                              | 2.34   | 4.07   | 16.89  | 14.0  | 14.0  | 26.3   | 9.40  | 8.52  | 9.21  | 8.14  | 1.63  | 9.00     |
| Cr                             | 2.78   | 3.25   | 5.44   | 3.98  | 3.71  | 12.8   | 4.92  | 4.07  | 3.07  | 7.08  | 5.48  | < 20     |
| Ni                             | 1.75   | 2.11   | 3.31   | 2.14  | 2.10  | 7.36   | 2.23  | 2.29  | 1.75  | 1.92  | 1.86  | < 20     |
| Cu                             | 0.47   | 59.35  | 1.52   | 1.06  | 0.54  | 7.91   | 1.40  | 2.77  | 11.3  | 8.89  | 0.82  | < 10     |
| Zn                             | 24.02  | 32.6   | 20.43  | 14.1  | 19.7  | 32.2   | 7.65  | 15.2  | 8.23  | 34.1  | 85.7  | < 30     |
| Ga                             | 20.0   | 17.40  | 16.7   | 16.70 | 14.70 | 17.4   | 13.9  | 14.00 | 20.6  | 13.00 | 20.2  | 21.00    |
| Rb                             | 762    | 542    | 27.90  | 245   | 270   | 26.60  | 233   | 275   | 104   | 317   | 668   | 432      |
| Sr                             | 5.70   | 15.50  | 259    | 45.90 | 49.20 | 232.30 | 33.80 | 52.00 | 38.10 | 49.00 | 8.00  | 39       |
| Y                              | 15.28  | 38.8   | 24.27  | 50.7  | 60.2  | 12.8   | 16.1  | 30.4  | 63.9  | 45.7  | 23.2  | 13.00    |
| Zr                             | 49.20  | 60.80  | 217    | 272   | 245   | 196    | 107   | 165   | 224   | 159   | 39.00 | 121      |
| Nb                             | 14.41  | 20.2   | 6.48   | 19.0  | 19.6  | 7.78   | 8.91  | 16.9  | 20.7  | 15.8  | 11.7  | 16.00    |
| Cs                             | 60.20  | 32.6   | 0.42   | 8.90  | 14.4  | 0.73   | 5.65  | 12.5  | 1.95  | 11.38 | 41.87 | 22.90    |
| Ba                             | 17.40  | 75.60  | 275    | 320   | 209   | 285    | 125   | 350   | 235   | 208   | 18.00 | 149      |
| La                             | 3.10   | 9.81   | 26.49  | 47.9  | 32.4  | 11.0   | 6.78  | 20.9  | 41.4  | 15.9  | 4.56  | 6.50     |
| Ce                             | 14.89  | 30.6   | 55.69  | 102   | 86.2  | 39.4   | 37.7  | 64.0  | 85.4  | 51.9  | 11.1  | 22       |
| Pr                             | 0.93   | 3.09   | 6.46   | 11.3  | 8.16  | 2.95   | 2.23  | 5.94  | 10.2  | 4.91  | 1.51  | 1.62     |
| Nd                             | 3.32   | 11.2   | 25.34  | 42.1  | 31.6  | 12.1   | 8.58  | 23.1  | 38.9  | 20.0  | 5.54  | 6.10     |
| Sm                             | 1.01   | 4.00   | 4.87   | 8.99  | 7.82  | 2.60   | 2.18  | 5.44  | 9.17  | 5.53  | 1.94  | 1.50     |
| Eu                             | 0.02   | 0.10   | 1.35   | 0.93  | 0.75  | 0.86   | 0.20  | 0.54  | 0.91  | 0.50  | 0.02  | 0.11     |
| Gd                             | 1.24   | 4.18   | 4.67   | 8.86  | 8.48  | 2.60   | 2.26  | 5.61  | 9.51  | 6.17  | 2.15  | 1.30     |
| Tb                             | 0.31   | 1.03   | 0.72   | 1.47  | 1.57  | 0.40   | 0.44  | 0.99  | 1.71  | 1.18  | 0.54  | 0.30     |
| Dy                             | 2.28   | 6.89   | 4.25   | 8.49  | 9.74  | 2.32   | 2.80  | 5.95  | 10.4  | 7.69  | 3.92  | 2.00     |
| Ho                             | 0.52   | 1.38   | 0.81   | 1.69  | 2.05  | 0.45   | 0.60  | 1.22  | 2.15  | 1.61  | 0.81  | 0.40     |
| Er                             | 1.77   | 4.55   | 2.27   | 5.07  | 6.28  | 1.31   | 1.92  | 3.62  | 6.59  | 4.97  | 2.66  | 1.60     |
| Tm                             | 0.33   | 0.81   | 0.31   | 0.73  | 0.94  | 0.18   | 0.32  | 0.54  | 1.00  | 0.78  | 0.48  | 0.30     |
| Yb                             | 2.47   | 6.10   | 1.91   | 4.71  | 6.22  | 1.20   | 2.19  | 3.53  | 6.64  | 5.20  | 3.57  | 2.50     |
| Lu                             | 0.41   | 0.93   | 0.29   | 0.69  | 0.94  | 0.19   | 0.34  | 0.54  | 0.99  | 0.81  | 0.54  | 0.42     |
| Hf                             | 2.66   | 2.93   | 6.77   | 2.94  | 8.01  | 6.74   | 6.24  | 3.38  | 4.96  | 5.21  | 2.05  | 3.20     |
| Ta                             | 8.47   | 9.20   | 2.06   | 4.00  | 5.05  | 2.54   | 4.01  | 4.35  | 5.21  | 6.12  | 5.66  | 6.20     |
| Pb                             | 24.36  | 19.2   | 4.34   | 7.67  | 12.9  | 6.06   | 9.81  | 9.75  | 3.07  | 18.3  | 16.3  | 18.00    |
| Th                             | 23.21  | 21.6   | 4.97   | 27.0  | 36.4  | 2.68   | 24.5  | 18.0  | 25.5  | 18.5  | 16.6  | 18.50    |
| U                              | 4.90   | 15.78  | 0.81   | 6.65  | 10.87 | 0.59   | 2.93  | 5.44  | 7.52  | 7.45  | 2.49  | 6.70     |
| A/CNK                          | 1.14   | 1.17   | 1.14   | 1.06  | 1.07  | 1.07   | 1.12  | 1.06  | 1.18  | 1.07  | 1.20  | 1.13     |
| A/NK                           | 1.15   | 1.18   | 1.76   | 1.17  | 1.20  | 1.71   | 1.16  | 1.19  | 1.25  | 1.19  | 1.23  | 1.16     |
| K/Rb                           | 52.60  | 60.37  | 265    | 154   | 131   | 268    | 135   | 142   | 136   | 122   | 54.06 | 85       |
| Rb/Sr                          | 134    | 34.95  | 0.11   | 5.34  | 5.49  | 0.11   | 6.90  | 5.28  | 2.73  | 6.47  | 83.50 | 11.08    |
| (Eu/Eu*) <sub>N</sub>          | 0.05   | 0.07   | 0.87   | 0.32  | 0.28  | 1.01   | 0.28  | 0.30  | 0.30  | 0.26  | 0.04  | 0.24     |
| (La/Yb*) <sub>N</sub>          | 0.85   | 1.09   | 9.38   | 6.88  | 3.52  | 6.19   | 2.10  | 4.01  | 4.21  | 2.06  | 0.86  | 1.76     |
| Nb/Ta                          | 1.70   | 2.20   | 3.14   | 4.75  | 3.89  | 3.07   | 2.22  | 3.88  | 3.97  | 2.59  | 2.06  | 2.58     |

**Table 6:** Major element oxides, selected trace element and rare earth element data of the meta-granitoids of the Eisenhut Plutonic Suite. Major oxides are given in weight percent, Rb and Sr contents are given in parts per million [ppm, i.e., µg/g].

American Commission of Stratigraphic Nomenclature (2005), which basically defines a suite as group of related, intrusive magmatic rock bodies (plutons) that formed in the Earth's crust during a common geological event or episode. Although the geochemical compositions and geochronological ages were used as supplementary information for this subdivision, the distinction is mainly based on petrographic observations including the modal rock compositions, texture and structure.

### 7.1.1. Lignitz Plutonic Suite

This suite comprises mostly fine-grained orthogneisses and some coarser grained granitoids of granitic composition, some resemble high-K calc-alkaline granitic magmas. Occurrences are mainly exposed in the western part of the Golling Complex (Fig. 2). The U-Pb zircon weighted mean ages range from ca. 480 to 501 Ma and indicate intrusion in the late Cambrian. Ti-in-zircon thermometry indicates a mean intrusion temperature

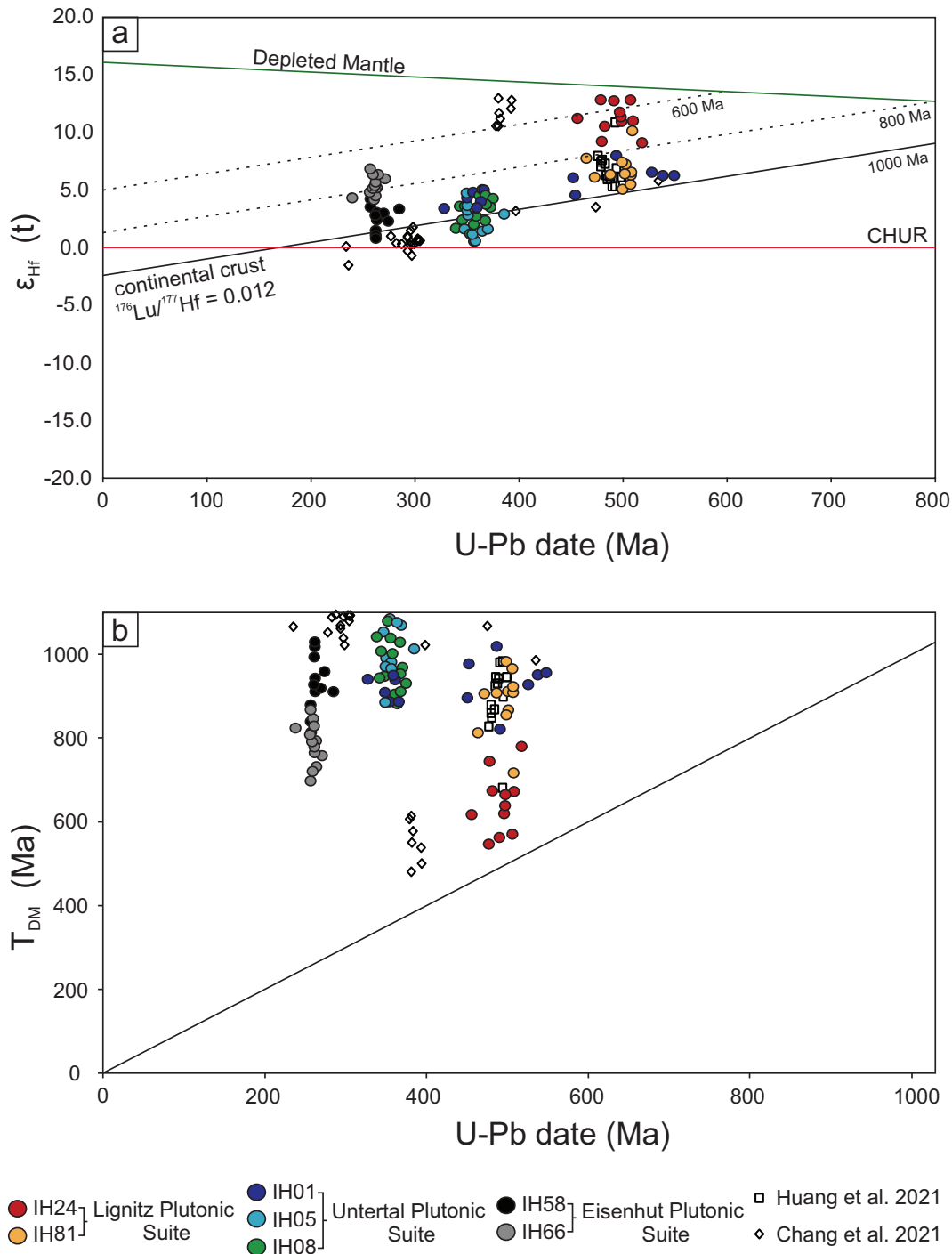


**Figure 8:** (a)  $\epsilon_{\text{Hf}}$  versus U-Pb age diagram and (b) depleted mantle model age ( $T_{\text{DM}}$ ) versus U-Pb age diagram of samples from each plutonic suite of the Schladming crystalline. CHUR: Chondritic Uniform Reservoir. The reference lines for CHUR, depleted mantle and average continental crust are taken or calculated from data from Bouvier et al. (2008), Vervoort et al. (2016), and Spencer et al. (2020).

of  $\sim 820^\circ\text{C}$ . This suite is highly differentiated ( $>71$  wt%  $\text{SiO}_2$ ) and has rather low Rb/Sr ratios. The rocks are meto-peraluminous, magnesian to ferroan and have a calc-alkalic character. The highly fractionated characteristics of the suite conceal bivariate trends of major and trace elements (Table 4). The calcalkaline nature indicates either a continental arc setting with a parental mantle melt enriched in LREE – probably contaminated during its as-

cent, or a syn- to post-collisional setting with melting of crustal source rocks due to decompression following slab break-off. The slight enrichment in LILE (Fig. 11b) rather supports crustal contamination of mafic magmas (e.g., Laurent et al., 2014).

The variability of highly incompatible trace elements (e.g., Rb, Ba, Pb, Th and LREE) in the Lignitz Plutonic Suite supports assimilation of crustal material or addition of

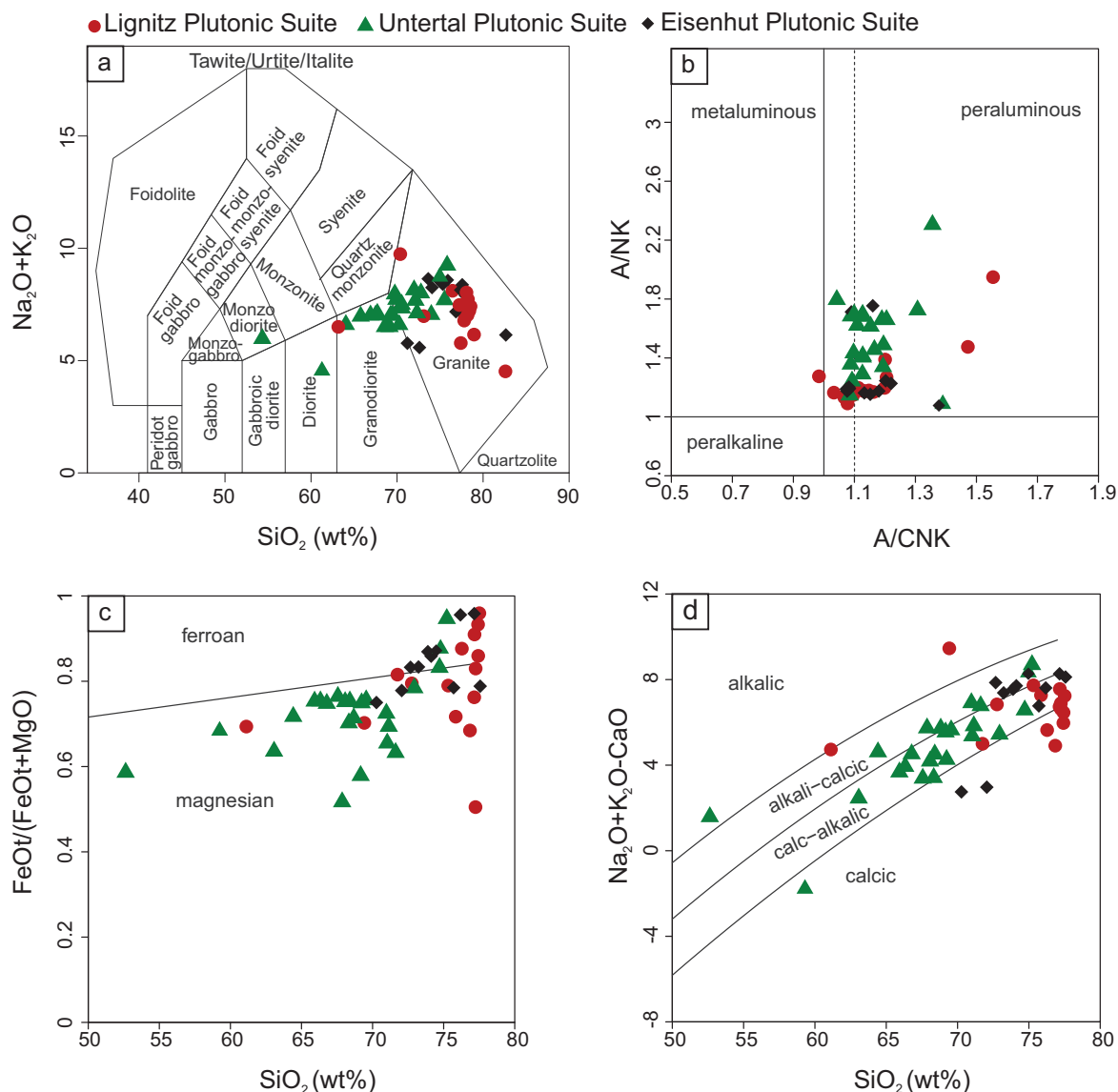


**Figure 9:** (a) TAS (total alkali vs silica, wt%) classification diagram (Middlemost, 1994) showing the composition (wt%) of the granitoids of the plutonic suites. (b) A/NK vs ASI plot; the division between metaluminous and peraluminous granites is at A/CNK 1.0 (Shand 1943), the division between I-type and S-type granites is at A/CNK 1.1 (Chappell and White 2001). (c) classification of ferroan and magnesian samples and (d) classification of alkalic, alkali-calcic, calc-alkalic and calcic samples for granitoids (Frost and Frost, 2008).

crust-derived melts to a basic melt. This is also indicated by discrimination plots (Fig. 9c-d), in which a crossing of the trend lines is interpreted as mixing of melts (Frost et al., 2001). Moreover, the high abundance of some incompatible elements (Cs, Rb, Ba, Sr) may indicate an enriched mantle source or a derivation from partial melting of alkaline mafic crustal rocks. Nevertheless, the melt source of the Lignitz Plutonic Suite is difficult to constrain as the intrusive bodies have a high compositional variability.

An origin from a mantle source with varying degrees of crustal contamination is supported by zircon Hf-isotopes. The  $\epsilon\text{Hf}(t)$  versus U-Pb age diagram (Fig. 8) shows two separate groups of zircons from the Lignitz Plutonic Suite. One group (sample IH24) lies slightly below the depleted mantle curve, which indicates a juvenile source without remarkable crustal contribution. In contrast, the

other group (sample IH81) also comprises recycled crustal material that was probably assimilated during pluton ascent through the crust. Samples IH81 and IH24 have the same zircon crystallization ages but different  $T_{\text{DM}}$  ages. While sample IH81 shows crustal contamination resulting in older model ages ( $T_{\text{DM}}$  717 to 982 Ma), sample IH24 has younger  $T_{\text{DM}}$  ages (548 to 781 Ma), that nearly overlap the crystallization ages. Hafnium isotopes from a plagioclase gneiss from the western part of the Golling Complex (Huang et al., 2021) are comparable to the mantle-influenced samples of the Lignitz Plutonic Suite. Huang et al. (2021) obtained similar model ages, even though the U-Pb zircon ages differ by up to ca. 30 Ma (464 and 487 Ma); the protolith was interpreted to have been derived from the lower crust.

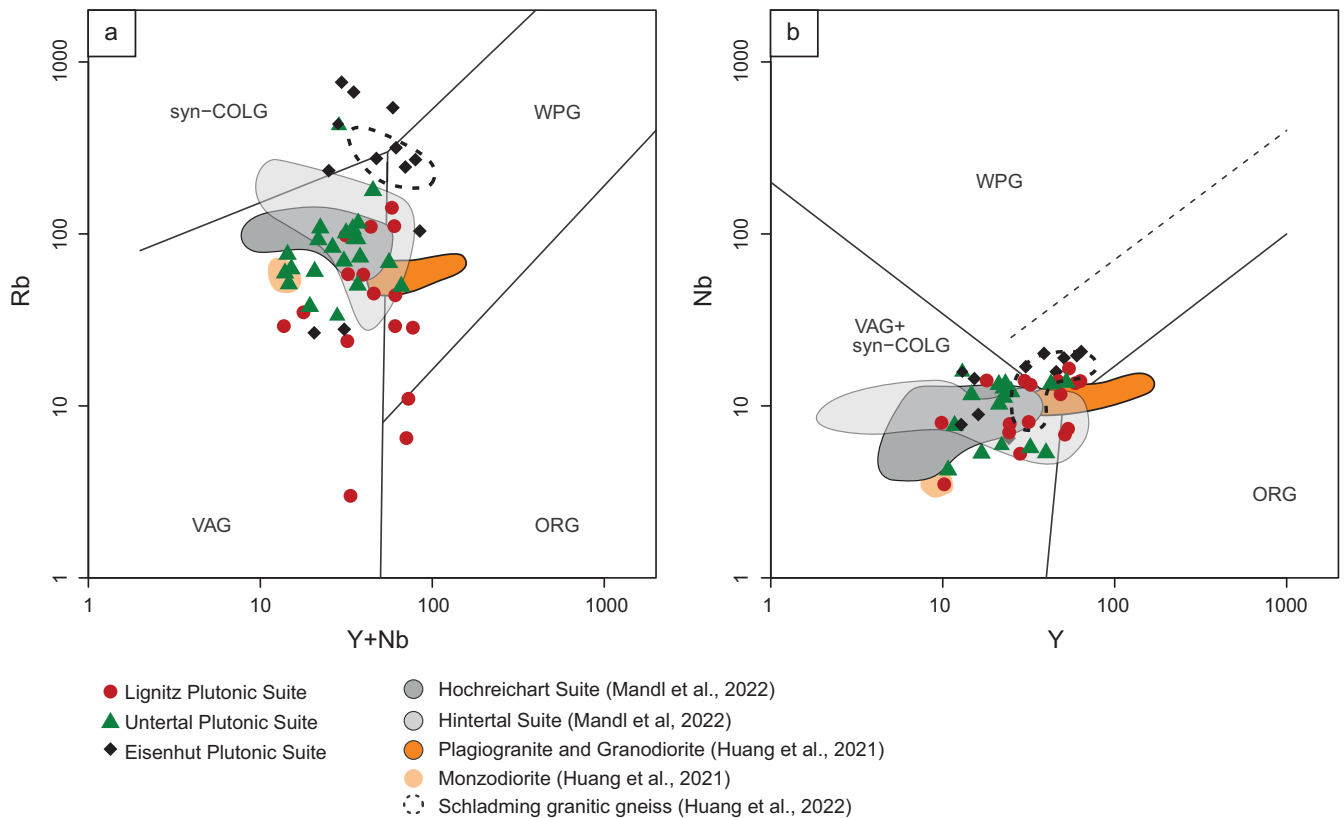


**Figure 10:** Geotectonic discrimination plots for granitoids (Pearce et al., 1984) of the three plutonic suites of the Schladming crystalline. The data sets presented by Huang et al. (2021, 2022) and Mandl et al. (2022) are displayed for comparison. VAG: volcanic arc granite, ORG: ocean ridge granite, WPG: within plate granite, syn-COLG: syn-collisional granite.

### 7.1.2. Untertal Plutonic Suite

The Untertal Plutonic Suite is characterized by coarse- to medium-grained meta-granites to meta-granodiorites, often showing well preserved plutonic textures. Its main occurrences are in the northern and north-eastern parts of the Riesach Complex (Fig. 2). The U-Pb zircon ages range from ca. 350 to 370 Ma, representing Late Devonian / Mississippian intrusion ages. Zircon cores commonly have late Cambrian ages (e.g.,  $497 \pm 5$  Ma for a zircon in IH15). The rocks are weakly peraluminous, mostly magnesian and have calc-alkalic to alkali-calcic affinities. According to Schermaier et al. (1997), the rocks can be generally described as high-K I-type granitoids. The granitoids of the Untertal Plutonic Suite show a slightly negative Eu anomaly and decreasing Sr/Y and increasing Ba/Sr ratio with increasing  $\text{SiO}_2$  (Fig. A6c–d). Such fractionation trends are compatible with crystallization of feldspar and to a lesser degree biotite, which are probably also accompanied by amphibole and the accessory minerals apatite, allanite, Fe-Ti-oxides and zircon. Zircon trace element data support co-crystallisation of titanite, apatite, or other LREE-bearing accessories (Schaltegger and Davies, 2017) (Fig. A2).

The Untertal Plutonic Suite comprises magnesian granitoids (Fig. 9c) derived from relatively hydrous, oxidizing magmas, which broadly originate from subduction-related processes (Frost et al., 2001) as indicated by

pronounced negative Nb, P and Ti anomalies (Fig. 11c) (Pearce and Peate, 1995; Schandl and Gorton, 2002). This is in agreement with the rather low Ti-in-zircon thermometry temperatures ranging from  $\sim 715$  to  $760$  °C, probably hinting to a cooler, wetter, origin.

The relatively high  $\text{CaO}/\text{Na}_2\text{O}$  ratios, the only mildly developed negative Eu anomaly and lack of a negative Sr anomaly favor only minor plagioclase fractionation (Fig. 11c-d). An intermediate to felsic composition and the rather low Th and high Ti, Ba, Sr, Cr contents, together with well-defined Harker trends point to an origin from a metabasic crustal source and basic igneous melts (Drüppel et al., 2009). Additional evidence for a remelted metabasic granulitic crustal source are  $\text{TiO}_2/\text{MgO}$  and  $(\text{Na}_2\text{O}+\text{K}_2\text{O})/\text{Al}$  ratios lower than one.

Zircon cores of a sample from the Untertal Plutonic Suite (IH01 in Fig. 4) point to recycled crustal material that was probably assimilated during pluton ascent through the crust. Cambrian U-Pb zircon core ages and Hf isotopes following an evolution trend of average continental crust probably indicate that material of the older Cambrian Lignitz Plutonic Suite was incorporated into the Late Devonian / early Carboniferous Untertal Plutonic Suite. Therefore, at least partial reworking of the older Cambrian granitoids into the Late Devonian / early Carboniferous Untertal Plutonic Suite must have occurred. Moreover, intermediate  $\epsilon\text{Hf}(t)$  values may indi-

cate mixing of old crust and mantle-derived material to form hybrid melts or recycling of older continental crust (Schaltegger et al., 2009).

### 7.1.3. Eisenhut Plutonic Suite

The Eisenhut Plutonic Suite is characterized by fine- to medium-grained metagranitic rocks, frequently with an augengneiss appearance. This suite only occurs in the southeastern part of the Riesach Complex, close to the Koralpe-Wölz Nappe System thrust contact (Fig. 2). The U-Pb zircon ages indicate Permian intrusion at 262 to 263 Ma. In the southern part of the Riesach Complex, an intrusion age of  $271.2 \pm 5.7$  Ma is observed. Schermaier et al. (1997) have already recognized these granitoids in the eastern part of the Schladming crystalline as a distinct group with clearly higher FeO/MgO ratios and lower  $\text{Al}_2\text{O}_3$  and CaO contents than the Untertal Plutonic Suite.

The rocks (except the altered samples IH40 and IH60) have high  $\text{SiO}_2$  and  $\text{K}_2\text{O}$  contents and are enriched in Rb, which is characteristic for highly differentiated granitic magmas. They have the highest Rb/Sr ratios of all three plutonic suites. Moreover, they have low contents of CaO, Ba, Sr and high Fe/Mg ratios. This suite is peraluminous, ferroan and has a calc-alkalic to alkali-calcic character.

Trends of decreasing FeO,  $\text{TiO}_2$ , MgO, CaO,  $\text{P}_2\text{O}_5$ , Zr and to a lesser degree in Ce and Y with increasing  $\text{SiO}_2$  indicate fractionation of accessory Fe-Ti-oxides, apatite, zircon, plagioclase and potentially allanite (Fig. A5). Negative correlations of V/Ti and Ti/Zr with  $\text{SiO}_2$  support Fe-Ti oxide fractionation (Fig. A6a–b). Additionally, pronounced negative Eu anomalies (Fig. 11f) as well as high Rb and low Sr contents indicate crystallization of plagioclase from acidic melts. This is consistent with REE in zircon, which show the most pronounced negative Eu anomalies of all suites, and co-crystallization of titanite and apatite or other LREE-bearing phases (Figs. A1f, A2). Enrichment of K, Rb, Th, U and the LREE in addition to increasing Rb/Sr and decreasing K/Rb with increasing  $\text{SiO}_2$  may point to a progressive crystal fractionation from an alkali-rich primitive melt (Fig. A5) (Drüppel et al., 2009). The high content of Rb, Th and K might also indicate upper crustal contamination. This is also indicated by the inherited older Untertal Suite zircon population in sample IGL21/41 (Figs. 6b–7).

The Nb/Ta ratios of the Eisenhut Plutonic Suite are higher or similar to ratios of the upper continental crust (2.2) (Barth et al., 2000) and indicate a crustal influence. The distinct negative Ba, Sr, Eu, Ti and P anomalies (Fig. 11e–f), as well as the low CaO content and the enrichment in Rb, Cs and overall high HFSE (Zr,  $\text{Zr}+\text{Nb}+\text{Y}+\text{Ce}$ ) contents point to partial melting of a halogen-bearing dry, granulitic residue that remained after the extraction of an earlier melt phase (Frost et al., 2001). REE patterns are characterized by high HREE contents, pronounced negative Eu-anomalies and only a slight enrichment of LREE relative to the HREE (Fig. 11e–f), which are typical for A-type granites (Schermeier et al., 1997).

The zircon Hf isotope signatures of the Eisenhut Plutonic Suite indicate crustal contamination and mixing of old crust and mantle-derived material to form hybrid melts or recycling of older continental crust (Schaltegger et al., 2009).  $\epsilon\text{Hf}(t)$  mean values of 5.2 and 2.7 probably indicate input of juvenile material. The Permian granitoids described by Chang et al. (2021) show  $\epsilon\text{Hf}(t)$  values between -1.5 and +3, slightly lower than those obtained from the Eisenhut Plutonic Suite. Hafnium isotopic variations of Triassic granitoids from the Riesach Complex (Huang et al., 2022) tend to show lower to similar values ( $\epsilon\text{Hf}(t)=0.2$  to 5.6) as the samples from the Eisenhut Plutonic Suite and were presumably derived from the lower crust (Huang et al., 2022).

In a post-collision to post-orogenic setting, it is commonly argued that crustal as well as mantle influenced sources might be involved (e.g., Bonin, 2004). Ferroan granites, such as the Eisenhut Plutonic Suite, are commonly interpreted to derive from anhydrous and reduced magma in an extensional tectonic setting. The granitoids of this suite might therefore be classified as A-type. The Ti-in-zircon thermometry hints at a rather low melt temperature of  $\sim 800^\circ\text{C}$ . Usually, such magmas are hotter and undergo extensive fractionation toward iron-rich alkalic compositions (Frost et al., 2001). In order to form granitic melts from a dry granulite, heat and mass input into the lower crust through mantle-derived basic magmas is required (Aranovich et al., 2014). Injection of basaltic magma into the lower crust or asthenosphere upwelling could provide the necessary heat that triggers melting in both mantle and continental crust within a regional extensional regime accompanied by thinning of the lithosphere (e.g., Klötzli et al., 2014; Schuster and Stüwe, 2008). Such a setting would be consistent with the observed Permian magmatism and high-temperature – low pressure metamorphism (Schuster and Stüwe, 2008) within several nappe systems of the Austroalpine unit.

## 7.2. Correlation within the Austroalpine unit

Based on its analogous tectono-metamorphic evolution and tectonic position, it is widely accepted that the Schladming crystalline is part of the Silvretta-Seckau Nappe System (e.g., Schmid et al., 2004; Kurz et al., 2024). We therefore correlate the pre-Alpine magmatic evolution of the Schladming crystalline with that of the Seckau Complex, which has been recently studied by Mandl et al. (2018, 2022).

In the Seckau Complex two plutonic suites were identified: The Hochreichart Plutonic Suite and the Hintertal Plutonic Suite (Mandl et al., 2018). U-Pb zircon dating of the Hochreichart Plutonic Suite revealed Cambrian ages of ca. 500 Ma that overlap the ages obtained for the Lignitz Plutonic Suite in the western part of the Schladming crystalline in this study. Therefore, the Lignitz Plutonic Suite is regarded as an equivalent of the Hochreichart Plutonic Suite of the Seckau Complex. The Lignitz Plutonic Suite, however, seems to be more fractionated than

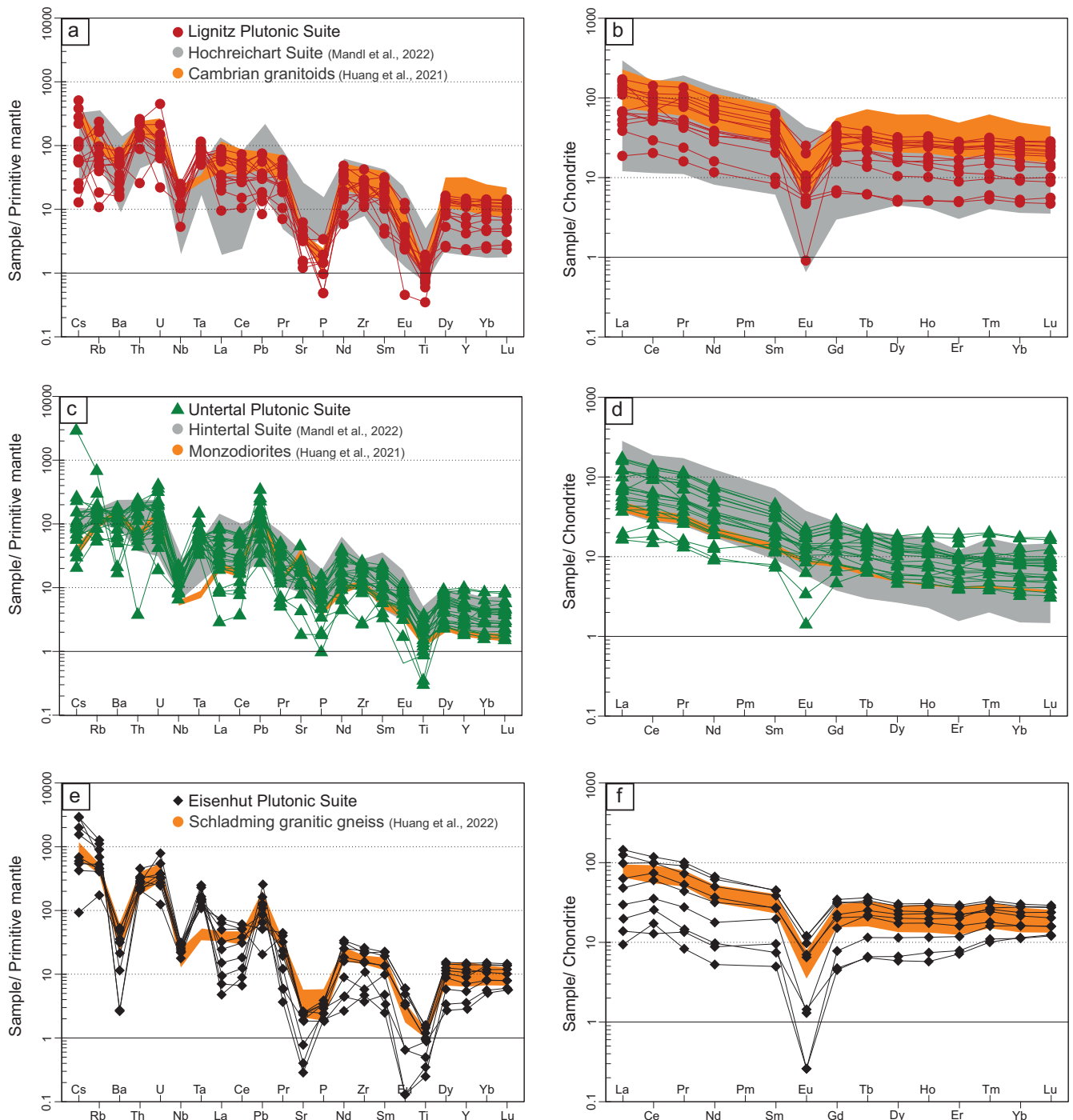


**Figure 11:** Primitive mantle-normalized trace element (Sun and McDonough, 1989) and chondrite-normalized rare earth element (Nakamura, 1974) plots for granitoids of the Lignitz Plutonic Suite (a, b), the Untertal Plutonic Suite (c, d) and the Eisenhut Plutonic Suite (e, f). Data sets of Mandl et al. (2022) and Huang et al. (2021, 2022) are displayed for comparison.

the Hochreichart Plutonic Suite (Fig. 11a, b). Granitoids of both suites widely show peraluminous, in parts of the Lignitz Suite metaluminous character (Shand, 1943), and indicate S-type to minor I-type affinity (Chappell and White, 2001). This might indicate that although the Lignitz Suite geochemically shows, for some portions, S-type character, it genetically evolved from metaluminous I-type melt. Selected trace element data from the Lignitz and the Hochreichart Plutonic Suites show that

the latter has higher contents of Rb, Ba, V and Cr, while the suites are similar in Sr, Nb and Sc. The Hochreichart Plutonic Suite and the Lignitz Plutonic Suite also have similar REE patterns with a clear negative Eu anomaly (Fig. 11a–b). Granitoids from the western Schladming crystalline described by Huang et al. (2021) also overlap the compositional range of the Lignitz Plutonic Suite.

The Hintertal Plutonic Suite of the Seckau Complex comprises Late Devonian / early Carboniferous (Missis-

sippian) zircon ages of ca. 350 Ma, which are comparable to the ages of the Untertal Plutonic Suite in the northern part of the Schladming crystalline. The  $\text{SiO}_2$  contents of the Untertal Plutonic Suite tend to be higher than those of the Hintertal Plutonic Suite (Fig. A4) whereas major element oxides of the Hintertal and Untertal Plutonic Suites are similar except for  $\text{K}_2\text{O}$  and  $\text{Na}_2\text{O}$  contents. While the Untertal Plutonic Suite has lower contents of  $\text{K}_2\text{O}$ , it is higher in  $\text{Na}_2\text{O}$ . Both suites show similar trace element contents and variations (Fig. A4), and their primitive mantle-normalized and REE patterns overlap and show no or only a slightly negative Eu anomaly (Fig. 11c–d). Based on geochemical data, Schermaier et al. (1997) already suggested a correlation of the Schladming I-type granites with the Seckau I-type granites.

The Permian ages of the Eisenhut Plutonic Suite occurring in the Schladming crystalline have not yet been reported from the Seckau Complex. However, ages within that range were described from the Speik Complex within the Gleinalm crystalline adjacent to the Seckau Nappe *sensu strictu* (Neubauer et al., 2022). Permian granites described by Huang et al. (2022) are geochemically similar to the Eisenhut Plutonic Suite and overlap with their high  $\text{K}_2\text{O}$  samples, however, they differ in their U-Pb zircon ages. The Permian Tweng granitoids described by Huang et al. (2021) do not correlate with any of the suites of this study and are part of the Lower Austroalpine Radstadt Nappe System instead.

The general similarities of U-Pb ages and geochemistry of the plutonic suites of the Schladming crystalline and the Seckau Complex allow a correlation of these units and indicate a common tectono-magmatic history. While the Hochreichart Plutonic Suite likely formed at a late Cambrian to Early Ordovician active margin, the Hintertal Plutonic Suite represents early Variscan granitoids that formed in a magmatic arc along the southern Bohemian active margin (Mandl et al., 2018; Mandl et al., 2022). It is very likely that the Lignitz and the Untertal Plutonic Suites were formed in equivalent tectonic settings.

A very similar assemblage of distinct magmatic suites has been recently described in the Troiseck Complex, another unit within the Silvretta-Seckau Nappe System, further east in the Eastern Alps (Reiser et al., 2024). A Late Cambrian U-Pb zircon crystallization age ( $502.4 \pm 6.8$  Ma) of granitic intrusions indicates late Cambrian/Ordovician magmatism. Pegmatite dikes have Late Devonian / early Carboniferous ages (ca. 353 Ma), while Pennsylvanian ages of overgrowth rims of Late Devonian / early Carboniferous zircons and inherited grains (ca. 320 Ma) indicate late Variscan metamorphism. Rhyolitic to andesitic volcanic rocks (ca. 271 to 264 Ma) are concomitant with Permian intrusions of porphyric granitoids now transformed to augengneisses (ca. 271 Ma) (Reiser et al., 2024).

Additionally, the ages of the studied plutonic suites correlate with magmatic ages documented in other parts of the Alpine realm. Cambrian to Late Ordovician acidic magmatic bodies are also widespread in the Eastern and Southern Alps. Such granitoids occur, e.g., within the Def-

eregggen Mountains to the south of the Tauern Window (Schulz et al. 2004, 2008), in the Ötztal-Stubai Complex (Hoinkes et al., 1997; Thöny et al., 2008) and the Silvretta Nappe (Nilius et al., 2016). South of the Periadriatic Fault, acidic igneous rocks are prominently exposed in the Strona-Ceneri Zone, the type locality for the Ceneric orogenic event (Zurbruggen 2015, 2017, 2020; Siegesmund et al. 2023; Finger and Riegler, 2023). These occurrences together with the Lignitz and Hochreichart Plutonic Suites may define a belt along a Cambrian active margin, and shed light on its paleogeographic arrangement.

### 7.3. Pre-Alpine Evolution of the Schladming crystalline and Paleogeographic framework

There is wide consensus that pre-Alpine crustal blocks, now incorporated into the Austroalpine unit, derived from the northern Gondwana margin (for summary see Mandl et al. (2022) and references therein). The meta-granitoids of the Schladming crystalline provide information on the late Cambrian to Early Ordovician, Late Devonian to Mississippian (early Variscan), and Permian magmatic history. These magmatic events are discussed within their paleogeographic context and tectonic setting in this section. The details of the magmatic and tectonic events that span from late Neoproterozoic / Cambrian Gondwana destabilization to formation of Variscan Pangea, are still discussed controversially. Therefore, paleogeographic reconstructions of the northern Gondwana margin in relation to Variscan and pre-Variscan plate tectonic settings are numerous and vary in definition and nomenclature of microcontinents, oceans, timing and components involved (e.g., Kroner and Romer, 2013; von Raumer et al., 2003; von Raumer et al., 2013; Stampfli et al., 2013). Additional paleogeographic reconstructions, also including the intra-Alpine pre-Alpine units, were recently provided by Finger et al. (1997) and Finger and Riegler (2023, 2025).

#### 7.3.1. Early Paleozoic evolution

Late Neoproterozoic to early Cambrian magmatism along the northern Gondwana margin has been widely recognized by several authors (e.g., Johnson et al., 2011; Neubauer, 2002; von Raumer and Stampfli, 2008). According to von Raumer et al. (2013), this magmatism corresponds to a Neoproterozoic to Cambrian active margin, which was followed by a Cambrian to Ordovician rifting period represented by alkaline granitoids (von Raumer et al., 2003). The detachment of crustal pieces was non-simultaneous along the northern Gondwana margin. Hunia (ca. 460 Ma) was presumably the first of several terranes in the east, which, similarly to Avalonia (ca. 480 Ma) in the west, detached in the Ordovician during opening of the Rheic ocean (Stampfli et al., 2011; von Raumer et al., 2013). Contrary to that model, other studies referred to an active margin of similar age, however, attributed it to a proto-Rheic – Quaidam ocean, that was closed during the Ceneric orogeny (Zurbruggen, 2017; Burda et al., 2021).

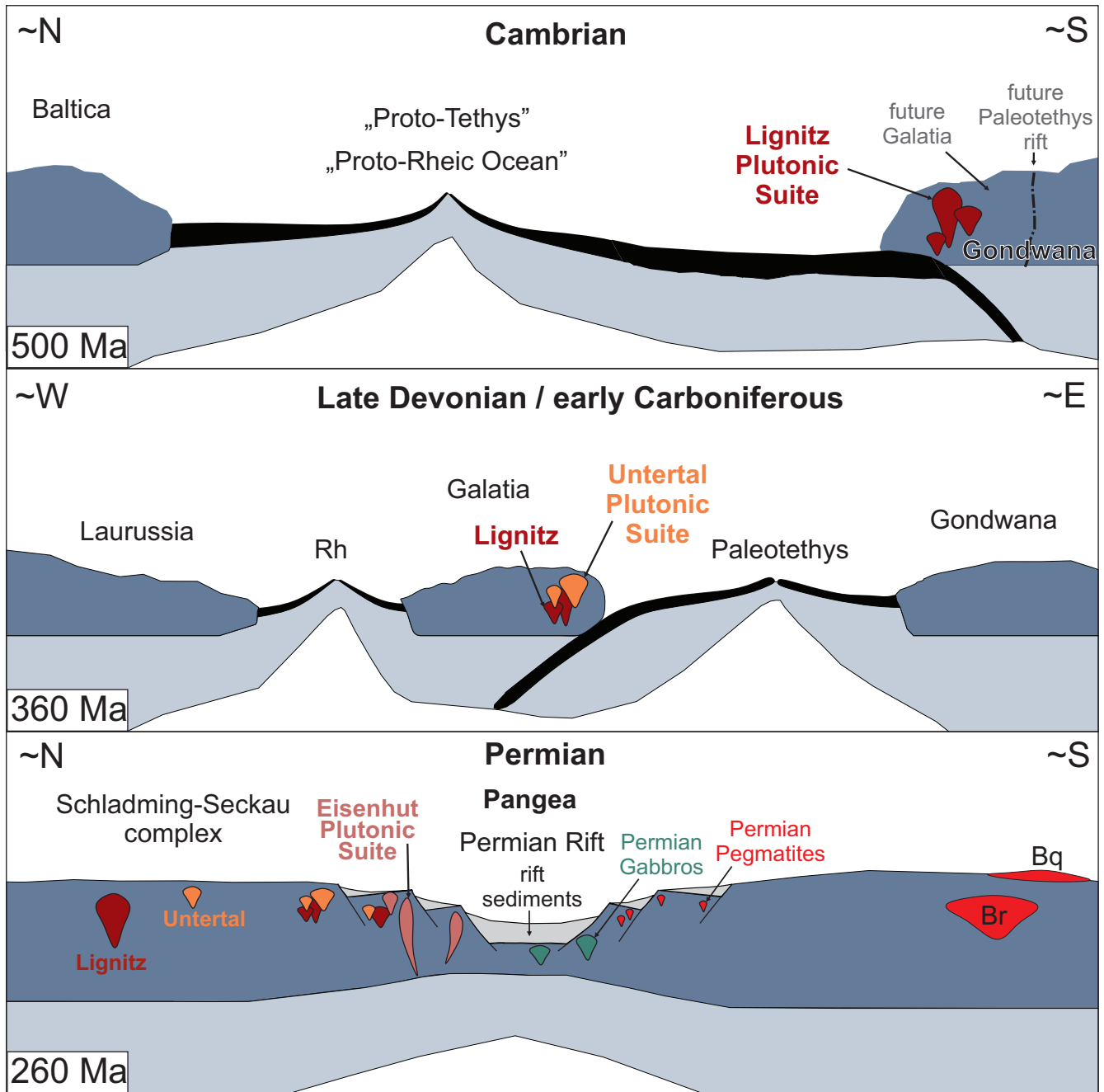


**Figure 12:** Simplified tectonic profiles for Cambrian to Permian (500–260 Ma) times showing the tectonic setting of the plutonic suites during and after their emplacement (modified after Stampfli et al., 2011, 2013). The profiles are not to scale. Br: Brixner-, Kreuzberg-, Ifinger-Granite, Bq: Bozner Quarzporphyr. Cardinal directions refer to the present geographic reference frame.

Therefore, important questions concerning the Cambrian evolution of the pre-Alpine basement units remain: (1) Is there a continuum or dis-continuum of Neoproterozoic to Ordovician orogenic phases that occurred along the northeastern Gondwana margin, i.e., between the Cadomian and Ceneric phases? (2) How can continuous Neoproterozoic to Ordovician rift processes that are preserved in low-grade Paleozoic sequences within the Alps and many extra-Alpine domains (e.g., the Tepla Barrandium within the Bohemian Massif), and simultaneous active margin plutonism that evolved in metamorphic

basement domains, such as the Schladming and Seckau domains, be explained?

(1) The Cadomian orogeny (ca. 550 Ma), as defined by an unconformity between Neoproterozoic basement and Cambrian molasse in the north Armorican domain, is known as a ubiquitous orogenic phase. Nowadays the Cadomian arc is considered an active and retreating continental margin that existed around 550 Ma and contributed to the dis-integration of northern Gondwana (e.g., Linnemann et al., 2008). Cadomian-aged rocks including oceanic remnants (Ötztal-Stubai Complex: Konzett et al.,

2005; Miller and Thöni, 1995; Speik Complex: Melcher and Meisel, 2004) and acidic gneisses (Silvretta Nappe: Müller et al., 1996; Nilius et al., 2016; Defereggeng Complex: Schulz et al., 2004) do exist within the Austroalpine unit, Ceneric ages between ca 500 Ma and 440 Ma are, however, much more abundant, as exemplarily shown for the Seckau Complex and Schladming crystalline (see above). This indicates that the Ceneric phase is rather an independent orogenic event and not just a continuous prolongation of the Cadomian orogeny. Such a scenario is also supported by detrital zircon age spectra showing distinct Cadomian and Ceneric frequency peaks (e.g., Haas et al., 2020, Haas et al., in prep.; Siegesmund et al., 2023).

The late Cambrian Lignitz Plutonic Suite is likely related to the Ceneric event along the northern Gondwana margin, since an active margin represents a suitable setting for the generation of such magmas (Fig. 12). Zircon Hf isotopes indicate a mixed depleted mantle and crustal source. Cambrian meta-basites (amphibolites) indicating bimodal magmatism might have formed in the back arc of the subduction zone (according to Huang et al., 2021). However, the exact position of the Austroalpine unit (including the Silvretta-Seckau Nappe System) along the extensive Prototethys active margin cannot be resolved from granitoid data alone. The position shown in Figure 13 is rather inferred from detrital zircon age spectra defining possible source regions in northern Gondwana (e.g., Haas et al., 2020; Burda et al., 2021).

(2) The Cambrian to Ordovician (Ceneric) active margin setting preserved within the medium to high-grade metamorphosed Austroalpine unit is in strong contrast to the magmatic and sedimentary evolution recorded in low-grade Paleozoic sequences (e.g., the Greywacke zone). All over the Variscan belt, Paleozoic basins (e.g., the Ossa-Morena Zone in Spain), the Saxo-Thuringian unit and the Tepla Barrandium (Bohemian Massif) show a continuous formation of extensional basins in the back of the Cadomian arc (Linnemann et al., 2007). Those basins formed subsequent to the Cadomian orogeny as back-arc basins behind the Cadomian magmatic arc. Slab break-off of the subducted oceanic plate resulted in voluminous magmatism and formation of rift basins since early Cambrian times. This process continued during late Cambrian to early Ordovician times (Linnemann et al., 2007; Linnemann et al., 2008; Hajná et al., 2018; Syahputra et al., 2022; Zák et al., 2023). For the Bohemian Massif, Zák et al. (2023) proposed the existence of a hyperextended passive margin (Gondwana shelf) where extension occurred in protracted phases between 524 and 480 Ma associated with emplacement of felsic magmatics, submarine basaltic volcanism at ca. 470 Ma and rapid basin subsidence at ca. 458–452 Ma. This is also widely documented in other Variscan massifs of western Europe (e.g., Vanderhaeghe et al., 2020).

In the Eastern Alps, extensive Ordovician acidic magmatism occurs in all low-grade Paleozoic sequences (Greywacke Zone, Gurktal Alps, Carnic Alps: for overview

see Hubmann et al., 2014). The most complete magmatic succession is preserved in the Greywacke Zone where continuous acidic magmatism between ca. 480 and 445 Ma evolved simultaneously with deposition of passive margin sediments (Nievoll et al., 2022). In addition, detrital U-Pb zircon ages from siliciclastic metasediments of the Troiseck Complex (Reiser et al., 2024) and the Seckau Complex (Mandl et al., 2018) indicate a late Ediacaran to early Cambrian deposition age of volcanoclastic sequences deposited at a juvenile continental magmatic arc along the northeastern Gondwana margin during late Ediacaran to mid-Cambrian times (Mandl et al., 2018; Reiser et al., 2024).

The inconsistency of the simultaneous evolution of active margin magmatism as described here and elsewhere in the Alpine chain (e.g., Strona Ceneri Zone: Zurbriggen, 2017), and an extensional passive margin (e.g., Zák et al., 2023) is evident. This scenario can be reconciled with the formation of a rift / drift basin, such as the Paleotethys ocean (Fig. 12), in a back-arc position of the nearby Ceneric subduction. Parts of the related magmatic arc are preserved in the Lignitz Plutonic Suite. Another explanation was provided by Finger and Riegler (2023), who place the intra-Alpine basement units in a domain where the Gondwana margin bends at a nearly right angle from west to north in the Ordovician (Fig. 13). According to this model, plate motion resulted in the evolution of a hyperextended margin along the west trending branch, and subduction-accretion and associated magmatism along the north trending Gondwana margin.

### 7.3.2. Variscan evolution

Variscan subduction and collision are best documented by the presence of eclogites that show significant age scatter within the Eastern Alps (390–313 Ma) (see Hauke et al., 2019, for summary). A first early Variscan high-pressure (HP) event occurred during Early Devonian times (ca. 390 Ma) (Faryad et al., 2002). Until now, no magmatic expression (i.e., granitoid age) has been detected that correlates with this metamorphic event within the Austroalpine unit. This HP event was followed by crustal extension along the northern Gondwana margin, starting with the formation of several back-arc basins during the break-off of the Galatian superterrane (e.g., Stampfli et al., 2011, 2013) that were probably closed diachronously. Similarly, rifting and subsequent drifting of terranes in combination with the opening of the Rhenohercynian ocean presumably occurred at the southern Laurussia margin (von Raumer et al., 2015; Stampfli and Borel, 2002) (Fig. 13). The terranes deriving from the northern Gondwana margin collided with the Laurussian-derived crustal fragments during the Late Devonian (von Raumer et al., 2003), which is considered as the main Variscan event (e.g., Stampfli and Borel, 2002, von Raumer et al., 2015). The amalgamation of these terranes was followed by subduction of the Paleotethys to the north and its subsequent closure (e.g., Stampfli et al., 2013) (Fig. 12).

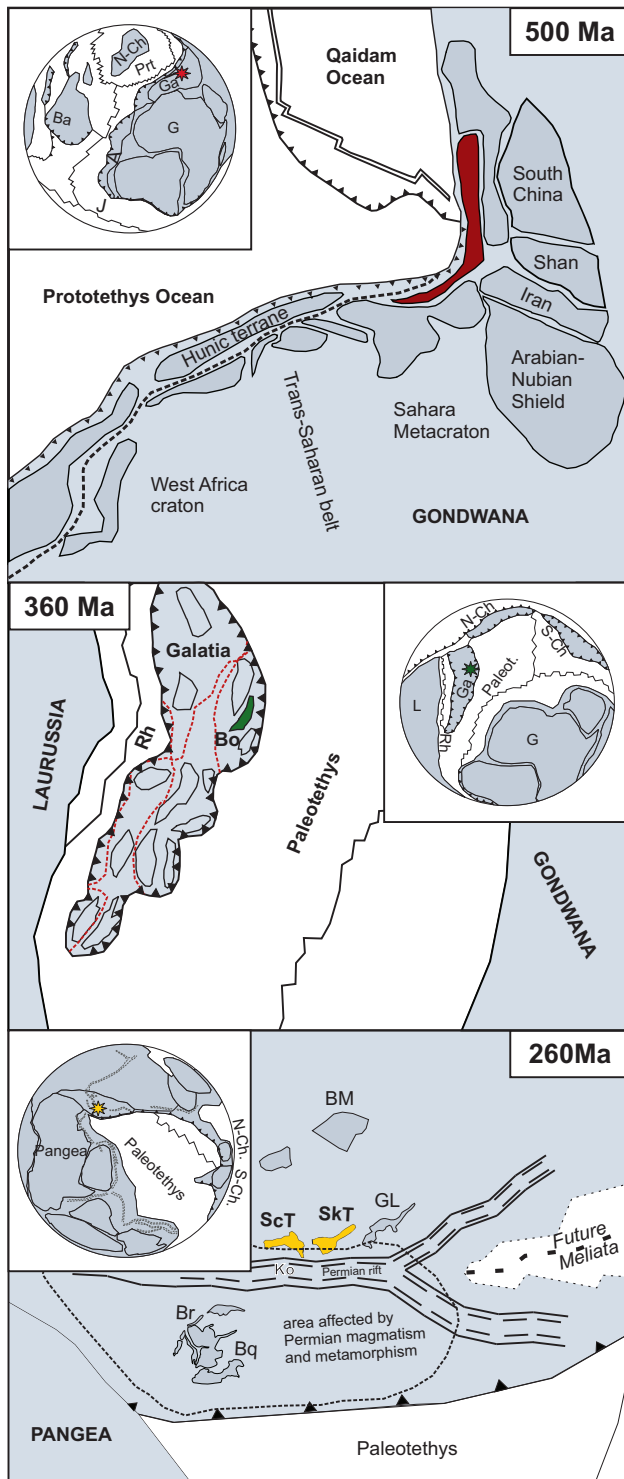


**Figure 13:** Paleogeographic position and evolution of the three suites through the Paleozoic. The assumed position of the Silvretta – Seckau Nappe System is shown by the red, green and yellow shading in the Cambrian, Late Devonian / early Carboniferous and Permian reconstructions, respectively. Dashed red lines mark micro-terrane boundaries / sutures within Galatia for the Late Devonian reconstruction. The paleogeographic reconstructions are modified after Burda et al. (2021), Mandl et al. (2018, 2022), Haas et al. (2020), von Raumer and Stampfli (2008), von Raumer et al. (2013) and Stampfli et al. (2013). A: Avalonia, B: Baltica, Br: Brixner-, Kreuzberg-, Ifinger-Granite, Bq: Bozener Quartzporphyr, N-Ch: North China, S-Ch: South China, G: Gondwana, Ga: Galatia, Bo: Bohemia; BM: Bohemian Massif, ScT: Schladminger Tauern, SkT: Seckauer Tauern, GL: Gleinalm, Ko: Koralpe (including Permian gabbro intrusions); Paleot.: Paleotethys, Prt: Prototethys, Rh: Rhenohercynian.

tian margin can most likely be excluded, as Late Mississippian to Pennsylvanian ages (the time of accretion of the Galatian microcontinent to Laurussia) have not been observed in the Untertal Plutonic Suite. A peraluminous character and depletion in Nb and Ti relative to LILE and REE (Fig. 11c-d), and low Nb/Ta and Nb/La ratios are characteristic for convergent margin magmatism initiated by dehydration of amphibole in a subduction zone setting (Foley et al., 2002). The geochemical signature is also consistent with volcanic arc granites (VAG in Fig. 10). This suite incorporated material of the older Lignitz Plutonic Suite, as indicated by zircon cores of Cambrian age and Hf isotopic composition (Fig. 8; Table 3). This magmatic event was also recorded in the Hintertal Plutonic Suite of the Seckau Complex, which is presumably associated with a continental arc setting (Mandl et al., 2018), and within the Troiseck Complex (Reiser et al., 2024). Similar and younger ages were reported for samples equivalent to the Untertal Plutonic Suite (Huang et al., 2021) and have been interpreted as metamorphic ages related to the thickening of Variscan crust.

A similar evolution is also documented for other basement complexes within the Alpine realm. Tonalites of the Gleinalm-Rennfeld Complex in the Eastern Alps (ca. 363–350 Ma) (Neubauer and Frisch, 1993) are interpreted as subduction-related magmatism (Neubauer et al., 2000). Additionally, slightly older metamorphic ages can be found within the Wechsel Gneiss Complex (Müller et al., 1999) and the Kaintaleck Complex (ca. 390 Ma) within the Eastern Alps and the Southalpine basement (Neubauer et al., 2002). Mississippian granitic to tonalitic magmatism is also described by Putiš et al. (2008) in the Western Carpathians. Furthermore, in the western Tatra mountains, metamorphic ages of ca. 360 Ma were interpreted to be related to an onset of subduction of the Paleotethys in the Devonian (Burda et al., 2021). In the western part of the Eastern Alps, e.g., the Ötztal-Stubai Complex and the Ulten Zone, high-pressure metamorphic units with Late Devonian to Carboniferous metamorphic ages have been documented (e.g., Miller and Thöni, 1995). It is very likely that these high-pressure units represent the subduction zone that correlates with the magmatic arc described above.

In the Schladming crystalline, intrusion of the Untertal Plutonic Suite occurred during Late Devonian / early Carboniferous times (Fig. 12). The calc-alkaline magmatism likely formed within a continental arc setting. A potential location of that arc is near the southern rim of the Galatian terrane (probably somewhere south of the present-day Bohemian massif) (Fig. 13). The Bohemian Massif itself is presumed to be part of Armorica at that time (Finger and Riegler, 2025). A location on the northern Gala-

### 7.3.3. Post-Variscan evolution

Collision following Paleotethys subduction and final Variscan orogeny (Fig. 12) culminated in the formation of Pangea and lasted until early Permian times (Stampfli et al., 2013). Rollback of the subducted Paleotethys oceanic slab resulted in lithospheric extension, also documented within the Alpine realm by Permian high-temperature metamorphism, magmatism, and the formation of rift basins (von Raumer et al., 2003; Stampfli and Borel, 2002). Following the collapse of the Variscan orogenic belt, the opening of the Neotethys ocean started during Permian times (Stampfli et al., 2002, 2013; Stampfli and Borel, 2002). Permian low-pressure – high-temperature metamorphism caused by lithospheric thinning accompanied by magmatic underplating and partial melting of the lower crust finally gave rise to the opening of the Meliata ocean, an embayment forming the western part of the Neotethys, and sag-stage subsidence (Schuster and Stüwe, 2008).

In the Schladming crystalline, the Permian evolution is recorded by the Eisenhut Plutonic Suite with granitoids of Permian age (ca. 260 Ma) (Fig. 12). Schermaier et al. (1997) have already recognized these granitoids in the eastern part of the Schladming crystalline as a distinct group and, based on geochemical correlations with similar granites in the Tauern Window, assumed a Permian age. The ferroan character, trace element and REE patterns of this suite are consistent with partial melting of a deep, anhydrous source (e.g., Aranovich et al., 2014). Moreover, this suite is characterized by signatures of within-plate granites and syn-collisional granites (Fig. 10), which points to a complex origin. Slightly elevated Hf isotope signatures (Fig. 8) support melting of a lower crustal source or may indicate a minor contribution of a mantle source. Melting of the lower crust with or without the contribution of a mantle melt might be related to mantle exhumation and related advective heat transfer within an extensional tectonic setting.

Permian rifting likely led to the formation of several graben structures similar to a Basin and Range-type setting, which have also been observed in other parts of the Alpine-Carpathian realm (Finger et al., 2003; Petra et al., 2011; Reiser et al., 2024). The Eisenhut Plutonic Suite was presumably emplaced along the southern border of a continental high (horst), comprising the later Schladming crystalline and the Seckau Complex (Fig. 12), while clastic sedimentary sequences were deposited within nearby graben structures, all of which were later incorporated into several Austroalpine units during Eo-Alpine nappe assembly.

Permian rifting and voluminous magmatism of Permian to Triassic age affected the entire Variscan chain (Stampfli et al., 2013). Magmatic ages of ca. 240 Ma within the Schladming crystalline are interpreted as a response to the subduction of the Paleotethys and the related opening of a back arc basin and spreading of the Meliata ocean (Huang et al., 2022). In the Southalpine unit, igneous rocks show age ranges of ca. 280–270 Ma (e.g.,

Klötzli et al., 2003), which have also been reported in the Carpathians (Putiš et al., 2019 and references therein). Within the Austroalpine unit, Permian granitoids were recognized in the Raabalpen Complex of the Wechsel crystalline basement (Yuan et al., 2020), the Troiseck Complex (ca. 271 Ma) (Reiser et al., 2024), and in the Pohorje Complex (Chang et al., 2020). The Orthogneisses of the Pohorje Complex (Chang et al., 2020), which are similar to the Eisenhut Plutonic Suite and are also attributed to the break-up of Pangea, however, show very different  $\epsilon_{\text{Hf}}$  values (ca. -13.7) representative of continental crust. Reiser et al. (2024) also suggested an extensional (rift-related) setting for high-temperature magma generation and bimodal magmatism preserved within the Troiseck Complex. Similarly, Chang et al. (2021) proposed that post-Variscan transtension and Triassic rifting started a long-lasting process that resulted in the break-up of Pangea and subsequent spreading of the Meliata ocean during Middle to Late Triassic times. The granitoids of the Eisenhut Plutonic Suite of this study, however, yielded older mid-Permian ages (ca. 261–263 Ma), which do not support a direct link to the opening of the Meliata ocean.

Within the Schladming crystalline, the granitoids of Permian age are generally located along its southern margin. Permian granitoids have not been reported so far from the Seckau Complex, however, Neubauer et al. (2022) recently described strongly sheared augengneisses, very similar to the augengneisses analyzed in this study, with a protolith age of  $272 \pm 5$  Ma from the Speik Complex within the Gleinalm crystalline unit. Pegmatites of the same age preferably pile up in those parts where the augengneisses discordantly cross the lithological units of the Speik Complex. These augengneisses represent the southernmost occurrences of Permian granitoids within the Silvretta-Seckau Nappe System. North of these exposures, neither Permian magmatism nor Permian metamorphism are present within this unit (e.g., Kurz et al., 2024). Towards south (in paleogeographic terms), however, Permian magmatism and high-temperature metamorphism are widely distributed, in particular within the Koralpe – Wölz Nappe System (e.g., Schuster and Stüwe 2008; Stüwe and Schuster 2010; Neubauer et al., 2022; Kurz et al., 2024), and within the Southalpine realm (e.g., the Brixen granite and the rhyolitic Bozen quartz-porphyr) (e.g., Cassinis and Perotti, 2007, and references therein) (Fig. 13). In these domains the lithosphere became continuously thinner, resulting in heat advection from the sub-lithospheric mantle associated with high-temperature – low pressure metamorphism and various magmatism. Permian gabbroic intrusions with ages of ca. 275 to 247 Ma (Thöni and Jagoutz, 1992; Miller and Thöni, 1997), later incorporated into the Koralpe-Wölz Nappe System and affected by Eo-Alpine eclogite facies metamorphism, likely formed within the central, highly thinned parts of that rift system (Figs. 12–13), probably involving mantle-derived melt. The Permian granitoids within the Schladming crystalline formed presumably adjacent to that rift system along its north-

ern margin (within the present geographical reference system) (Figs. 12–13). The heterogeneous geochemical composition of these granitoids may be related to the various local sources that were affected by and assimilated during melting and/or the varying degree of melting.

## 8. Conclusion

New U-Pb zircon ages, geochemical whole rock, zircon trace element and Hf isotope data indicate that pre-Alpine crystalline basement units of the Schladming crystalline comprise pre-Variscan, Variscan and post-Variscan igneous suites:

1. The Lignitz Plutonic Suite basically originated from a highly fractionated granitic melt. This suite is characterized by a met- to peraluminous, magnesian to ferroan and calc-alkalic character. Its high compositional diversity may be related to a mafic magma source contaminated by crustal components. This suite has Cambrian intrusion ages of ca. 500 Ma, similar in age and characteristics to the Hochreichart Plutonic Suite of the Seckau Complex. The Hf-isotopes indicate a varying degree of crustal contribution within the suite, where a melt from a juvenile source assimilated crustal material during magma ascent through the crust and/or emplacement in the crust. We propose an active margin setting, probably related to the Ceneric magmatic arc along the northern Gondwana margin.
2. The Untertal Plutonic Suite is characterized by meta-granites to meta-granodiorites. Similar major element characteristics and U-Pb zircon ages ranging from 350 to 370 Ma correlate this suite with the Hintertal Plutonic Suite of the Seckau Complex. It is a less fractionated suite within the Schladming crystalline. The rocks are peraluminous, mostly magnesian and have calc-alkalic to alkali-calcic affinities. Zircon cores and Hf-isotopes indicate reworking of at least some of the material of the Cambrian Lignitz Plutonic Suite. A crustal influence and a metabasic granulitic crustal source align with incorporation of material from the older Lignitz Plutonic Suite during magma ascent. Magmatic activity around 355–360 Ma is the major Variscan magmatic event preserved within the Silvretta-Seckau Nappe System (and the entire Eastern Alps) that probably occurred within a magmatic arc along the southern Bohemian active margin. The active continental margin was probably located near the southern rim of the Galatian terrane.
3. The meta-granitoids of the Eisenhut Plutonic Suite only occur within the southeastern part of the Schladming crystalline. U-Pb zircon ages range from 261 to 263 Ma and probably correlate with similar aged rocks within the Gleinalm crystalline unit and the Troiseck-Floning Complex. This highly fractionated granitic suite shows crustal affinity and comprises within plate granite and syn-collisional

granite signatures. This suite is peraluminous, ferroan and has a calc-alkalic to alkali-calcic character. It probably originated from partial melting of a dry granulitic residue after extraction of an earlier melt phase. Hf-isotopes are consistent with such a scenario and indicate assimilation of crustal material. It is very likely that this suite formed during lithospheric extension along the northern margin of a wider Permian rift in the context of the breakup of Pangea.

## Acknowledgements

This study was supported by the University of Graz by providing a four years doctorate position for I. Haas. The authors thank Fritz Finger and Jonas Vanadois for their reviews and constructive comments, and Hugo Ortner as handling editor of AJES.

## Supplementary figures and tables

Supplementary figures and tables are provided at the TETHYS Research data base system of Geosphere Austria (<https://doi.org/10.24341/tethys.289>).

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Received: 24.2.2026

Accepted: 28.7.2026

Editorial Handling: Hugo Ortner